NONLINEARITY OF CONCRETE MODULUS AND ITS INFLUENCE ON THE INTERPRETATION OF INSTRUMENTED PILE LOAD TESTS

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SUMMARY

The paper addresses the problem of the concrete stiffness nonlinearity under compression and its influence on the interpretation of the distribution of soil resistance along piles. The author analyzes some results of static load tests on instrumented driven piles. The piles were equipped with vibrating strain gages at different levels along the shaft. A number of gages in each pile were placed above the ground level and the strains measured were used for the interpretation of the secant concrete modulus. During the Static Loading Tests (SLT) the piles were loaded to the level of force allowing the application of tangent stiffness procedure by Fellenius. The results of the static tests are presented and analyzed and the discrepancies arising from application of different values of concrete stiffness are shown.

Keywords: *concrete modulus, driven pile, static load test (SLT), strain gage.*

1. INTRODUCTION

When calculating displacements of a reinforced concrete construction, a standard value of the concrete modulus is often taken from the codes or manuals. Deformation of a construction element working under compression e.g. column is generally small and consequently it can be assumed that the inaccuracy of the concrete modulus of 20÷30% induces an inaccuracy of some tenths of a millimetre in the estimated deformation. For that reason in a common design practice the concrete is usually assumed to be a linear elastic - ideally plastic material and adopting a standard value of the concrete modulus from a code or a manual is considered to be acceptable. It is however well known that the σ-ε characteristic of concrete under compression is nonlinear since the very beginning of the loading process. This nonlinearity plays an important role in the interpretation of a force distribution along a pile equipped with strain gages. It has been shown in the literature [4] that assuming the concrete to be a linear elastic material can lead to errors in the interpreted pile shaft friction and pile tip resistance. The same is true, even to a larger degree, when taking a standard concrete modulus value from the literature. In the measurements carried out on strain gages instrumented pile there are some procedures applied for the interpretation of the concrete stiffness, which are generally accepted by the geotechnical researchers [7], [11]. One possibility is placing a number of strain gages at the part of the pile which is not embedded in soil, preferably at some distance below the pile head. The load applied to the pile head and the measured strains are then used to derive the σ-ε characteristic of the pile material. This procedure, however, has some disadvantages. The second practical approach is the method of tangent stiffness proposed in [3].

In the presented paper the author analyzes results of static load tests on instrumented driven piles. The piles were equipped with vibrating strain gages at different levels along the shaft. A number of gages in each pile were placed above the ground level and the strains measured were used for the interpretation of the secant concrete modulus. During the Static Loading Tests (SLT) the piles have been loaded to the level of force allowing for the application of the tangent stiffness procedure by Fellenius [3]. The results of the static tests are presented and analyzed and the discrepancies arising from application of different values of concrete stiffness are shown.

2. BACKGROUND

Even though the nonlinearity of the σ-ε characteristic of concrete under compression is well known [4], [11] and application of a single value of concrete modulus in the interpretation of the load distribution in an instrumented pile has been criticized, it is not uncommon in geotechnical research to treat concrete as a linear elastic material also in the recently published papers [2]. The reason for such a practice is probably the belief of engineers that application of more elaborated methods does not improve the achievable reliability, since the methods induce other inaccuracies during the interpretation. Other phenomena linked to the pile behavior, which are far from being solved and are also very difficult to handle e.g. residual forces [1], [7], [14] can be viewed as a support for this point of view.

In the Polish geotechnical literature there is only a few papers dealing with the problem of the concrete stiffness nonlinearity. Author of [9] points out that the nonlinearity of the concrete in a pile is significant both based on the laboratory and field measurements. He carried out laboratory tests on concrete samples taken from the piles and also interpreted the concrete modulus from strain measurement on the piles in question. He concluded that the σ-ε characteristic of the concrete is nonlinear and the values of the secant modulus from the laboratory and the site measurements differ quite significantly. In the interpretation of load distribution in the instrumented piles Krasiński [9] used the site-interpreted concrete parameters and in this point his approach is similar to that of Fellenius [3]. The calculation in [9] has however been made based on the secant modulus.

In contrast to concrete, steel can be treated as a linear elastic - ideally plastic material and this is probably one of the reasons for using rather steel than concrete in advanced research on instrumented piles [5], [6]. However the characteristic of the steel-soil and concrete-soil interface differ [6], [8], [13] and the differences cannot be disregarded or simply treated within any theoretical framework. Since concrete is more frequently used in piling engineering than steel the problem of correct interpretation of the concrete stiffness is vital if a reliable method of pile capacity calculation should be created based on instrumented piles load tests.

Apparently the simplest method for a reliable estimation of the concrete stiffness is placing some strain gages in pile above the ground level. A very important question is then a correct measurement of the load applied to the pile head and this is usually done by application of a load cell. With such a configuration it is theoretically possible to obtain a direct relation between the load or the stress and the strain. There are however some additional problems to be solved then. The first one is the “end-effect” i.e. the gages placed close to the pile top can suffer from the stress non-uniformity directly below the point of load application. In case of an axially loaded column the distance between the level of the measurement and the force level should be approximately 1.5D, where D - dimension of the column cross section. The problem of the end-effect can be therefore easily overcome in a precast pile. When the gages are to be placed in a bored pile, the pile must be artificially elongated over the ground level or excavated. In the first case the properties of the concrete below the ground level are certainly different from that above it. Moreover in a bored pile the distribution of the pile’s cross section is rarely uniform along the pile and the dimensions can be only roughly assessed. In case of a precast pile it can assumed be with a certain degree of reliability that the conditions of the concrete curing are uniform along the pile but this is probably not the case when analyzing the segment of a bored pile below and above the ground water level. The last but not least when placing additional strain gages in a common engineering survey is the question of the cost.

At least part of the abovementioned problems must have contributed to the development of alternative procedure of the tangent modulus. The detailed description of the proposal can be found in [3]. The general idea is described below. It is assumed that the pile head load increments and respective strains measured at different levels in the pile are known from measurements. If plotting the relation between the pile head load or theoretical pile head stress and the strain at any level any of such characteristic is curved. The first source of the curvature is the natural nonlinearity of the concrete stiffness and for the points below the ground level (BGL) the second source is the pile shaft friction. Obviously in a typical case the strains BGL are smaller than that measured at the pile head level. When the skin friction is however fully mobilized the strain increment at some level BGL is equal to the strain increment above the G.L. and as a result any load increment is fully reflected in the strain increment without any contribution of the soil.

3. TEST ARRANGEMENT

3.1 Location and geotechnical conditions

The site is located in Kutno in central Poland. The area is the property of Aarsleff Sp. z o. o. From the ground surface a sand fill is encountered to a depth of ca 2m. The fill is underlain by a sand layer to a depth of 11.6mbgl Sand is middle dense to dense and in the depth range of 5-6m is interbedded with layers of a medium strength organic clay of low plasticity. From 11.6mbgl a layer of stiff to very hard boulder clay of low and middle plasticity is encountered. The water level lies in sand at a depth of ca 2mbgl but its seasonal fluctuations are quite large because of the proximity of a river running ca 300m from the site. The piles of groups T7 and T8 are driven to a depth of 7m and 15m respectively and therefore the toes of the T7 piles penetrate ca 1m into the sand below the organic clay and the toes of the T8 piles ca 3.5m below the sand into the boulder clay.

3.2 Piles tested

The analyses in the paper are based on the measurement of strain in piles during compression Static Load Test (SLT). Six piles were instrumented. The details regarding the piles and the instrumentation are given in Tab. 1. All the piles analyzed were driven precast piles with square cross section 0.4mx0.4m made of concrete with minimal compression strength of 50N/mm^2. Both longitudinal and shear reinforcement is made of rib bars with yield stress f_y=500MPa.

Table 1 *Test piles and instrumentation details*

Pile No	Pile length (m)	Pile reinforcement	Number of gage levels	Location of gages below the pile head (m)
T7A	8.0	4ϕ25	5	1; 3; 5; 6.5; 7.5
T7B	8.0	4ϕ25	5	1; 3; 5; 6.5; 7.5
T7C	8.0	4ϕ25	5	1; 3; 5; 6.5; 7.5
T8A	16.0	8ϕ32	9	1; 3; 5; 7; 9; 11; 13; 14.5; 15.5
T8B	16.0	8ϕ32	9	1; 3; 5; 7; 9; 11; 13; 14.5; 15.5
T8C	16.0	8ϕ32	9	1; 3; 5; 7; 9; 11; 13; 14.5; 15.5

All the piles were equipped with vibrating-wire strain gages Geokon model 4000. The gages were welded to a steel pipe 63.3x4.5mm placed centrally in the pile and running along its full length. The gages were covered by casings made of 1mm thick steel sheet (Fig. 1).

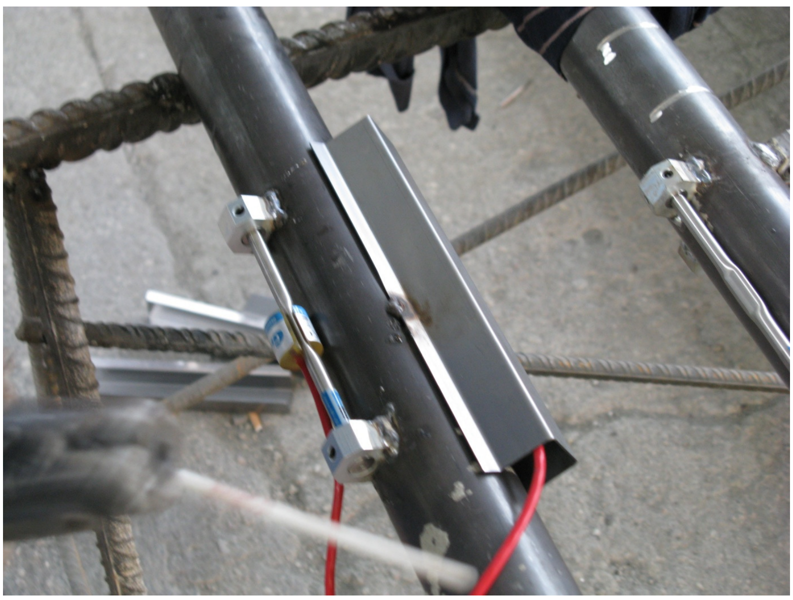

Fig. 1 *Strain gages and cover assembly*

The strain gages were placed in pairs on the opposite sides of the pipe except for the highest level, where three gages in 3x120^o arrangement were used in each pile. After filling the gage covers with polyurethane foam the pipe was set in the reinforcement cage (Fig. 2) and the piles were cast in plant on the 30th Oct. 2009. The concrete of nominal class C40/50 with crushed-stone aggregate was used. No sample was taken at the day of casting, nonetheless the samples are taken and tested every 7 days for the production control. No sample tested between Sept. and Dec. 2009 showed the 28-days strength below 64N/mm^2.

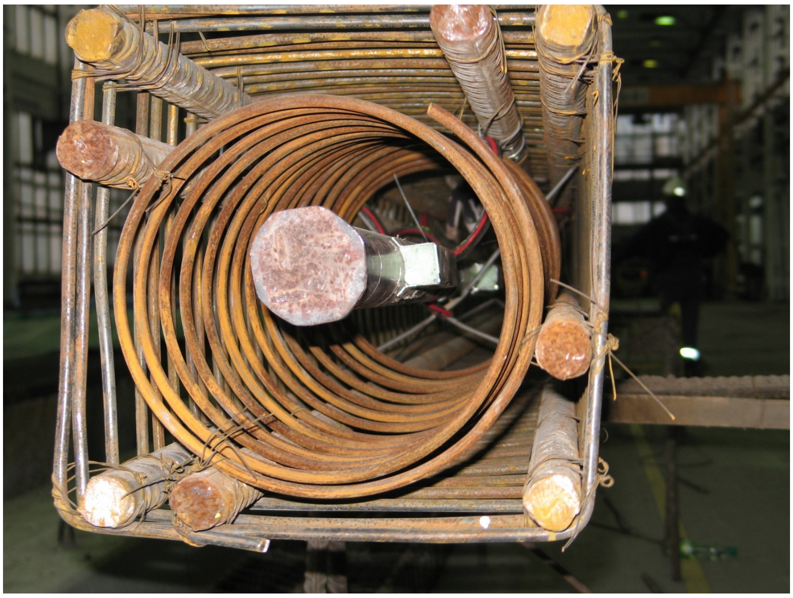

***Fig. 2** Reinforcement cage of a pile T8 with the instrumentation*

The piles were driven into the soil on the 8th and 9th Apr. 2010 using a free-fall hammer with the weight of 60kN. The piles were driven so that their embedment in soil was always by 1m smaller than the total length given in Tab. 1. Since the highest level of instrumentation (G1) was placed 1m below the pile head, the location of strain gages after the pile driving was just at the ground level (G.L.). Therefore the gages can be properly used for the assessment of the concrete stiffness.

3.3 Measurement performed

The piles of groups T7 and T8 were first loaded in tension in May 2010. After the tension SLT the piles were restruck on the 1st June to minimize the effect of the applied tension. The values of compressive strain measured in the piles of group T7 after the redriving but before the compression SLT were approximately equal to the values before the start of the tension SLT. The redriving was therefore effective in suppressing any residuum of tensile strain. The situation is more complicated for the T8 piles which were loaded in tension to a force almost five times larger than the T7 piles. Significant tension strain remained locked at the levels BGL in the T8 piles even after the restriking. Consequently, the question arises: do the concrete stiffness estimated during the compression SLT at the level of the pile head apply to the lower levels? This will be addressed further in the paper.

The Static Load Tests in compression were carried out on the 7th, 9th and 15th July 2010 for pile T7A, T7C and T7B respectively. During the SLT load was applied in steps with the aid of a calibrated hydraulic jack with nominal capacity of 1850kN. The only exception was the SLT on the pile T7A. This was the first compression SLT during the program and to avoid the situation that the pile has the capacity larger than the capacity of the jack a set of two similar jacks was used. The value of the additional force in each step during any test was set to ca 1/15 of the estimated pile capacity in soil. The force was measured by a load cell, Geokon model 4900. The duration of each step was variable but was at least 1200s. Before application of any load an extensometer was placed in the central pipe in the pile which allowed for the measurement of the total shortening of the piles. The data were collected automatically every 120s. The distance between the point of load application during the compression SLT and the uppermost strain gages was at least 0.7m i.e. more than 1.5 cross sectional dimension of the pile. This should be sufficient to ignore the end-effect.

4. RESULTS

4.1 Data reduction

The strain readings of any level have been roughly checked trough a comparison with the total shortening of the pile obtained from the extensometer readings. For this purpose the strain measured at any level have been assumed to be constant to the lower level. Based on such strain the total shortening of the pile have been calculated. The values calculated from the strains and the measured have never differed by more than 7%, which is thought to be satisfactory.

For the evaluation of the modulus of the reinforced pile cross section the measurement of the uppermost strain gages was used. The strain gage covers occupy ca 2% of the total cross section at the pile head and ca 1.2% at all remaining levels. The cross section of all the cables is 0.1% of the pile cross section. The central pipe void area is ca 2315mm^2 and this is 1.5% of the pile cross section. For simplicity all the inclusions were ignored in the analyses i.e. pile cross section is treated as uniform square column 0.4mx0.4m. Such a simplification is acceptable as other inaccuracies are likely to be larger than the influence of any of the aforementioned inclusions.

Between casting and driving the piles they have been stored both within isolated buildings and outside. As a result they have been subject to temperature and moisture changes. At some intervals during this period all strain gages have been read. All strain gages are equipped with temperature sensors and the temperature of the piles was registered. This allowed for the assessment of the changes of the strain readings in reaction to the temperature changes. The registered strain are in this case the result of the difference in thermal expansion of steel and the concrete. Some 40 days after the piles had been cast they were transported from outside to a building and stored so they could expand freely. Their temperature increased slowly from ca 3^{o}C to ca 12^{o}C and resulting coefficient of thermal strain expansion was was -1.7με/^{o}C to -2.1με/^{o}C for the T7 piles and -1.2με/^{o}C to -1.7με/^{o}C for the T8 piles. This means the increase in the temperature is indicated as compression strain and more compression is induced in the less reinforced piles T7. Both results are consistent with expectation since the theoretical expansion of the gages itself are identical to that of steel and thermal expansion coefficient of cured concrete is smaller than that of steel. During the SLTs the temperature changes were minor and they were not accounted for in the analyses.

It should be noted all three piles of the group T7 i.e. T7A, T7B and T7B are located within 3m from each other and the same refers to the piles of the group T8. For the purpose of clarity only some results of the measurement done within the group T7 are presented here. In the Fig. 3 plot of the average strain registered at the pile head level (first gage level) versus nominal compressive stress at the level of the pile head is presented for the piles of group T7.

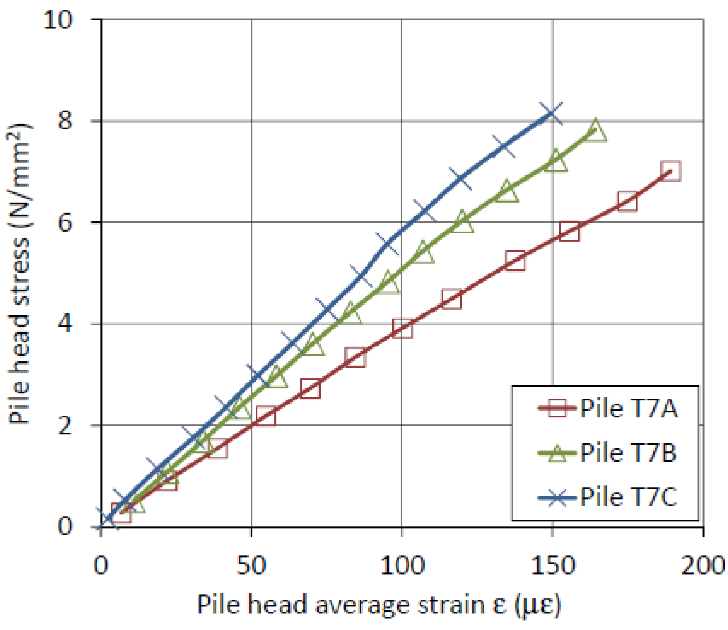

Fig. 3 *Stress-strain relationship for T7 piles at the first gage level*

It can be noted the plot for pile T7A differs from the plots for two remaining piles. Moreover, after calculating the secant modulus of the pile cross section it appears the values for the pile T7A are below $40{\cdot}10^3$N/mm^2 which seems to be too small for such concrete with reinforcement and taking into account the range of the strain measured. The discrepancies between the piles T7B and T7C are smaller. When analyzing similar plots from other gage levels in the piles of the T7 group it appears that the discrepancies between the piles are much smaller and it is concluded that some errors must be involved in measurement presented in Fig. 3. It is not known why so small modulus is measured in the pile T7A. It is not likely that the reason is the influence of the tension loading carried out about 50 days earlier. As already mentioned the readings taken after the redriving show this is not the case. Additionally the relationship in Fig. 3 for the pile T7A is uniform with no drops. In the case of tension residuals they would have probably been equalized at the first loading steps in compression. When analyzing Fig. 3 the relationships for piles T7B and T7C are similar up to a strain value of 70με and then a drop in the plot for pile T7C is apparent. It cannot be stated which of the two plots is "correct" if not both. To support the following interpretation the tangent modulus analysis is done. Tangent modulus is calculated according to Eq. 1.

$$E_t = \frac{d\sigma}{d\varepsilon} \tag{1}$$

where dσ is stress increment at the pile head level and dε strain increment at the level in question during respective loading step. Stress increments at the levels BGL are in principle not equal to the stress increments at the pile head since the load value at any level is the load applied to the pile head minus the shaft friction from that level to the G.L. It should be however noted that after full mobilization of the shaft friction above the analysed level any load increment at the pile head is fully reflected in strains at the level in question. The plot of the tangent modulus versus average strain registered in pile T7B at the depth of 2m is presented in Fig. 4.

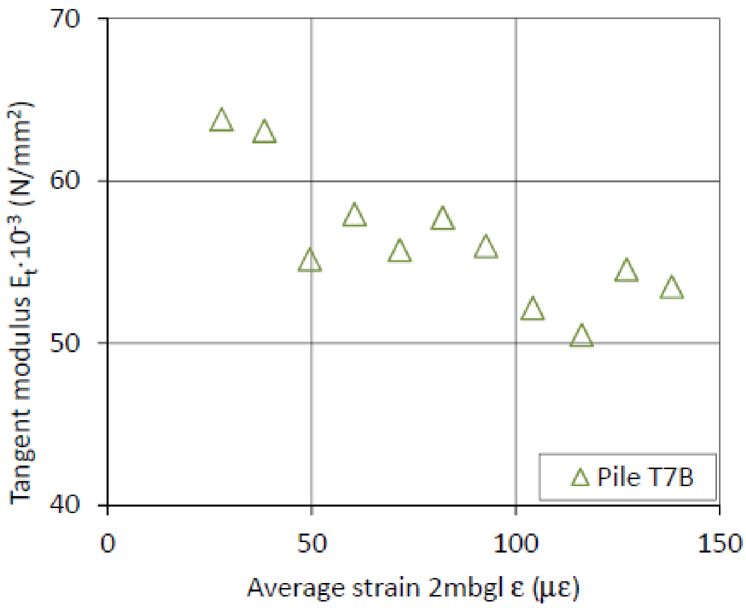

***Fig. 4** Tangent modulus plot for gages 2mbgl in pile T7B*

It is seen that when the strain increases over ca 50με the points of the tangent modulus values become more or less linear with respect to strain though with some scatter. A trend line running along the value of some $55{\cdot}10^3$N/mm^2 would be probably a good representation of the tangent stiffness after removing the points below 50με. After rejecting such points the remaining data from the level 2mbgl for all the T7 piles can be drawn in one plot disregarding the fact that the points belong to different piles. Such trend leads to Eq. 2 which should be theoretically representative for the tangent modulus of the T7 piles.

The number of points indicating full mobilisation of the skin friction is relatively small here and it was not possible to make similar evaluations for the lower strain gages. Alternatively an analysis of the tangent modulus is therefore carried out for the T8 piles. The details are not presented here but it should be mentioned it was possible to build plots for the gage levels 4m and 6mbgl. After correction for the difference in steel cross section in the piles of groups T7 and T8 the tangent modulus for the piles of group T7 is given in Eq. 3. The secant modulus of piles T7 can be calculated based on the measurement results shown in the Fig. 3. Relationship between the secant modulus and the strain for pile T7B is presented in Eq. 4. It can be seen the values of the modulus in Eq. 2 to Eq. 4 slightly decreases with increasing strain. The plots are not presented because of space limitation.

$$E_{t1} = 59.2 - 0.04 \cdot \varepsilon \tag{2}$$

$$E_{t2} = 53 - 0.016 \cdot \varepsilon \tag{3}$$

$$E_{s7B} = 51.6 - 0.016 \cdot \varepsilon \tag{4}$$

where E_t and E_s are tangent and secant modulus respectively both in $N/mm^2 \cdot 10^3$ and ε is measured strain in με. For the purpose of clarity only comparison of the force distribution in the pile T7B is made next. In the following Fig. 5 and Fig. 6 the distribution of the force in the pile with depth and the distribution of unit shaft resistance are shown respectively. The distributions are made based on the strain measurement during the last load step during the SLT under the assumption of different concrete moduli. The cases are:

i) Tangent strain-dependent modulus acc. to the Eq. 2;

ii) Tangent strain-dependent modulus acc. to the Eq. 3;

iii) Secant strain-dependent modulus acc. to the Eq. 4;

iv) Uniform value of secant modulus $E_s=40 \cdot 10^3 N/mm^2$ independent of the strain level;

The last modulus value can be thought as a result of a typical table-value for C50/60 concrete $E_s=37 \cdot 10^3 N/mm^2$ after correction to account for the reinforcement. Though the number is debatable it is consistent with that, what could be assumed by a design engineer based on [15].

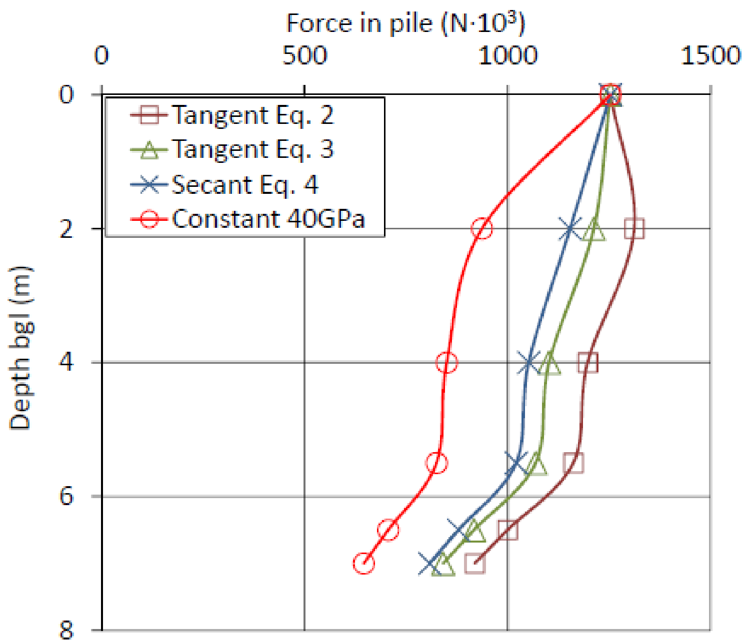

***Fig. 5** Force distribution at ultimate state for pile T7B*

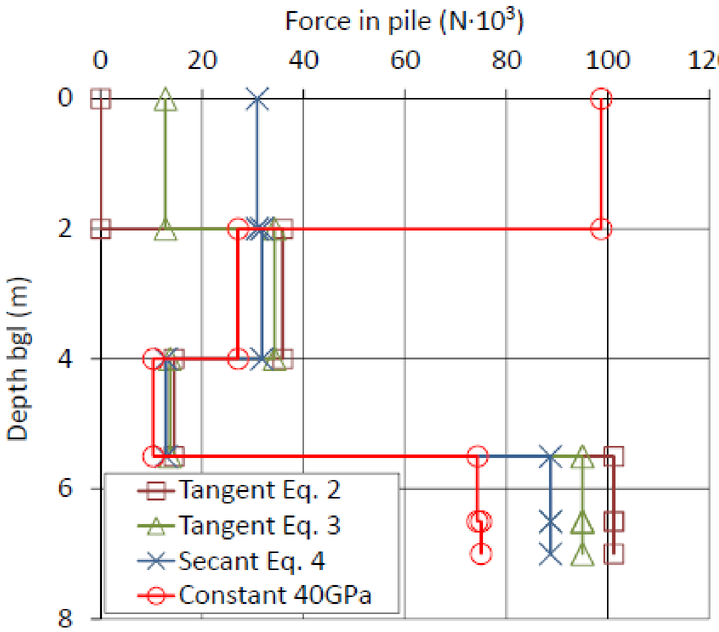

Fig. 6 *Unit skin friction distribution at ultimate state for pile T7B*

The data presented in the Fig. 5 and Fig. 6 are for the pile ultimate capacity. It should be mentioned the data are not just the result of the strain measured during the SLT. In a pile driven into the soil some non-zero load exist prior to any pile head load application. This non-zero value is usually called post-driving residual load [1], [4]. The problem of residual load measurement or interpretation is a very demanding task in itself and is not addressed here. It should however be noted that during the experimental program depicted in this paper a trail of a measurement of the residual forces was undertaken. The measurement appeared to be not straightforward and the results were not reliable at some instrumentation levels. Consequently also an interpretation was done according to the method used in [4]. The estimation of the residual forces at the beginning of the compression SLT was done based both on the measurement and the mentioned interpretation. The values of forces calculated with the strain measured during the SLT were corrected to account for the residual forces.

5. DISCUSSION OF RESULTS

It is clearly seen that both the force distribution and the skin friction distribution are strongly dependent on the assumed concrete modulus. Without reference to the soil profile it is not easy to decide which interpretation is correct.

It can be said that the very steep force distribution in the depth range 0-2m interpreted with the constant modulus value is not correct. The skin friction of 98kPa is impossible in the analyzed case. The skin friction of 27kPa resulting from the same modulus for the depth range of 2-4m seems to be rather low although not impossible for the soil profile in question. Similar comment can be made to the same curve in the depth range below 5.5m. All remaining values of ultimate skin friction don't differ significantly from the values based on other moduli and it cannot be said any of them is incorrect.

Referring to the above it can be said that the single modulus value of $40 \cdot 10^3 N/mm^2$ if applied to the analyzed case leads to an incorrect interpretation of the force distribution in the instrumented pile. The value is very low in view of the results. The likely reasons are as follows. The age of the concrete in the pile during the measurement was over 200 days but even after 28 days its actual class was probably higher than the nominal one. Additionally the table values of the concrete modulus apply rather to the strain range expected for stress of ca 40-50% of the compressive strength and this is not the case since the maximal force applied to the pile head could have led to a stress value of ca 7.5MPa which is about 15% of the compressive strength of the concrete.

In the force distribution based on the Eq. 2 the value at the level of 2mbgl is larger than the load applied to the pile head which is clearly impossible. For that reason the value of skin friction in the Fig. 6 for the depth range 0-2m was zeroed. Consequently it is thought the tangent modulus based on the strains measured in the piles of group T7 is in error. The reason is probably too small number of the measurement points the Eq. 2 was based on. The remaining skin friction values resulting from the application of the Eq. 2 are in general agreement with the soil profile.

Both the moduli interpreted based on the Eq. 3 and Eq. 4 lead to a very similar distribution of force and skin friction. It can be argued if an interpretation of the concrete stiffness based on one group of piles can be applied to another group. Though all piles of both groups were produced at the same day and from the concrete with the same recipe but significant differences in strength and stiffness are not uncommon in similar cases. Additionally it should be emphasized that before the compression loading all the piles were loaded in tension and some tensile residual strain remained in the piles T8 even though they had been redriven. In spite of this it is believed both the distributions based on Eq. 3 and Eq. 4 are generally correct and the analysis is reliable for the geotechnical purposes. If a secant modulus is interpreted in the piles T7A and T7C and applied for these piles, this leads to skin friction distributions which differ significantly from each other and from the plot presented in Fig. 6 for secant modulus. The reason for such discrepancies in the secant stiffness are not known but there must have been some errors involved in the strain measured at the highest instrumentation level.

The closest agreement between the distributions in the T7 piles has been obtained if the tangent modulus procedure is used according to the Eq. 2 or Eq. 3 but the Eq. 2 has again led to unreliable values in the 0-2m depth range.

6. CONCLUSIONS

The reliability of different methods of the concrete stiffness assessment for the interpretation of an instrumented pile loading test is evaluated in the study. Precast concrete piles were equipped with vibrating wire strain gages and driven with an impact hammer. After some period Static Loading Tests (SLTs) were carried out on the piles. All together 6 piles were instrumented and tested: 3 piles of group T7 with 7m embedment in soil and 3 piles of group T8 with 15m embedment. The concrete modulus was interpreted based on the strains measured at different levels in the piles. Different procedures were applied to assess the concrete stiffness in the piles. Subsequently the interpretation of the force distribution and skin friction distribution in one of the piles was done based on the evaluated concrete stiffness and the strain measured in the pile. The interpretations have been done based on the secant concrete stiffness as measured in the head of the analyzed pile, the tangent stiffness method presented in [3] and also on a single modulus value taken from [15].

General conclusion can be drawn from the presented analyzes that the interpretation of skin friction along an instrumented pile is quite sensitive to the assumed concrete stiffness. It has been shown that the application of a single concrete modulus value from literature leads to an erroneous skin friction distribution. A standard table value of concrete stiffness should therefore not be used in the interpretation of SLT on instrumented piles.

Application of the secant modulus based on the strains measured at the pile head level of the pile T7B have led to a reliable interpretation of the skin friction distribution in this pile but the values in two remaining piles of the group T7 are considered to be in error. It has been concluded the strains measured in the heads of the piles T7A and T7C were not fully correct.

Unexpectedly, application of the tangent modulus evaluated based on the strains measured in the piles of the group T7 have led to unreliable values when applied during the interpretation of the skin friction in these piles. The reason is probably too small number of measurements and also the fact that the tangent stiffness could be only interpreted at one measurement level.

Alternatively the tangent modulus have been assessed based on the strains measured in the piles of the group T8. It was possible to calculate the modulus at three strain gage levels and the number of values allowing for the evaluation was larger than in the piles T7. The obtained tangent modulus has been corrected to account for differences in the reinforcement cross section between the pile T7 and T8. Application of the tangent stiffness from the piles T8 to the strains measured along the piles T7 allowed for an interpretation of the skin friction distributions which were thought to be the most correct. The similarity of the distributions in different piles of the T7 group was reasonable and the general trend was also consistent with the soil profile.

7. AKNOWLEDGEMENTS

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