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Screw displacement pile shaft deformations measured by vibrating wire and fiber optic systems during a static load test

Déformations de l'arbre du pieu à déplacement de vis mesurées par des systèmes à corde vibrante et à fibre optique lors d'un essai de charge statique

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ABSTRACT: This paper describes a full scale static load test performed on a 400 mm diameter screw displacement pile equipped with four different strain measuring systems. Three types of vibrating wire strain gauges (VWSG) were used: global - retrievable, local attached to steel pipe and local concrete embedded. The fourth system was distributed fiber optic sensors based on Rayleigh back scattering (DFOS) - three in the pile cross section. It is generally assumed that the combined cross section deforms equally. However, especially in the upper part of the pile, stress and therefore strain distribution might be non-uniform. In the case of steel tube (installed centrally in the pile axis), additional sliding effect may occur. Pile bending and local shaft imperfection may also affect strain readings, therefore using multiple gauges in a single plane might be necessary for proper result interpretation. Those assumptions were verified in the paper as the differences in readings have significant influence on final load distribution interpretation. Adaptation of several strain measurement techniques in one test allowed their applicability assessment and effectiveness verification.

RÉSUMÉ : Cet article décrit un essai de charge statique à grande échelle effectué sur un pieu à déplacement de vis de 400 mm de diamètre équipé de quatre systèmes de mesure de déformation différents. Trois types de jauges de contrainte à corde vibrante (VWSG) ont été utilisés : global - récupérable; local attaché au tuyau d'acier; capteurs locaux à fibre optique intégrés et distribués dans le béton basés sur la rétrodiffusion de Rayleigh (DFOS) - trois dans la section transversale du pieu. On suppose généralement que la section transversale combinée se déforme d'une manière uniforme. Cependant, en particulier dans la partie supérieure du pieu, la distribution des contraintes et donc des déformations peut être non uniforme. Dans le cas d'un tube en acier (installé au centre dans l'axe du pieu), un effet de glissement supplémentaire peut se produire. La flexion du pieu et l'imperfection locale de l'arbre peuvent également affecter les lectures de contrainte, par conséquent, l'utilisation de plusieurs jauges dans un seul plan peut être nécessaire pour une interprétation correcte des résultats. Ces hypothèses ont été vérifiées dans l'article, car les différences de lecture ont une influence significative sur l'interprétation de la répartition de la charge finale. L'adaptation de plusieurs techniques de mesure de déformation en un seul essai a permis d'évaluer leur applicabilité et de vérifier leur efficacité.

KEYWORDS: static pile load test, instrumented pile, vibrating wire strain gauge, fiber optic, pile load distribution

1 INTRODUCTION.

Static load tests on instrumented piles equipped with strain measuring devices are performed in order to determine the axial force distribution along the pile shaft. Compared to a standard load capacity test, instrumented pile measurements provide detailed and quantitative information on pile - soil interaction. Instrumentation is also used for pile condition control - possible presence of any imperfections and discontinuities. General principle of such test is to insert a strain measuring systems into the pile shaft before the load test and take readings during static incremental loading (Krasinski and Sienko, 2010). Several measurement techniques are currently available, most of which rely on the vibrating wire systems and optical fiber cables (embedded). Older measurement methods, such as steel rods embedded in pile shafts or electro-resistive strain gauges, have been virtually abandoned due to high workload, low measurement accuracy, and high sensitivity to other factors, such as temperature and humidity (Fellenius et al, 2000). Based on the pile shaft deformation measurements, carried out at various depths, axial load distribution along the pile is determined (Sinnreich, 2011).

However, there are several factors that must be considered in proper load distribution determination. One of them is concrete modulus estimation (required for strain to stress conversion). A good practice is to uncover the soil from the first section of the pile, where the first strain gauge is located. Then modulus values can be estimated from the strain - stress characteristic. Problems regarding concrete modulus determination and a critical view on possible methods for its estimation were presented by Lam and Jefferis (2011).

Another factor that affects proper load distribution is the residual force, which might be present in the pile shaft even before the load test was started. Such forces are generated after pile installation by soil reconsolidation process (very common in displacement pile technology). Residual forces cause the presence of locked in strains in the shaft and during the load test when force direction in soil changes those strains remain unmeasured (as there was no relaxation in the pile shaft, only force direction has changed). The issue of residual forces has been studied by Fellenius et al. (2000, 2015), Siegel and McGillivray (2010), Sahajda (2015), Van Impe et al. (2013) and other researchers.

Load distribution may also be affected by local pile imperfections (e.g. soil inclusions, diameter change) or concrete modulus changes along the shaft, that highly influence strain readings (Krasinski and Wiszniewski, 2017).

Strain measurement techniques have been significantly improved and became much more accessible in recent years. Vibrating wire strain gauges (VWSG) are still the most commonly used. Available are local spot gauges, that can be placed at several depths along pile shaft or global retrievable strain extensometers placed centrally in the pile axis. Impressive progress has been made in the field of fiber optic technology resulting in the development of distributed fiber optic sensors (DFOS). This system allows for a continuous strain measurement along the structure. Sensors map physical fields acting on the fiber by exploiting the scattering processes that take place in it, and probing the fiber with proper interrogation systems (Palmieri and Schenato, 2013). Raman, Brillouin and Rayleigh scattering might be chosen to generate back propagating light than can be used to “read” the local properties. Raman scattering is successfully used in temperature sensing. Rayleigh scattering gives higher special resolution than Brillouin, might be even lower than 1 mm (while Brillouin 0.5 m). Rayleigh based interrogators are also easier to operate.

This paper focuses on deformation measurements. A comparative study of four different strain measuring systems (DFOS and VWSG) applied in a screw displacement pile is presented. Retrievable extensometers that measure sectional deformations and two types of spot strain gauges were used, one attached to the steel tube, the other embedded directly in concrete body. The reason for that was to verify if both materials deform equally, especially in top part of the pile. Study presents a use of a Rayleigh based DFOS system which is a great alternative to VWSG. Optical fiber sensors provide detailed continuous strain information along the entire pile shaft. Advantages and disadvantages of each technique are discussed in the paper.

2 MATERIALS AND METHODS

2.1 *Experimental field conditions*

Pile testing was conducted at private experimental field located near the city of Elblag in Poland. The subsoil mostly composed of normally consolidated cohesive soils. Boring indicated a 2.70 m thick layer of uncontrolled embankment (fine sand mixed with clayey sand and stones), then around 1.0 m of gravel, next 5.5 m sandy clay with fine sand interlayers, and then 6.0 m of sandy clay with some stones. The result of CPTu sounding performed at the exact pile location is shown in Fig. 1. Ground water table was located 1.70 m below the ground level.

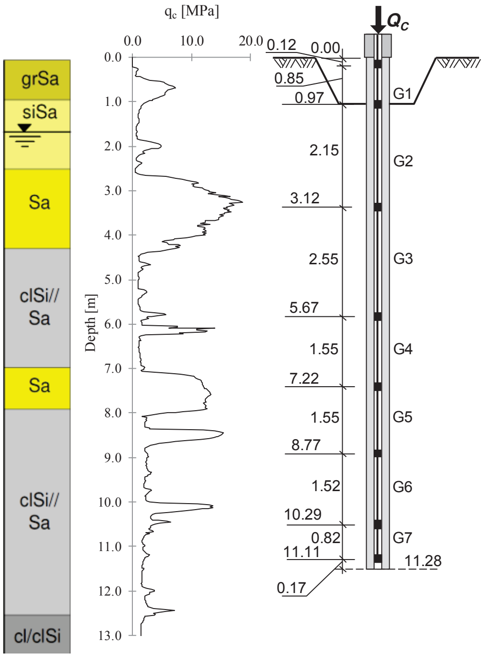

Figure 1. CPT sounding, soil and pile profile.

2.2 *Test pile*

In total 10 screw displacement piles were installed at the experimental field (4 test piles and 6 reaction piles). In this study, pile No 9 with diameter of 400 mm and length of 11.30 m is considered. Pile scheme with divided measuring sections is show in Fig.1. The 300 mm outer diameter reinforcing cage consisted of six Ø16 main rebars and Ø6 spiral reinforcement with 250 mm spacing. Concrete class of C25/30 was used.

2.3 *Strain measuring systems*

Pile was equipped with four independent strain measuring systems. Pile cross section and installed gauges are shown in Fig.2 and Fig.3.

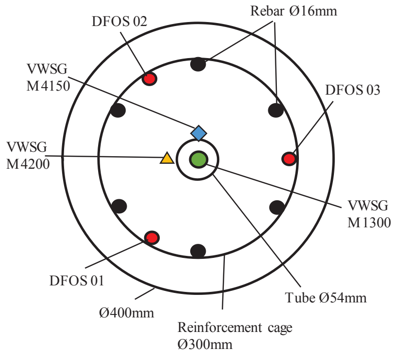

Figure 2. Pile cross section.

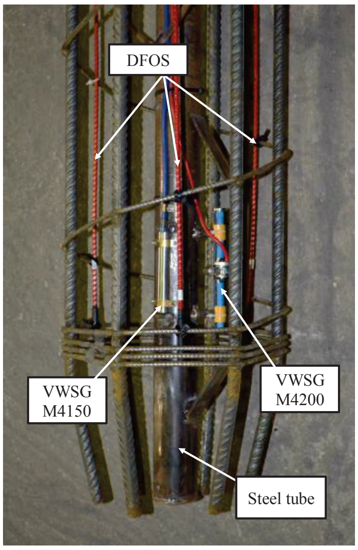

Figure 3. Reinforcement cage with instrumentation.

2.3.1 *Vibrating wire strain gauges (VWSG)*

Three types of VWSG were used in the pile, all manufactured by Geokon Company (Geokon.com):

1. Model 1300 (A-9) Retrievable Extensometer System, which consisted of 7 strain gauges that were installed just before the test in a steel tube casted in the pile structure (see Fig.4). The tube was placed centrally in the pile, which allowed to assume that measured strain is the average strain of the whole cross section (to be verified later in the paper). System certainly has some advantages, first of all, it is reusable (strain gauges can be used multiple times), as only the steel tube is “lost” in each test and that makes it economically viable and very efficient; allows to measure total shortening of the pile shaft; generally, only one tube placed centrally is used to determine the average cross section strain, that cuts the costs, makes it easier and faster to operate, but at the same time it might be a system’s disadvantage,

when pile is subjected to substantial bending. Strain is measured in relatively large sections, which allows to only approximate the strain value in the middle of each section. If the subsoil is highly non-homogenous and there are possibilities of pile shaft imperfections (changes in diameter or soil inclusions), then it could be a serious disadvantage of the system, as it would give false readings with no indication where exactly anomalies are located, making it hard to interpret the results properly (often very difficult is to predict or assess how significant the imperfection could be). In the test, sections lengths were set to (from the pile top to bottom): 0.85, 2.15, 2.55, 1.55, 1.55, 1.52 and 0.82 m, which allowed to determine the strain values at the depths of 0.55, 2.05, 4.40, 6.45, 8.00, 9.53 and 10.70 m below the pile head level (pile sections were shown in Fig.1.)

Figure 4. VWSG Model 1300 A-9 installation in a pile.

2. Model 4150, which is a spot weldable strain gauge. System consisted of 4 gauges, placed at 0.50, 3.60, 7.00 and 11.00 m. VWSGs were glued to the steel tube in a single line (only one gauge in the pile cross section, placed centrally). Gauges were 51 mm long and allowed to measure only local strain at certain depths (in opposite to previous sectional system). It is a single use (lost) system, which makes it more expensive to utilize. Usually gauges are installed in pairs (each on the opposite cross section side) to determine the average strains (in case of pile bending) and that makes it even more costly.

3. Model 4200, which is a concrete embedment strain gauge. System consisted of 4 gauges, placed in one line next the model 4150 (same depths). Installing those two different systems (first on the steel tube, second embedded in concrete), allowed to assess if any differences in measured strains occurred along the pile shaft. Steel tube has smooth surface and is empty inside (only surrounded by concrete mix) plus the load is applied only to the concrete surface as sensor cables come out from the tube. All that creates a potential risk of sliding effect and differences in strain readings.

2.3.2 *Distributed fiber optic sensors (DFOS)*

Test pile was also instrumented with 3 lines of distributed fiber optic sensors (model EpsilonRebar) as shown previously in Fig.2 and Fig.3. Gauges were manufactured by a Polish company SHM System. Thin optical fiber is covered in protective fiberglass coating. Materials are combined into one uniform element, which looks similar to a steel reinforcement bar. Gauge's feasibility allows their simple and easy installation. DFOS cables were fixed to the reinforcement cage from the pile head to the pile toe. Fiber optic technology allows a continuous strain measurement along the entire pile shaft, which is a great advantage comparing to previous techniques. In the study an optical reflectometer based on Rayleigh back scattering was used. Spatial resolution was set to 1 cm. Interrogation unit (OBR4600 Luna Technologies) provided strain data with a resolution of 1 με. Details of Rayleigh-based distributed fiber optic technology can be found in Palmieri and Schenato (2013). As the readings were only taken during the short time of static load test, there was no need for additional temperature gauge installation (all VWSG had temperature thermistors).

2.4 *Static pile load test*

Static load testing was performed 28 days after pile installation. Steel beam and reaction piles were used to setup the test. Loads were applied by a single hydraulic jack and measured with a load cell. The pile head displacement was measured by 4 analog gauges attached to a reference frame. Test was performed as a maintained load test, in which the applied load was increased in stages and maintained constant for 30 minutes at each stage. Single load increase was equal to about 80 kN. Time/displacement curve was recorded at each stage.

3 TEST RESULTS

3.1 *Static pile load test results*

The pile was loaded up to the maximum value of 1163 kN and the pile head displacement reached 38.37 mm, which corresponded to 9.59 % of the pile diameter. Fig. 5 shows the load-displacement curve at the pile head level.

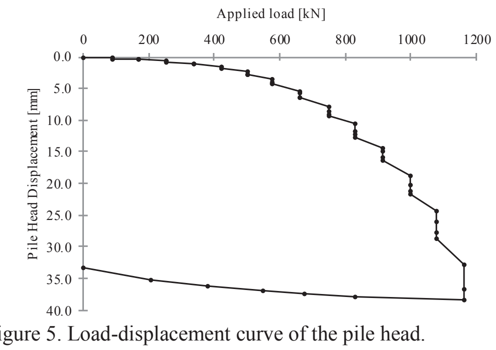

Figure 5. Load-displacement curve of the pile head.

3.2 *Strain measurements*

All gauges (VWSG and DFOS) worked correctly through the test, none was damaged while the reinforcement cage installation. Fig.6. shows strains measured by seven retrievable extensometers during the static load test. Values correctly decrease with depth. Maximum strain reached 375 με for 1163 kN at the first measuring section. Strain in last pile section was equal to 40 με for the same load. Fig.7. shows deformations measured by both spot VWSGs. Concrete embedded gauge recorded generally higher strain values, e.g. for maximum load at 0.5 m: concrete embedded - 454 με and steel attached - 370 με, which is a 23 % difference; at 3.60 m 209 με and 186 με (12 %), at 7.00 m 117 με and 100 με (17%), at 11.00 m 27 με and 28 με (6 %).

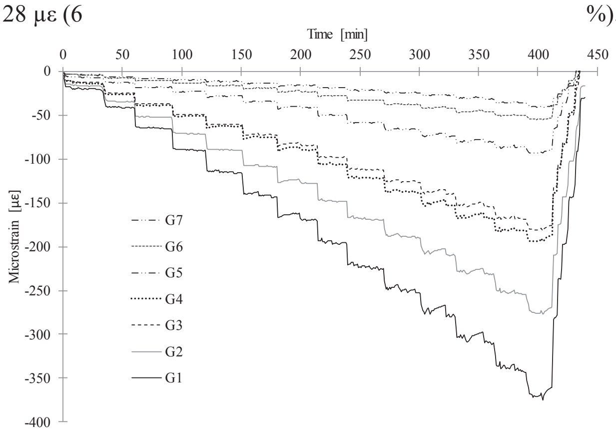

Figure 6. Strain measured by retrievable extensometers.

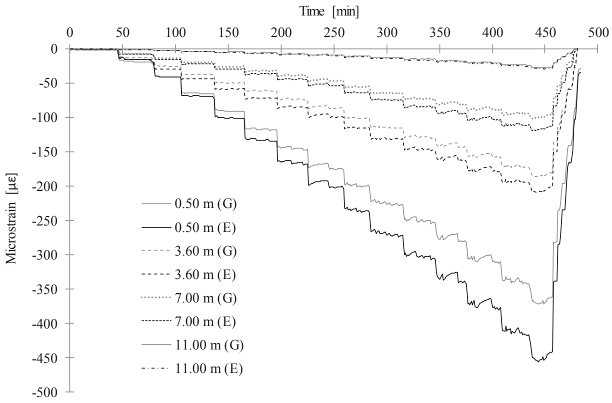

Figure 7. Strain measured by steel attached (G) and concrete embedded gauges (E).

Fig.8. presents strain distribution measured by 3 DFOS cables along the pile shaft. DFOS 02 recorded higher strain values than other gauges in the first section of the pile (first 1 m), DFOS 02 - 530 με while DFOS 01 - 270 με and DFOS 03 - 330 με. That means DFOS 02 showed almost two times greater strain than DFOS 01 (196%). The difference significantly decreased further down the pile (from about 1.5 m below the pile head level) and the readings from all three gauges were more uniform (differences of about 20 %). This shows that the compression loads were distributed more equally in pile cross section further down the pile and it took about 1.5 m to equalize this load distribution. Differences in particular DFOS readings for the maximum load value at several depths are presented in Fig. 9. All three gauges have also shown an increase in strain values at the depth of 4 to 5 meters, which indicated possible shaft imperfections (either geometrical - diameter change or material - lower concrete stiffness).

Fig.10. presents the average strain distribution measured by three DFOS gauges along the pile length during the static load test. Readings are presented for all 14 load stages. For the maximum load value of 1163 kN, maximum strain at the depth of 0.5 m was equal to 382 με and generally decreased with depth to a value of 30 με at the pile toe. Strain distributions decreased similarly for the other load stages. Load distribution is calculated accordingly to measured strains (higher strain equals higher load), which means that the load applied at the pile head was mostly carried by soil friction resistance around the pile shaft, not by the resistance under the pile base.

The use of fiber optic continuous measurement technology allows the pile core quality assessment. The most significant strain discontinuities were observed at the depth of 3.90 to 5.00 m (visible even at the initial phases of the loading test and getting more pronounced as the load test progressed). Some small changes have also been noticed at the depths of 1.55, 2.05, 6.37, and 9.20 m. Applied load cannot increase at a certain depth to cause an increase in strain. Negative skin friction is not a case here, it may develop in a longer time period, not during a quick static load test. Therefore, strain increase indicates some local changes in pile shaft stiffness (EA), either a decrease in shaft diameter or a decrease in concrete quality (sometimes both). Local imperfections might be caused by piling machine operator's fault such as: improper speed of pile concreting, improper pressure during concrete mix pumping or breaks during pile installation. Imperfection may also be caused by the soil conditions: presence of very soft organic soils that might cause soil inclusions in the pile shaft, soil layering, e.g. cohesive organic and non-cohesive sands will have very different reaction to pore water pressure increase during pile installation and same during the excess pressure dissipation after the installation. Soft cohesive soils tend to rebound more than non-cohesive stiffer soils and therefore tend to decrease the pile diameter, especially near the area of soil layer change. Increased water outflow from concrete mix in sandy soils is also possible and may cause an increase in pile shaft stiffness. Continuous strain measurement system gives a chance to identify the presence of mentioned above anomalies and to apply required corrections in order to determine a proper strain distribution and later a proper load distribution along the pile.

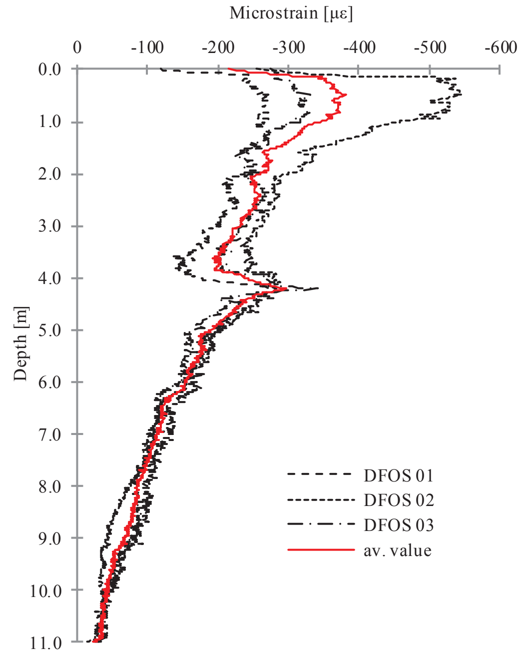

Figure 8. DFOS strain distribution along the pile shaft for the maximum load value.

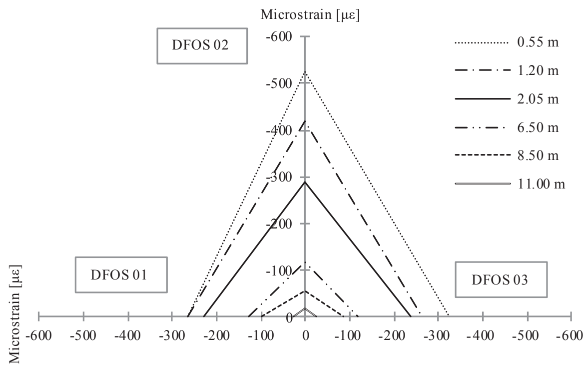

Figure 9. Discrepancies in DFOS strain readings at chosen depths for the maximum load applied.

A comparison of strain readings at various depths and for all loading stages has been performed between DFOS and other three VWSG systems. Measurements at the same depth and under the same load for the pairs of gauges are shown in Fig.11.

For DFOS vs. local M4115 glued gauge (A) a good agreement was achieved, readings correlate well along the red equality line for all loads, at all depths. In case of DFOS vs. local M4200 (concrete embedded) gauge (B), the difference of ~20 % at 0.5 m depth was recorded. At other three depths results correlate very well. As for the DFOS vs. M1300 (retrievable) (C), the results at 4.40 and 6.45 m depths move away from the equality line due to mentioned earlier pile shaft imperfections. At other depths results also correlate pretty well.

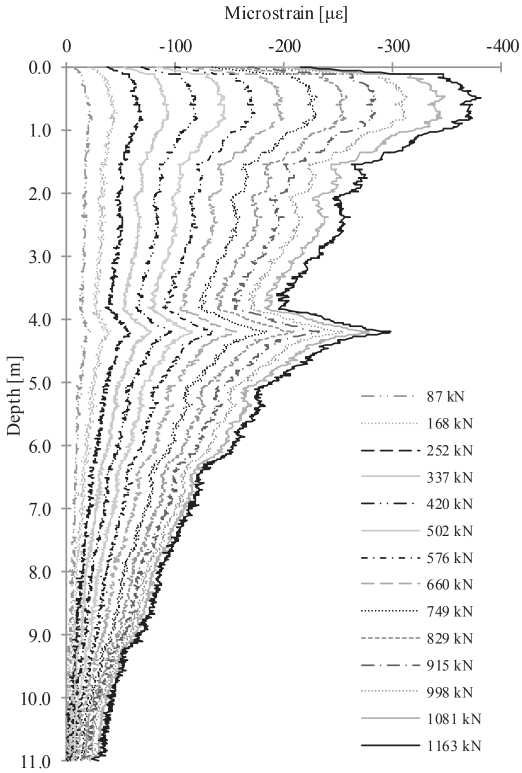

Figure 10. DFOS strain distribution along the pile shaft during the test.

Fig. 12. presents strain distributions along the pile shaft measured by all four systems for three selected load values: 252 kN, 576 kN and 1163 kN. Results from retrievable extensometers are shown in the middle points of each measuring section. Local VWSGs correspond pretty well with DFOSs, except for the first M4200 gauge, which has shown higher strain values. At a depth of 0.5 m for the load 576 kN concrete embedded gauge showed the strain equal to 200 με while all other gauges around 170 με, which is ~ 18 % difference; for the load of 1163 kN the difference increased to ~ 23 %. The reason is not necessary the sliding effect of the steel tube, it might be the fact, that there was only one M4200 gauge at certain pile cross section and also not perfectly centered in the pile axis (distanced 3 cm from the steel tube). As shown in Fig.8. the load was not equally distributed in the upper part of the pile (first 1.5 m). Therefore, the M4200 gauge readings at the 0.5 m depth were closer to the DFOS 02 readings rather than to other centrally places VWSGs or averaged DFOSs readings. For greater depths (where strains equalize in pile cross section, as shown previously in Fig.8.) strain readings of concrete embedded gauges (M4200) correspond pretty well with other measuring systems (DFOS and M4150).

The M1300 A9 Retrievable extensometer system was unable to properly identify local imperfections of the pile shaft. As strains are measured in relatively long sections (0.85, 2.15, 2.55, 1.55, 0.82 m) any local strain peaks are accumulated within the total strain of each measuring section and are difficult to investigate. Therefore, readings at 4.40 and 6.45 m depth did not agree with other gauges at those depths. This shows some potential limitations of the system. However, at the other depths (without any anomalies) retrievable extensometers correspond very well with local VWSG and DFOS systems

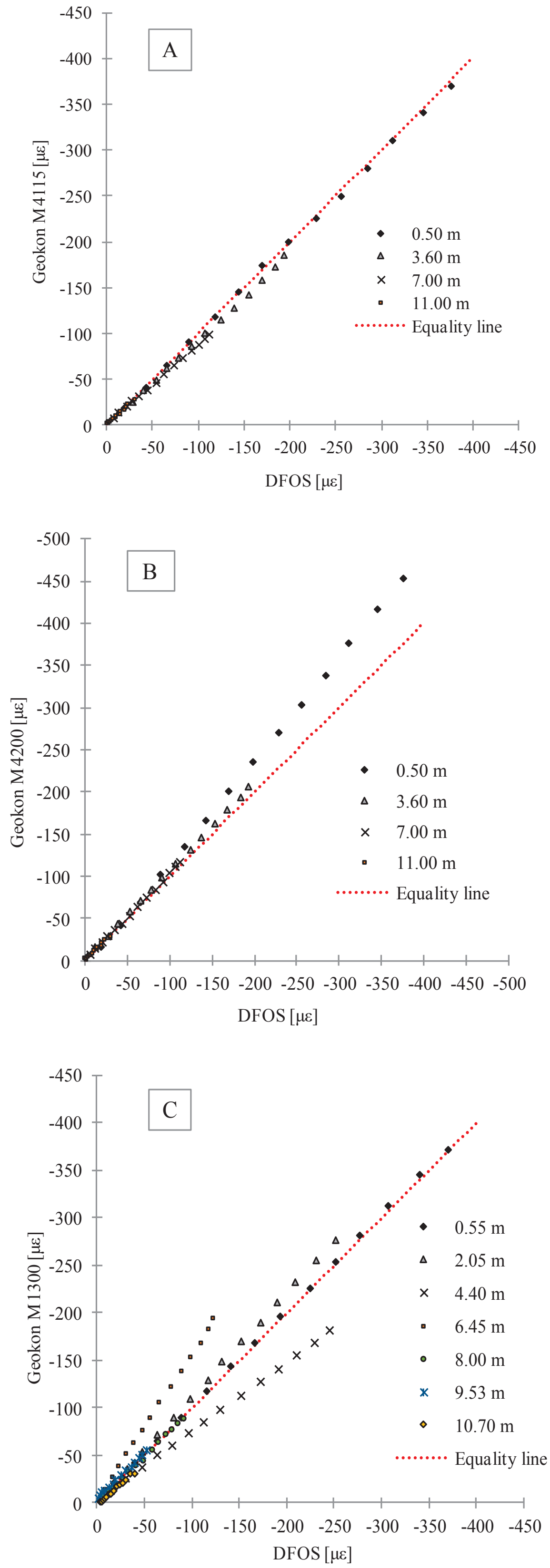

Figure 11. Strain comparison at various depth for all loading stages: A - DFOS and local M4115 (glued), B - DFOS and local M4200 (concrete embedded), C - DFOS and global M1300 (retrievable).

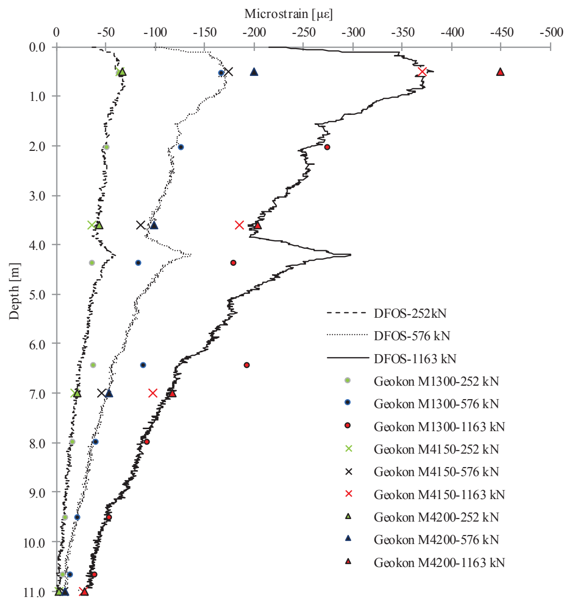

Figure 12. Strain distribution measured by DFOS and VWSG along the pile shaft at selected load values.

4 CONCLUSIONS

Static load test was performed on a screw displacement pile instrumented with vibrating wire strain gauges (VWSG) and distributed fiber optic sensor (DFOS). Test provided sufficient information for determining strain distributions along the pile shaft. Several conclusions are listed below. Findings are consistent with the results of other researchers (Kania and Sorensen, 2018; de Battista et al., 2016).

- DFOS measurements provide comprehensive information about strain distribution along the pile shaft during the load test. High resolution readings (10 mm) allow to assess the pile shaft quality (homogeneity) and determine any possible imperfections

- Three fiber optic cables were sufficient to successfully determine strain distribution. However, authors recommend using 4 cables - 90 degrees from each other (working in two pairs). In case of three cables, if one gets damaged, it might be difficult to properly establish average cross-sectional strains. When using four cables, if one gets damaged, the other pair may still be successfully utilized

- Continuous measurement of fiber optic technology is a great advantage over the local strain gauges. There is no need for interpolation between sensing points. Either the number of spot sensors or their location may not be sufficient to properly determine pile shaft imperfections

- Strain measurements confirmed a high agreement between spot vibrating wire strain gauges and distributed fiber optic sensors

- Single line strain gauges placed centrally in pile axis were proved to give reliable results in comparison to 3 gauges in one cross section (not taking into account pile imperfections)

- Retrievable extensometer system is a cheaper and easy to operate alternative for concrete embedded strain gauges. However, one must be aware of its limitations. Sectional measurements combined with pile shaft imperfection may give results difficult to interpret

- Gauges placed on a steel tube (attached to the reinforcement) have proven that the tube deforms equally with the entire cross section. No sliding effect of the tube in the upper parts was observed

- Highest cross-sectional differences in measured strain occurred in the top section of the pile (DFOS readings). It might be wise to use multiple gauges, at least in the upper part of the pile as cross-sectional load distribution equalizes at some depth from pile head level (~1.0-1.5 m)

5 ACKNOWLEDGEMENTS

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