*Proceedings of the International Conference „Innovative Materials, Structures and Technologies"*

doi: 10.7250/iscconstrs.2014.24

# TIME DEPENDENT FACTORS IN PILE QUALITY AND CAPACITY CONTROL

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**Abstract**. This work presents the results of field testing and further analysis of length estimation and capacity of piles. Concerning the CFA pile quality control, the measured elastic wave velocities examined between the 5th and 15th day after the C20/25 concrete embedding ranged from 3,000-4,000 m/s. However, the standard deviation is relatively high, the time seems to be the crucial factor. Load tests (capacity tests) as well as the tests of the length and integrity of the foundation piles belong to the set of indispensable control procedures, which verify the design and the execution of pile foundations. Bearing in mind the applied piling technology and the soil conditions, it is necessary to define the minimal time span between the piling and the beginning of the tests. At the same time, the pressure from the contractors often causes the control procedures to begin and finish before that time. The research conducted at Wroclaw University of Technology shows that in the case of driven piles, the increase of capacity can be observed mainly in cohesive soils, where the reconsolidation of soil around the pile affects strongly the pile-soil shaft adhesion.

**Keywords:** integrity test (PIT), CFA pile, static load test (SLT), driven pile

## Introduction

Regarding the issue of pile quality (continuity and length) tests by means of non-destructive methods (PIT, SIT), it seems essential to estimate the velocity of the elastic wave in the concrete. For example, considerable differences are observed in the measurement of the wave velocity before and after the pre-cast concrete piles are driven. For reinforced concrete piles made of the C40/50 concrete, the elastic wave velocity measured before driving reaches 4,500 m/s, and after driving it oscillates around 4,000 m/s. That is associated with the micro-cracking caused while driving the pile. The errors in velocity estimation may lead to proportional faults in the estimation of the pile length (10%). It is even more complicated to determine the wave velocity in the process of the young concrete setting (before the 15th day of concrete embedding). Very few publications on that subject (Niederleithinger, Taffe, 2006) show large changeability of the estimated velocity and suggest that calibration should take place each time at the construction site. Calibration, however, is possible only when the person who runs the tests is in possession of fully credible information about the length of the examined (controlled) piles (Rybak, Schabowicz, 2011).

In general, as far as the pre-cast concrete piles are concerned, the possibilities of testing their load capacity are conditioned only by the subsoil type together with the phenomena that occur in the pile environment after it is driven or vibrated into the ground. It is observed, almost in all of the ground types, that the load capacity increases in time (the phenomenon described in literature as „setup" (Skov, Denver, 1988, Svinkin, Skov, 2005, Jardine et al., 2006 and König, Grabe, 2006) and thus reducing the testing time does not bring about the risk of overestimating pile load capacity (Rybak, 2008). When, contrarily, the result of the load capacity test is negative, such test may be always repeated after the time necessary for the reconsolidation of the subsoil around the pile.

## Integrity testing - Review of publications

Measurements of acoustic wave velocity in concrete are generally related to the search for correlation between this velocity and the strength of concrete in concrete (or reinforced concrete) components, or to the identification of defects in these elements. These examinations aim at evaluating the quality of the concrete itself, whereas wave velocity is calculated on the basis of the time the wave needs to cover the segment of known length. The tests made on concrete samples in successive days elapsed from concrete work confirm that the relation of velocity versus time, until concrete attains its full strength, is of logarithmic type and it stabilizes after about 4 weeks at about 4,000 m/s.

Final velocity depends on various factors such as: concrete grade, additives used, maturing conditions, etc. An extensive review of non-destructive diagnostic methods for concrete elements can be found in the publication of Hoła&Schabowicz (2010). Regarding foundation piles, estimation of acoustic wave velocity is attributable to their non-destructive diagnostics, both with regard to pile load carrying capacity (high strain testing) and their quality (length and integrity) in low strain testing. As far as the dynamic testing of bearing capacity (high strain) is concerned, it is justified, for analysing the strain wave, to take the velocity determined for specific concrete strength class after the completion of concrete setting (testing is usually performed after 4 weeks from pile completion). However, for continuity testing with a low strain method, the pile material is not required to attain its full strength. Integrity testing is admitted as early as "7 days after casting or after concrete strength achieves at least 75% of its design strength, whichever occurs earlier" as recommended by ASTM D 5882 – 07 and equipment/software providers.

In practice, this period is additionally shortened by the will to progress quickly at the construction site. Functional relations reported which describe changes in acoustic wave velocity in concrete are usually prepared for testing calibration for a single construction site. Hence, they are distinguished by small diversification of random sample, resulting from small number of piles under testing, short testing time and – what could be the most important – pile homogeneity as far as their length, diameter and grade of concrete are concerned.

The proposed velocity-versus-time relationships for bored foundation piles for time *t* elapsed from pile completion were published by:

- Amir (1988):

  $$c = 3946 \cdot \sqrt[6]{\log(t+1) \cdot f_c/30}$$

  where $f_c$ is concrete strength in MPa
- Finno, Gassman (1998):

  $$c = 217 \cdot \ln(t) + 3339 \quad \text{for } 1 < t \le 14 \text{ days}$$

  $$c = 12 \cdot \ln(t) + 3887 \quad \text{for } 14 < t \text{ days}$$
- Thasnanipan et all. (2000)

  $$c = 204 \cdot \ln(t) + 3235 \quad \text{for } 5 < t \le 62 \text{ days}$$
- Niederleithinger, Taffe (2006)0:

  $$c = 182 \cdot \ln(t) + 3497 \quad \text{for } 3 < t \le 25 \text{ days}$$

All publications confirm that velocity rises in time and stabilizes after some 4 weeks. It is necessary to stress that the testing results differ significantly due to various piling technologies, concrete recipes and, in general, different time of observations.

The results of author's experience, collected from the sample of about 140 bored piles made of C30/C37 concrete, as shown in Figure 1, are the closest to the findings of Thasnanipan et al. (2000) and are as follows:

$$c = 281 \cdot \ln(t) + 2891 \qquad \text{for } 12 < t \le 33 \text{ days}$$

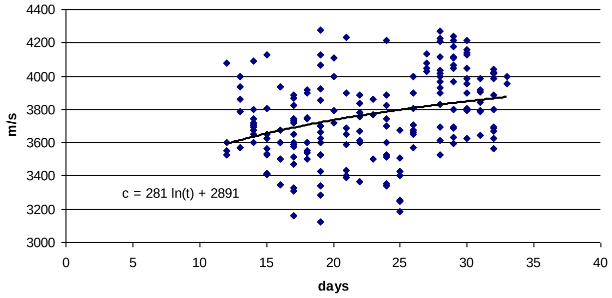

**Fig. 1.** Velocity increment for C30/C37 concrete of bored piles.

These results confirm both the rising trend in time domain and relatively large variability of velocity for particular piles. Attention is attracted to large scatter of the results obtained. It is all the more striking that the measurements were taken from merely three construction sites and the piles were made with the same piling machine. It indicates that mistakes could be made in evaluating the length of piles, and – what is worse – in evaluating the quality of placed concrete.

Independent testing for 131 concrete columns made in CFA process with C20/25 concrete is provided in the paper of Rybak&Schabowicz (2011). The functional relationship was then as follows:

$$c = 380 \cdot \ln(t) + 2607 \qquad \text{for } 5 < t \le 12 \text{ days}$$

Average values of acoustic wave velocity in the CFA piles determined by the author in the second week from concreting were significantly lower than the values found in literature and the author's own testing (for bored piles) summarized in Fig. 2. It could result from such factors as:

- a unique composition of concrete mixture (sand concrete in the CFA piles),
- lower strength class of concrete (C20/25) than that in the remaining research works,
- testing was run in winter season, which could affect the quality of concrete mixture and the conditions of its curing within the pile head zone.

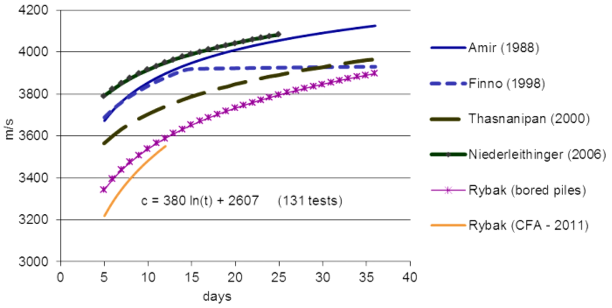

**Fig. 2.** Increment in velocity for CFA piles of C20/25-C30/37 concrete grades.

Significant discrepancies of formulae describing the rise of acoustic wave velocity taken versus concrete ageing time justified more complex statistical analysis aimed at finding, for the statistical sample as large as possible, both the relationship describing the increment in wave velocity and the variability coefficient for this feature. This coefficient could be an indication of a possible scatter of results and in this way it might define the accuracy of the method. The first attempts of such estimation were given in the work of Amir (1988), where standard deviation was found at the level of 160 m/s, which represented about 4% of the measured velocity value.

The results of wave velocity analyses in successive days of young concrete curing in CFA piles are shown in Table 1 from paper of Gorska&Rybak (2011).

**Table 1** Juxtaposition of the acoustic wave velocities for varying time

| Time | Population | Mean value | Standard deviation | Coefficient of variation |
|---|---|---|---|---|
| [days] | [pcs] | [m/s] | [m/s] | [%] |
| 5 | 29 | 3226.45 | 100.25 | 3.1% |
| 6 | 19 | 3275.79 | 129.08 | 3.9% |
| 7 | 13 | 3298.54 | 136.38 | 4.1% |
| 8 | 19 | 3405.79 | 153.24 | 4.5% |
| 10 | 16 | 3542.63 | 151.74 | 4.3% |
| 11 | 16 | 3523.06 | 191.16 | 5.4% |
| 12 | 19 | 3559.58 | 181.31 | 5.1% |

These results, in quality and quantity aspects, confirmed the conclusions of the Amir's paper (1988). Some anxiety could be however felt that the standard deviation values were rising in time, and as a consequence, the coefficients of variation went higher for the estimated velocity of acoustic wave in concrete. Due to small sample sizes, an attempt was made to collect the results of continuity testing with the PIT, available to the author, which could be verified in pile records.

## Description of velocity tests

This paper presents the research programme carried out so far, as a part of which 937 CFA piles were screened in the course of 31 subsequent days – on 4th to 35th day after the concreting the piles. The signals were recorded by means of the PIT device. The tests were performed on the CFA piles with the diameters of 600 and 800 mm and the length varying from 5 to over 20 m.

It must be underlined that the PIT equipment enables one to perform wave speed test of each pile. The procedure is the following: the PIT tests are executed at the top of the test pile and 1m below the top, then the PIT software determines the wave speed extracting time of wave travel in upper 1 meter of the test pile. Such procedures are not frequently used and were not used for the purpose of this study because of technical limitations on the building site. However, this procedure could probably confirm the presented and future studies. Following the methodology from ACI 228.2 R-98, a sample signal (without noise reduction) was shown in Fig. 3. One may notice a distinct echo from the pile bottom at the depth of about 13.0 m below the pile head. Wave velocity corresponding with that pile length, in a pile tested on the 10th day after concreting, equalled approximately 3,500 m/s. Analogical analysis was carried out for 937 signals from those piles, the length of which could be confirmed in piling reports.

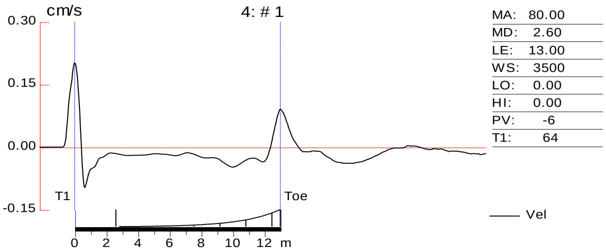

**Fig. 3**. A sample PIT signal for a 12.55m pile.

## Velocity test results

The velocity test results, calculated on the basis of the PIT signals and the time elapsed since concreting, confirming the expected increase of velocity in time, have been juxtaposed in Fig. 4. Despite the visible variability in the observations on subsequent days, there is a distinct upward trend, and the results dispersion, measured by means of the coefficient of variation falls within the range of 3-4%. Such variability can also be partially confirmed by the results of tests carried out in laboratory conditions (Schabowicz, 2011).

It must be stressed that the observed result dispersion may also arise, to some extent, due to the imperfection of piling works (as far as the piling depth is concerned), as well as due to the absence of marking the level of hacking of the pile heads.

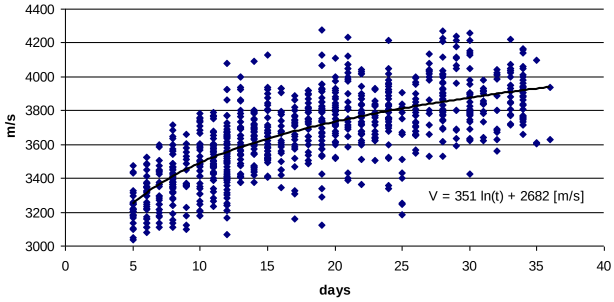

**Fig. 4.** The increase of acoustic wave velocity.

The functional relationship,

$$c = 351 \cdot \ln(t) + 2682 \qquad \text{for } 5 < t \le 36 \text{ days}$$

obtained from a cloud of results which describe wave velocity *c* versus time *t* can be used to evaluate the pile length with the PIT method. This function can be also applied in sonic logging testing (type CHSL).

Figure 5 shows the histograms of wave velocity for the 7th, 21st and 35th day (the proportion of piles for which the wave velocity was calculated in every interval of 100 m/s within a range 3,000-4,000 m/s).

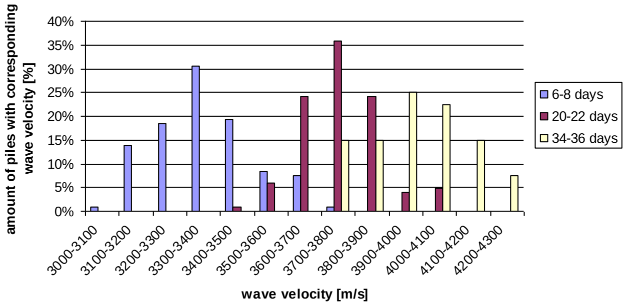

**Fig. 5.** Histogram of velocity on selected days.

It seems that the observed distributions of the identified velocities on subsequent days after concreting are similar to a normal distribution, and such thesis can be confirmed on a large statistic sample. Hence, examinations of C20/25 concrete CFA piles at construction site in Poland prove that specific composition of concrete mixture used in these piles affects significantly the evaluations of their length with PIT method over the first days after concreting. Also the conditions of concrete curing differ, in many cases, from typical laboratory environment, especially when constant temperature is considered. These factors influence the delay of concrete strength rise in the pile. What seemed however important, it has no significant effect on final value of velocity determined after 5 weeks, being in general somewhat over 4,000 m/s.

Finally, Figure 6 provides data based on review of almost 1,000 PIT tests for CFA piles compared with earlier relationships analysed and obtained mainly for bored piles.

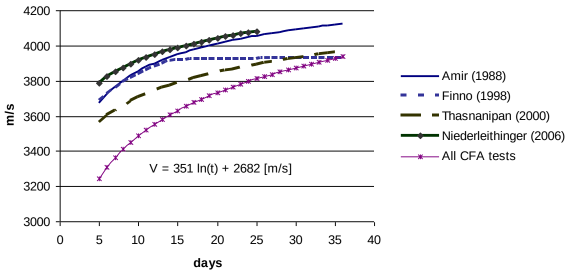

**Fig. 6.** Results of concrete tests for CFA piles compared with those for bored piles.

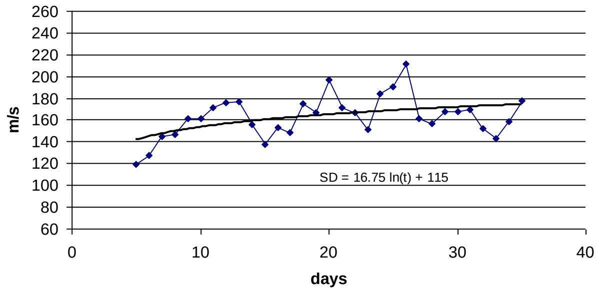

**Fig. 7.** Standard deviation (SD) of wave velocity versus time.

The above-shown variation of standard deviation calculated for measurements of wave velocity in concrete, made in successive days (see Fig. 7), is very close to the value of 160 m/s presented by Amir (1988). When the relation which approximates the standard deviation is referred to the formerly proposed functional relationship, describing variation of acoustic wave velocity during concrete curing, a virtually constant coefficient of variation at the level of 4.4 % is attained.

## Capacity testing

The use of prefabricated driven piles leads to the shortening of piling works time. However, the time span, which should be preserved between the driving in of a pile and its static bearing capacity testing, becomes crucial. Required time intervals are presented in Chart 14 in the code PN-83/B-02482 (see Table 2 below). Therefore, it might become troublesome to postpone the decision about the continuation of pile work until the static load test results are known.

**Table 2.** Time span between the pile driving and its testing

| Piling technology | Ground conditions | |
|---|---|---|
| | non-cohesive | cohesive |
| driven | 7 days<br>or 20 days (if saturated) | 30 days |
| bored | 30 days | 30 days |

Another organisational difficulty arises from the necessity to adjust the building site only in order to install the piles in the testing site. That disadvantage is crucial especially when the number of piles is small and the costs of re-adjustment of the building site or the standstill in the works caused by the testing methodology are irrelevantly expensive in comparison with the contract value. The conditions presented above form the basis for the undertaken attempt at the analysis of the influence of the time – elapsing between the pile installation and the static load test – on the test results. Such an influence reported by Skov (1988) and Svinkin (2005) should be significant, especially in the case of stiff cohesive soils where so called soil "setup effect" accompanied by dissipation of pore pressure at the soil pile interface zone may last for years. The detailed analysis of setup in sands is a subject of recent studies by Jardine (2006) and König (2006). Even a 20% increase of bearing capacity in sand is noteworthy in terms of money.

## Repeated static load test (SLT) and dynamic load test (DLT) in Policko

Driven piles were tested by means of the static and the dynamic method at a bridge construction site. After pile driving under the bridge abutments was finished, the constructor started immediately (2 days after driving the piles) pile load capacity tests. Both the static load test (on the 3$^{rd}$ day) and the dynamic test carried out earlier on the other bridge abutment showed reserves in pile bearing capacity. However, as the requirements of the code of practice was not met: for the piles driven in saturated non-cohesive soil, the tests should have been carried out after 20 days. The supervisor of the construction ordered to repeat the tests. The examination carried out after approximately 30 days proved additional increments (setup) in the pile load capacity (Fig. 8). Selected results of analysis for selected pile capacity evaluation methods were juxtaposed in Table 2 below.

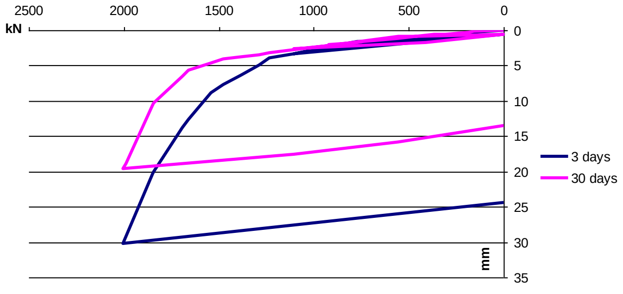

**Fig. 8** Load-settlement curve for static load tests after 2 and 30 days respectively.

What is interesting – the values of the estimated ultimate load capacity increments proved to be similar regardless of the testing method: 1% for static test and 4% for dynamic test, respectively. But the so-called critical load (design load accepted for the pile) increased significantly.

**Table 3.** Results of static and dynamic load tests

| Evaluated value | 3rd day | 30th day | Increase [%] |
|---|---|---|---|
| SLT – ultimate load (Chin) | 2188 | 2207 | 1% |
| SLT – design load to PN | 1300 | 1490 | 15% |
| SLT – design load (DeBeer) | 1232 | 1475 | 20% |
| SLT – design load to EC7 | 1421 | 1433 | 1% |
| DLT – ultimate load (CAPWAP) | 2565 | 2662 | 4% |

## Repeated dynamic load tests (DLT) of 15 driven piles in Raciborz

Load capacity tests were carried out for the piles which had been installed approximately 6 days before. The measurements were repeated on the 55th day after the piles had been installed. Measured values of the pile limiting load capacity are characterized by a considerable discrepancy. In the first series, for the piles 11.0 m in length (L=11.0), the obtained values ranged from about 610 kN to 810 kN, for the piles whose L=12.0 m – from 610 kN to 890 kN, and for the piles 13.0 m long – from 550 kN to 650 kN. In the second series, the obtained results were as follows: for the piles 11.0 m in length, the limiting load capacity varied between 640 kN and 920 kN; for the piles 12.0 m in length – between 700 kN and 970 kN, and, finally, for the piles whose L=13.0 m – between 660 kN and 860 kN. The authors of the survey explained that the discrepancy of the load capacity measurement was due to heterogeneity of the geological structure.

The strata, which have the decisive impact on the pile load capacity and the change of the pile load capacity in time, were sands and gravels with the admixture of silts. The made ground (deposit) above the bottom of the basin had no influence on the change of the pile load capacity in the considered time interval. Very soft aggregate muds at the bottom of the basin, with thickness of about 2.0 m, had no significant importance from the point of view of the pile load capacity and its change in time, either. The piles numbered from 1 to 15 show a gain in the load capacity, in the period starting from about the 5th day until the 55th day after the piles had been driven in the ground.

When we assume the formula (1) given by Skov (1988), describing the change of the pile load capacity values in time, it is easy to predict the load capacities measured in the second series, 55 days after their driving.

$$Q/Q_0 - 1 = A \cdot \log_{10}(t/t_0) \tag{1}$$

Q – load capacity in time (t)

- $Q_0$ – the load capacity at the moment of the first test
- A – the empirical constant
- t – time elapsed from the moment of the pile installation
- $t_0$ – the time of the first load capacity test

The constant A=0.20 typically used for sands, gives the increase of 19%. The average of the load capacity increments for all of the piles (see Fig. 9) is 16%, and the corresponding standard deviation is approximately 10%.

When we consider heterogeneous geology, the interbeddings of silt, sand and gravel, as well as the measured load capacities of all of the piles, it turns out that it is safe to assume the constant A=0.20, which leads to a good mean result (Fig. 9).

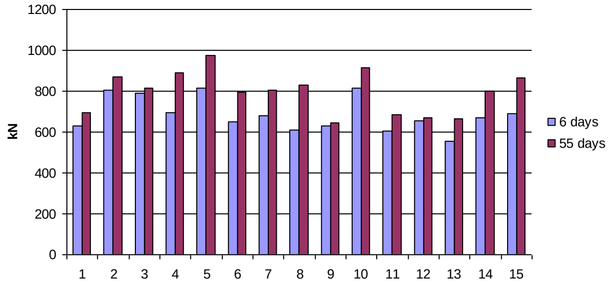

**Fig. 9** Pile capacity increase between 6th and 55th day after driving in sands.

In the case of silt or clay, the constant A=0.60 may be used. Another dozen of piles was examined at the end of driving and after 2 weeks. Skov's formula gives the increase of 67%. The average of the load capacity increments for 11 tested piles is 68% and the corresponding standard deviation is approximately 35%. Due to high changeability of cohesive soils parameters, it turns out that the conformity of results for the constant A=0.60 in silts is surprisingly quite good (Fig. 10).

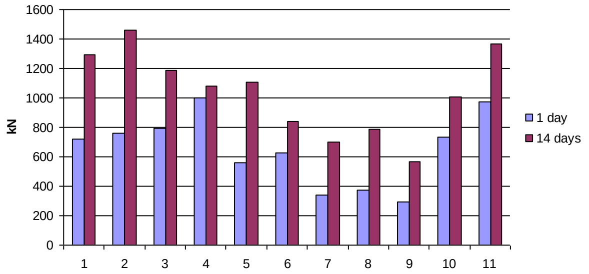

**Fig. 10** Pile capacity increase between 1st and 14th day after driving in silts.

Those results, formerly published by Rybak et al. (2008), prove that the formula (1) given by Skov provides a good estimation of pile capacity increase and may be cautiously used in engineering practice.

## Conclusions

Haste is recommended when catching flees, as an old Polish proverb says. Accelerating the time of pile testing, as far as both their load quality and capacity are concerned, is possible. That demands, however, the consciousness of the phenomena that take place in the pile as well as in its soil environment after the pile has been installed. Conservative regulations in codes of practice often oppose construction policy and practice, as haste is frequently the main factor in decision making. It is possible to carry out necessary inspection procedures even before the time defined in the codes of practice, after consistent collecting data for different concrete types, with tests starting on the 3rd-4th day after concreting (when the pile heads are uncovered) until the 28th day needed for its stabilization.

The outcomes attained are of considerable practical significance because they mean that pile length evaluation with the PIT method (even when we consider the unfinished process of concrete curing, and wave velocity in pile is estimated on the basis of earlier experience) is not worse than 4.4%. For piles under testing whose lengths not infrequently reach up to 20 m, it means that the error which could be made is no other than about 1 m. Estimation of wave velocity in concrete for low strain dynamic tests of piles must be made on the basis of the field tests and piling reports available, and also through critical analysis of proposals from data base. Selection of velocities from laboratory tests of soil samples is risky because the curing conditions (temperature and moisture) are significantly dissimilar. The concrete used for piles is of specific nature (sand-cement grout and fine-grain concrete). Numerous points observed which diverge from the trend (outliers up and down the waveform) could be attributable to the unique conditions at a given construction site.

Regarding capacity testing, especially for big pile contracts, rate of time increment capacity ought to be recognized to establish balance between haste and local soil conditions. In general, field tests prove that the formula (1) given by Skov (1988) provides a good estimation of pile capacity increase and may be cautiously used in engineering practice.

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## Acknowledgements

The author would like to express his gratitude to KELLER Polska Sp. z o.o. and AARSLEFF Sp. z o.o. for making available the results from the pile integrity tests and load capacity tests respectively.