Field tests on effect of concrete age on pile integrity testing

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Summary

This article reports on a series of integrity tests on four bored piles in a construction site near Vienna. The aim of these tests is to investigate the effect of concrete age on pile integrity tests. Extensive field tests were carried out within the 156 days after pile installation. The field tests were supplemented by laboratory tests (ultrasound measurements and compression tests) on core samples from bored piles. Based on the test results, some recommendations are made for the practice.

1. Introduction

Bored piles are widely used in foundation engineering. The prediction of the behaviour of bored piles requires both engineering knowledge and practical experience. The behaviour of foundation piles is affected by several factors, which are difficult to quantify, such as the installation methods, rate of installation and workmanship. The bearing capacity of piles depends not only on the physical properties of piles and soil conditions but also on the method of construction. Better knowledge of the soil behaviour and higher construction quality give rise to better design and increase the higher vertical and horizontal bearing capacity of piles. This in turn implies an increased demand on the material quality and workmanship. The quality control of bored piles has increasingly gained importance.

The integrity test, also called sonic integrity test (SIT), is a non-destructive testing method that can indicate anomalies in piles such as major cracks, necking, soil inclusions or voids, which may have negative impact on strength behaviour of piles [Finno and Gassman, 1996; Kirsch and Klingmüller, 2003; Middendorp and Verbeek, 2006]. Pile integrity testing can provide valuable information on the integrity of the pile shaft and therefore ensure the quality of pile construction. The integrity tests are usually carried out on matured concrete before construction of the superstructure. In practice, integrity tests are sometimes carried out at early stage, e.g. 7 days after pile installation. Frequently, short construction time requires integrity testing at early concrete age. The properties of the concrete depend on the age which in turn influences the wave propagation characteristics. An estimation of the shaft length and the pile integrity are both dependent upon the wave propagation velocity in concrete [Niederleithinger and Taffe, 2006].This paper investigates the effects of the concrete age on the results of pile integrity testing. In addition, we look into the minimum time after placing concrete, when non-destructive testing methods can be reliably evaluated.

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2. Testing method

In the present investigation, field measurements of wave velocities were carried out on four installed bored piles with a length of about 13 m and a diameter of about 90 cm. Both the ground conditions and the pile installation were carefully documented. The field wave velocities were compared with the measurements in laboratory. Those laboratory measurements were performed on a concrete beam with an ultrasonic device. Moreover, some axial compression tests were carried out on cylindrical specimens obtained from bore cores of the test piles.

2.1. Field conditions

For the purpose of field testing, four bored piles (without steel reinforcement) with a diameter of about 90 cm and length of 13 m were installed (Fig. 1). Before the integrity testing, the pile heads were cut by about 80 cm to remove the disturbed concrete. The field tests were carried out within a period of 156 days. The properties of the concrete material are given in table I. The pile length and diameter are selected so that the difference in compressive strength at measured level and at the pile tip is minimal. For this purpose the ratio of length to diameter of the pile is chosen to be about 14.

The ground conditions are depicted in figure 2. The top layer consists of fine sand with a thickness of about 1.1 m. It is followed by a massive stratum of

Tab. I - Properties of concrete.
Tab. I – Caratteristiche del Calcestruzzo.

Cement	CEM II /A-S 42,5 N
Concrete type	C25/30
Casting temperature [°C]	+18
W/C ratio	0.60
Maximum size of aggregate [mm]	32
Flow diameter [cm]	60

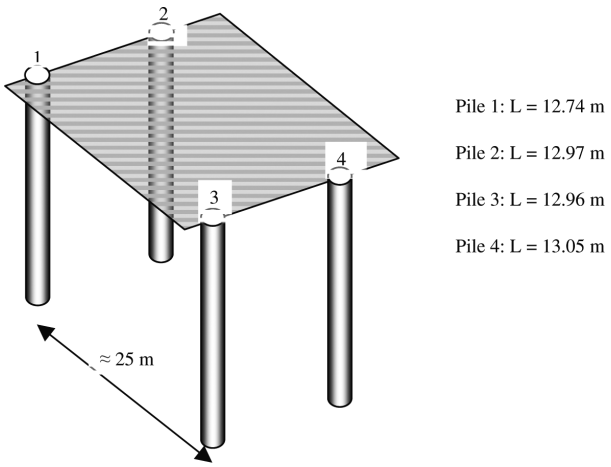

Fig. 1 – Layout of test piles.
Fig. 1 – Schema di prova dei pali.

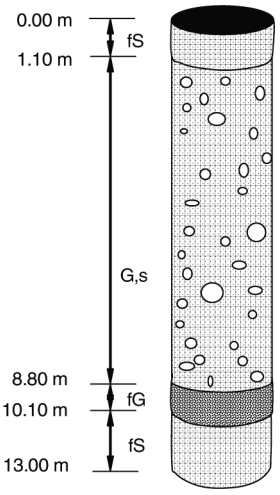

Fig. 2 – Typical soil profile at testing site.
Fig. 2 – Stratigrafia tipo del sito di prova.

sandy gravel up to the depth of 8.8 m below ground level. The sandy gravel is underlain by a layer of fine gravel till the depth of about 10.1 m. A massive stratum of fine sand is expected below the fine gravel layer. The groundwater level is below the pile tip and does not have to be considered.

In order to obtain reliable correlations between field tests and laboratory tests, an extensive testing program was envisaged. The following tests were carried out:

– Three set of tests on the fresh concrete at the site (density, water content, flow diameter, air content) and tests on specimen cubes from the same batch of concrete;
– Compressive strength tests on concrete cubes (15×15×15 cm³) and bored samples (d=100 mm at the age of 89 days);
– Travel time measurements with ultrasound on 6 beams (10×10×40 cm³) at the ages of 1, 3, 6, 12, 21, 28, 56 and 365 days and also in pile cap and shaft after 89 days;
– Measurements of static Young's modulus of concrete in 7, 28, and 365 days on three measurement beams with the size of 10×10×40 cm³;
– Sonic integrity tests at the age of 1, 2, 3, 5, 7, 14, 21, 28, 56, 89 and 156 days.

2.2. SIT test and ultrasound measurements

The pile integrity tests were conducted by using a measuring system of the company PROFOUND form the Netherlands. The software 6.1.1 FPDS SIT was used for signal recording and the software 7.0.0 FPDS SIT was used for signal interpretation [MIDDENDORP, 2004]. The principle of this measurement method was developed in the mid-60s by TNO IBBC in the Netherlands. A shock wave is produced with the help of a hammer blow on the pile head. This shock wave travels at the speed of sound to the pile tip and will be reflected there. The reflected waves travel back to the pile head. The echo on the pile head as a result of a hammer blow and its reflections are recorded with the help of a geophone. The acceleration is integrated over time and presented as time velocity chart [TIMOSHENKO and GOODIER, 1970]. The ultrasound measurements were performed with the device TICO. This device can produce a frequency of 54 kHz. Wave velocities were measured directly in the pile shaft as well as in the reference beam (10×10×40 cm³) in laboratory.

Concrete is made of elastic aggregates embedded in cement matrix as a semi-plastic binder. Whereas the dynamic Young's modulus of the concrete is primarily dependent on the elastic properties, the compressive strength depends mainly on the semi plastic properties of concrete. The short-term mechanical stresses during the pile integrity testing are mainly sustained by the aggregates. The ultrasound waves also cause periodic stresses of small amplitudes in concrete for a period of about 6-10 seconds, which result only in elastic strain.

The cement and aggregate are known to have different mechanical properties. At the interface between aggregates and cement, ultrasonic waves are reflected provided the wavelength is smaller than

Fig. 3 – Concrete at pile head (a) immediately after concreting (b) 1 hour later (c) 4 hour later.
Fig. 3 – Calcestruzzo alla testa del palo: a) immediatamente dopo il getto; b) un'ora dopo; c) quattro ore dopo.

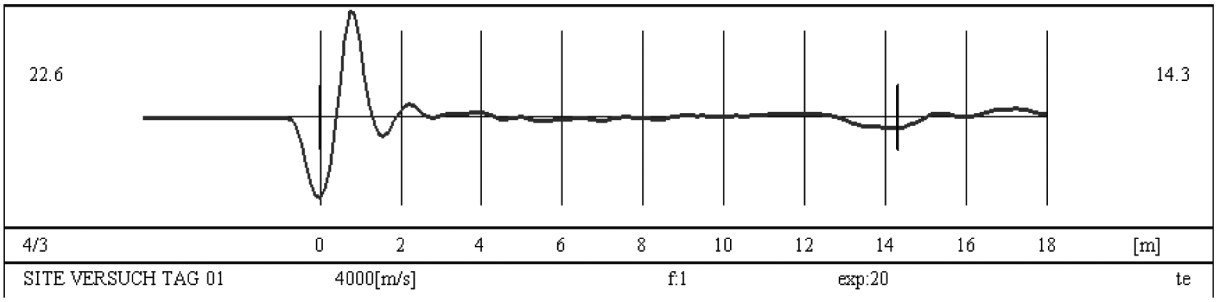

Fig. 4 – Measuring signal: Test series, Pile 3, Day 1 after concreting.
Fig.4 – Forma d'onda misurata: prova sul palo n. 3, un giorno dopo il getto.

the mean diameter of the aggregates. As for the measurement of longitudinal waves, a frequency of 54 kHz was selected. With this frequency it can be ensured that inelasticity of concrete does not affect the measurements. With an expected wave velocity of about 4000 m/s and a test frequency of 54 kHz, a wave length well above the maximum size of aggregate can be obtained.

The sound wave for the integrity tests gives rise to deformation in both longitudinal and lateral direction. However, the signals in the lateral direction were not measured. Note that the material particles move under the imparted stress with the particle velocity, which in contrast to the ultrasonic wave velocity, is independent of the applied force.

3. Analysis and interpretation

Due to thermal effect some cracks were observed in the pile heads (Fig. 3). However, the measured signals did not show any indication of cracks along the pile shaft. The cracks at the pile head can be regarded as separation cracks. The setting process in concrete starts immediately after pile installation. During this setting process, the concrete heats up very quickly. At the initial stage, the concrete is in plastic form and possesses very low compressive strength. With increasing E-modulus, however, the borehole boundary will exert some constraint on concrete and some stress relaxation will increase steadily. The difference between the increase in E-Modulus and cooling due to heat dissipation into the borehole-wall gives rise to the separation cracks at pile head.

3.1. Integrity test results

The first readings using SIT were taken approximately 24 hours after concreting (Fig. 4). The fresh concrete at this stage behaves very much like a fluid. In fresh concrete waves propagate mainly through the aggregates since the solid matrix has not yet been formed by the hydration process. The reflection at pile tip is very weak. Along with increasing concrete age, the reflection at the pile tip can be clearly identified (Figs. 5 and 6). As can be seen from figure 5, the pile length can be reliably determined by SIT some 5 days after concreting.

Figure 7 shows the development of wave velocity (c_{Pile}) for the entire maturity period of concrete, which can be divided into three phases. The SIT test results of the four test piles show that after about 10-15 days, there is no significant increase in wave propagation speed in concrete. The maximum rise in wave velocity (c_{Pile}) lies in the first phase (acceleration phase). There is only minor increase in wave velocity in the following two phases. Since the w/c ratio of the concrete after 24 hours is higher than the w/c ratio after 28 days, the changes in wave velocity (c_{Pile}) seem to be proportional to the hydration level of concrete. This is because the density of concrete

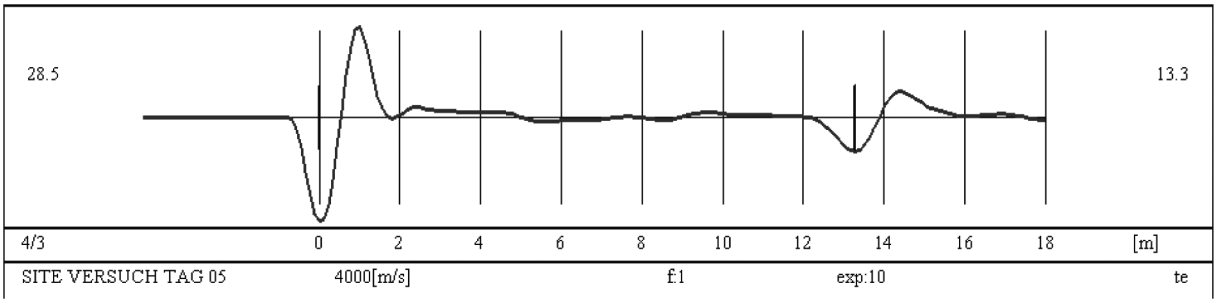

Fig. 5 – Measuring signal: Test Series, Pile 3, Day 5 after concreting.
Fig. 5 – Forma d'onda misurata: prova sul palo n. 3, cinque giorni dopo il getto.

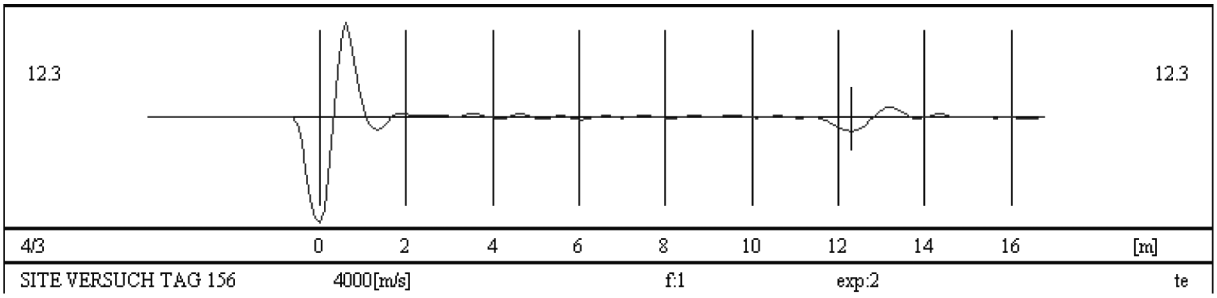

Fig. 6 – Measuring signal: Test Series, Pile 3, Day 156 after concreting.
Fig. 6 – Forma d'onda misurata: prova sul palo n. 3, 156 giorni dopo il getto.

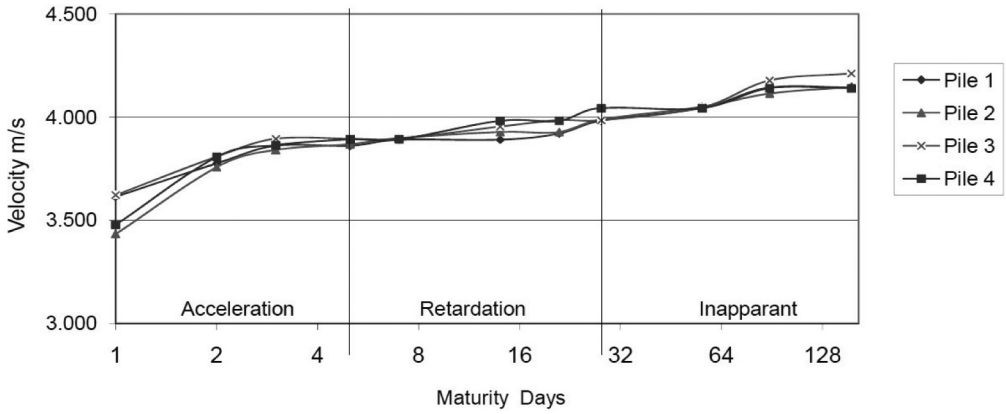

Fig. 7 – Development of wave velocities.
Fig. 7 – Incremento della velocità con il tempo di stagionatura.

and soil remain unchanged. These changes in wave velocities also imply changes in tensile and compressive stresses of concrete along with the degree of maturity.

The three maturity phases are characterized by different growth rates of wave velocity (c_{Pile}), which are specified by the standard in Austria [ÖNORM B 4710-1, 2004]. The highest growth rate in wave velocity occurs in the acceleration phase because it is in this phase that the development of concrete from fresh concrete to fully matured concrete takes place.

The growth rate of c_{Pile} in figure 8 is estimated from the data in figure 7. It can be seen from figure 8 that the growth rate decreases after concrete placement. The decrease is most significant in the first phase till day 3 and 5. In the subsequent phases the wave speed (c_{Pile}) rises only marginally by about 0.05% per day. This growth rate is only about one-tenth of the previous period.

3.2. Ultrasound measurements

In order to correlate the field measurements with laboratory data, some tests were carried out on concrete beams to measure the wave speed with an ultrasonic device. The measured wave velocity (c_{US}) on a reference beam with an ultrasound device at

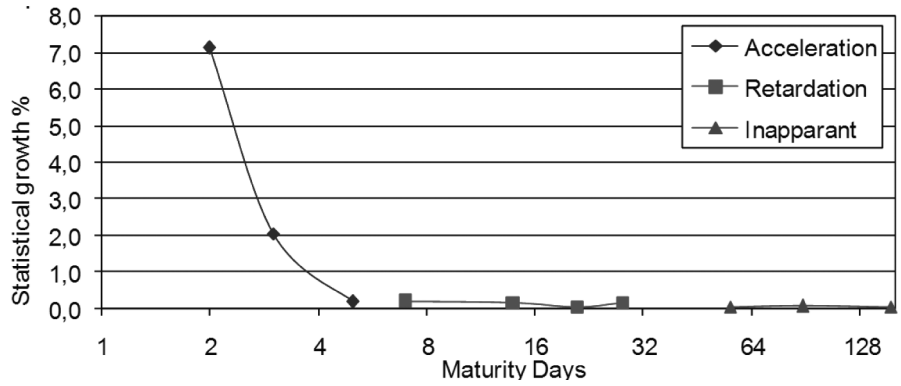

Fig. 8 – Growth rate of c_{Pile} in the three stages.
Fig. 8 – Andamento del fattore c_{Pile} con la stagionatura, suddiviso in tre stadi.

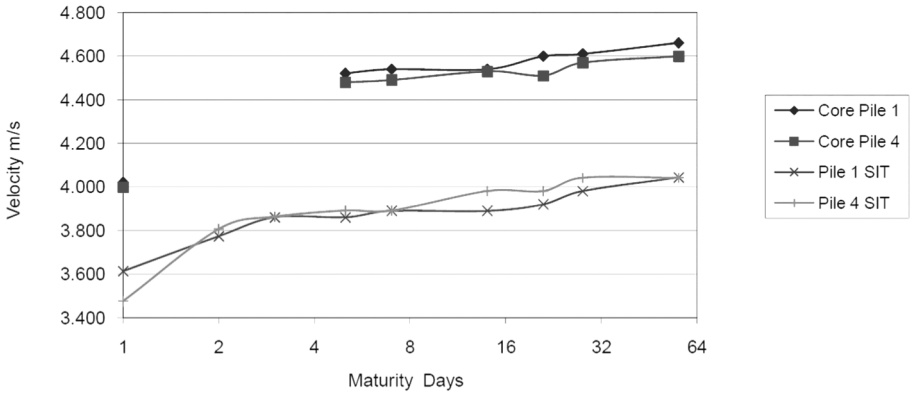

Fig. 9 – Development of wave velocities c_{US} and c_{pile}.
Fig. 9 – Crescita delle velocità c_{US} and c_{pile} col tempo di stagionatura.

different concrete ages are shown in figure 9. For comparison, the measured wave velocities c_{Pile} from SIT are also presented in the figure. The difference between c_{Pile} and c_{US} are ascribed to the different boundary conditions in field and laboratory. In case of SIT on piles, the imparted kinetic energy is dissipated through shearing deformation between the pile and surrounding soil [VOIGT *et al.*, 2004].

We proceed to compare the dynamic modulus from SIT and ultrasonic tests. From the wave speed in SIT, the dynamic E-Modulus can be calculated with the following well known equation:

$$E_{dyn}[N/mm^2] = c_{Pile}^2 \rho \qquad (1)$$

where c_{pile} is the wave velocity measured by SIT and ρ denotes the density of concrete. Strictly speaking, the above formula is only valid for one dimensional propagation of stress waves along a long rod with stress-free boundaries. A bored pile, however, is embedded in ground. The earth pressure at the mantle surface and at pile tip of the pile differs from the stress-free boundary conditions of the rod. Nonetheless, the SIT testing practice shows that SIT tests can be reasonably well evaluated based on the one dimensional wave propagation along long rods. This good agreement is probably due to the low strain in the SIT tests. The wave speed is mainly dictated by the property of concrete. In testing practice, this wave speed is usually assumed to be about 4000 m/s.

As we know, the wave length generated by an ultrasonic device is smaller than that in a SIT test. This gives rise to some deviation from the one dimensional wave theory for the SIT tests. The difference in wave speed from SIT and ultrasonic measurements is usually less than 10% [AMIR and AMIR, 1998]. For the ultrasound measurements on the reference beams, the dynamic E-modulus is calculated based on the propagation of p waves in an infinite domain by the following equation.

$$E_{dyn}[N/mm^2] = \frac{(1+\mu)(1-2\mu)}{1-\mu} c_{US}^2 \rho_1 \qquad (2)$$

where c_{US} is the wave speed measured by ultrasound, ρ denotes the density of concrete and μ stands for the poisson ratio of concrete. The above formula is widely used in ultrasonic speed measurement along concrete beams, although the beam geometry obviously differs from an infinite do-

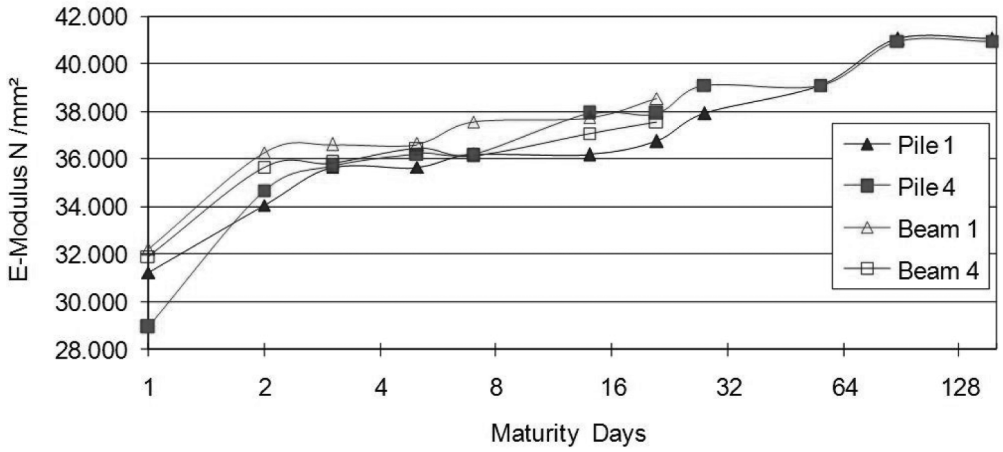

Fig. 10 – Calculated dynamic E-modulus from wave speed (c_{US} and c_{pile}) measurements.
Fig. 10 – Modulo dinamico E calcolato dale velocità c_{US} and c_{pile} misurate.

main. The development of dynamic modulus from SIT and ultrasonic tests are shown in figure 10. Good agreement between the two kinds of tests can be observed. The slightly higher E-modulus from the ultrasonic measurements is ascribed to higher wave speed from the ultrasonic measurements.

3.3. Compressive strength and wave speed

As stated above, a short-term mechanical stress pulse resulting from the imparted energy during pile testing propagates mainly through the elastic components. The compressive strength, however, is influenced by semi-plastic and less firm binding materials [PLASSMANN, 2002]. Next an attempt is made to correlate the static modulus from compression tests to the dynamic modulus obtained in the last section. This is done by comparing the static modulus according to some widely used empirical formula. Usually the compressive strength is measured in the compression tests on the concrete specimens. From the measured compressive strengths (N) of the pile concrete samples, the static E-modulus (E_{stat}) can be calculated using one of the following empirical equations:

$$E_{stat}[N/mm^2] = \frac{5.55 \cdot 10^4 N}{N + 20} \quad (3)$$

$$E_{stat}[N/mm^2] = 9500 \sqrt[3]{N+8} \quad (4)$$

$$E_{stat}[N/mm^2] = 2100 \sqrt{N} \quad (5)$$

Equations (3), (4) and (5) are proposed by DURIEZ [1959], ROTH [1977] and KAINRATH and LUDWIG [2005], respectively. The above relationships are widely used in practice in Austria and Germany. The next step is to relate the static modulus with the dynamic modulus. There are numerous relationships between the static and dynamic modulus for concrete in the literature, e.g. KOLIAS and WILLIAMS [1980] and PESSIKI and JOHNSON [1996]. In the present paper, the following empirical relationship proposed by SELL [1958] is used to obtain the dynamic modulus from the static modulus:

$$E_{dyn}[N/mm^2] = 1.66 \cdot 10^4 + 0.674 E_{Stat} \quad (6)$$

Note that the unit in the above relationship is [N/mm^2]. The dynamic modulus calculated from the above formula are compared with those from the SIT tests based on equation (1). These calculated dynamic modulus are shown in figure 11. The following observations can be made in figure 11. There is only minor difference between equations (3) and (4). However, large discrepancy can be observed for equation (5), which indicates that this equation is not suitable for the concrete investigated here.

Despite the good agreement shown in figure 11, the correlation between the compressive strength and the wave speed should be regarded with some caution, sine they represent behaviour in different regimes, i.e. elastic and plastic regimes. Nonetheless, the correlation may serve as a useful to detect the variation in compressive strength. To use this correlation reliably, some calibration is necessary.

3.4. Tests on drill core samples

After 60 days of concreting, core samples of size about 100 mm in diameter were taken from the piles from a depth of 0.9 m and 7.4 m below the pile head. The bore core samples were placed in an oven at 50°C for 3 days. After then the unconfined compressive strength tests were conducted.

The result showed that the compressive strength increases from the top to the bottom of the

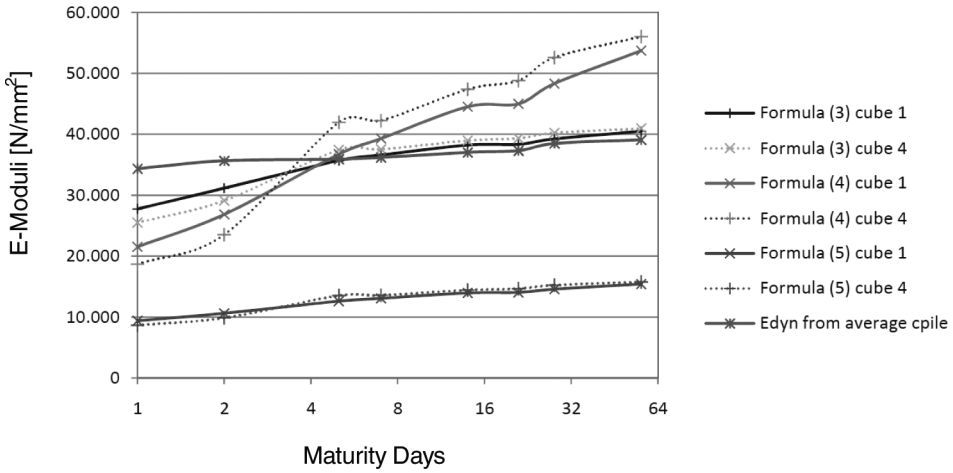

Fig. 11 – Comparison of static E-modulus using different empirical formula. The dynamic modulus calculated from (3), (4) and (5) are based on uniaxial compression tests on concrete specimens from concrete batches before placement. The dynamic modulus E_{dyn} calculated from c_{Pile} are based on the SIT tests with the help of formula (1).
Fig. 11 – Confronto del modulo statico E calcolato usando 3 diverse espressioni. Il modulo calcolato dalla (3), dalla (4) e dalla (5) è ricavato da prove di compressione uniassiali su provini preparati da calcestruzzo prelevato dalla betoniera prima del getto. Il modulo dinamico E_{dyn} calcolato dalla velocità c_{Pile} si basa sui risultati di prove di integrità utilizzando l'espressione (1).

Tab. II - Results of drill core sample test.
Tab. II – Risultati delle prove sui provini carotati.

Tests	Measurement level -0.9m	Measurement level -7.4m
Unconfined compressive strength, N [N/mm²]	52.9	60.4
Wave velocity c_{US} [m/s]	4230	4400

Tab. III - E-modulus and wave speed obtained from tests on drill core sample.
Tab. III – Modulo E e velocità delle onde ricavati da prove su provini carotati nei pali.

Tests	Measurement level -0.9 m	Measurement level -7.4 m
Static E-modulus [N/mm²], from Eqn. (3)	39900	41300
Dynamic E-modulus [N/mm²], from Eqn. (6)	43500	44400
Wave velocity c_{pile} [m/s], measured from SIT	4040	
Wave velocity c_{pile} [m/s], calculated from c_{US}	4012 (Difference - 0.7%)	
Wave velocity c_{pile} [m/s], calculated from N	4330 (Difference + 6.7%)	

piles. Moreover, the compressive strength increases from the centre to the boundary of the piles. The density of concrete remains fairly independent of depth and position. The average values of compression strengths and wave velocities from ultrasound measurements are given in table II.

Using equations (3) and (6), the static and dynamic modulus and the wave velocity of the core samples as well as in piles are calculated and presented in table III. The calculated values show that while using equation (3), there is a very good correlation between the wave velocity c_{pile} and the compressive strength. Therefore the compressive strength of concrete can be reliably estimated from the measured wave velocity.

Conclusions

The present investigation shows that the SIT measurements are capable of describing the setting and hardening process as well as the compressive strength of concrete in a reliable way. The test results show that the integrity test after 2 days of concreting can provide reliable results. However, in practice integrity test after 3 days of concreting will

be more realistic and appropriate, as suggested by NIEDERLEITHINGER and TAFFE [2006]. As a matter of fact, the hardening process of concrete in piles after placement is rather complex and depends on the size and length of piles and on the properties of concrete. Although reliable testing results were obtained in our tests after 2 days, it ought to be recommended to conduct some tests after some time, e.g. 3 or 5 days after placement. The comparison among them shall provide some insight into the validity of the SIT tests at such early stage.

The wave speed measured in SIT correlates well with that from laboratory tests on concrete beams with ultrasonic method. Further correlations are obtained by relating the static properties from compression tests to the dynamic properties from SIT and ultrasonic tests. However, these correlations should be used with some care and some calibration work is recommended.

Acknowledegements

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Sperimentazione in situ sugli effetti della stagionatura del calcestruzzo nei test di integrità strutturale dei pali

Sommario

L'articolo descrive una serie di prove per la verifica dell'integrità di quattro pali trivellati realizzati in un cantiere vicino Vienna. Scopo delle prove è indagare l'incidenza della stagionatura del calcestruzzo sui risultati delle prove. Una vasta campagna di prove è stata condotta durante i 156 giorni successivi alla realizzazione dei pali. Le prove in sito sono state integrate da prove in laboratorio (misura delle velocità delle onde elastiche con metodi ultrasonici e prove di compressione) su provini carotati dai pali. Sulla base dei risultati delle prove, si propongono alcune raccomandazioni per la pratica professionale.