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MODULUS OF ELASTICITY IN DEEP BORED PILES

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Abstract The modulus of elasticity of pile material (E) is an important parameter for the interpretation of both static and dynamic loading tests on piles. This value is commonly assumed to be constant with depth though it may not be true for deep bored piles due to the chosen casting method and/or self-weight consolidation. To provide evidence to support this proposition, the results of compressive strength tests on core samples taken from four different studies have been presented. The results show a marked increase in the strength and stiffness values with depth. The results of crosshole ultrasonic tests conducted at another site also confirm the same pattern. It is therefore recommended that before load testing a pile the distribution of the E values along the pile axis should be investigated. This will ensure the use of a realistic elastic modulus value and hence the correct interpretation of the distribution between the shaft and end resistances.

Introduction

The modulus of elasticity of pile material (E) is an important parameter for the interpretation of both static and dynamic load tests on piles. Multiplying E by the strain measured by either strain gauges (e.g. ASTM D4945) or tell-tales (e.g. Geffen and Amir, 1971) gives the stresses acting at a given pile section. Typically, in the absence of better information, the value of E is derived from laboratory tests on concrete cubes or cylinder specimens taken on site and is assumed to be constant along the pile. While this may be correct for pre-fabricated concrete piles that are cast in horizontal molds, it may not be true for cast-in-place piles that are produced in the vertical position.

There are at least two factors that may contribute to the change in concrete properties with depth in a bored pile. First, the casting methods may be by free fall in dry holes (e.g. Kiefer and Baker, 1994) or by using a tremie tube if support fluids are used. In the former case, the earlier batches reach the bottom of the pile bore at a higher velocity and are thus compacted under higher energy. Second, regardless of the casting method, the fresh concrete in the pile bore will always consolidate at least partially under its own self weight. The materials in the lower parts of the pile will therefore experience a higher consolidating pressure. This can reduce the pore volume and the water content in the wet concrete, thus changing the properties of the hardened concrete. Recent research by Justs et al. (2011) has shown that even a relatively small pressure can have a significant positive effect on concrete properties such as compressive strength and stiffness. However, the possible change of concrete properties with depth is commonly ignored by foundation engineers in the current design practice.

Compressive strength versus depth

As a quality assurance measure, core samples are sometimes taken from completed bored piles and suitable specimens chosen for measurement for their compressive strength. Results of 69 such tests on cores obtained from four different studies have been collated and are shown in Fig. 1a (Kiefer and Baker 1994; Arup 2010; Harris et al. 2011; Chernauskas, 2013). Despite the scatter, which is probably due to the different site conditions, equipment used, pile dimensions and casting methods, the results show a marked increase of the compressive strength with depth at a rate of about 0.43 MPa/m.
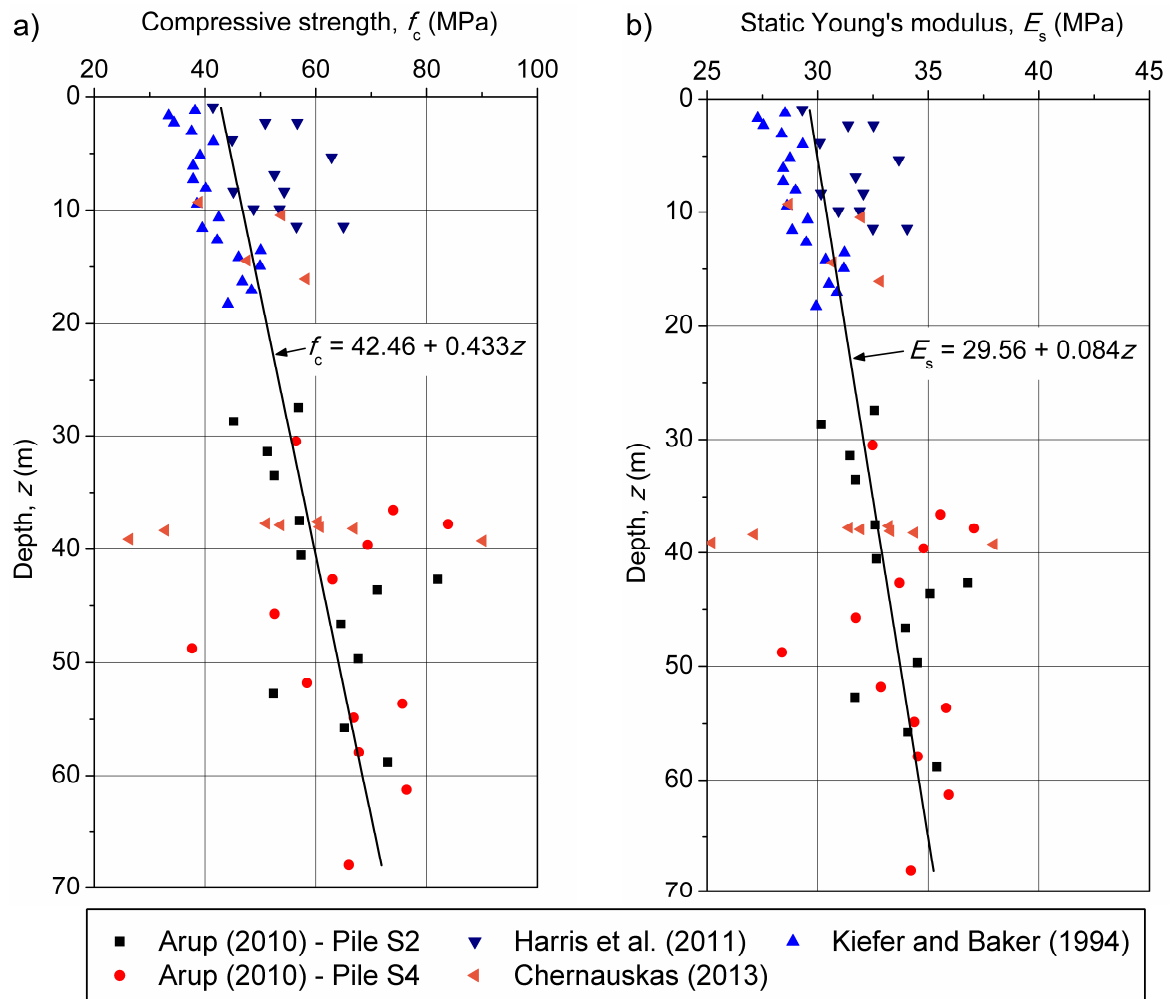
Fig. 1. Compressive strength (left) and modulus (right) versus depth for four different studies (data after Kiefer and Baker 1994; Arup 2010; Harris et al. 2011; Chernauskas, 2013).

Static Modulus of Concrete

Concrete is not a linearly elastic material and thus its Young's modulus (stiffness) is not a constant. For the purpose of the following discussions, a distinction needs to be made between the static and dynamic moduli of concrete. The static modulus (E_s) is commonly obtained from conventional static load tests on cube or cylinder specimens. According to ASTM C469, concrete cylinders are tested for compressive strength and the secant modulus calculated over the 0–40% compressive strength range. British standard BS1881-121 also requires testing of cylinders but the secant modulus is calculated over the 0–33% the compressive strength range.

The value of E_s can also be inferred from the compressive strength (f_c) by using the following empirical relationship (CEB, 1993):

$$E_s = 8.48(f_c)^{1/3} \qquad\qquad \text{Equation 1}$$

where E_s is given in GPa and f_c is in MPa. Using Eq. 1, the f_c data shown in Fig. 1a have been converted to the static modulus values and the results are shown in Fig. 1b. It can be seen that the value of E_s at a depth of 70 m is about 20% higher than that close to the top.

Dynamic Modulus of Concrete

The dynamic modulus (E_d) can be obtained directly from non-destructive laboratory testing of cubes or cylinders using an ultrasonic concrete tester or by the resonant frequency method according to BS 1881-209 (BSI, 1990) or ASTM C215 (ASTM, 2008a). There are several empirical relationships linking dynamic and static moduli. For example, BS8110 Part 2 (BSI, 1985) gives the following equation which is also widely quoted in textbooks on reinforced concrete:

$$E_s \text{ (GPa)} = 1.25\, E_d - 19 \qquad\qquad \text{Equation 2}$$

Recent research by Popovics (2008) found a somewhat similar relationship by comparing the results of static and dynamic tests conducted according to ASTM 469 and ASTM C215, respectively:

$$E_s \text{ (GPa)} = 1.197\, E_d - 15.43 \qquad\qquad \text{Equation 3}$$

The transition from static to a fully dynamic loading, however, is gradual rather than instantaneous. From laboratory experiments using microconcrete, Shen and Lu (2008) found that the ratio of dynamic to static moduli (E_d/E_s) is highly dependent on the governing strain rate. It was found that E_d/E_s increased by 35.7% when the strain rate increased from 10^{-5} s^{-1} (practically static state) to 10^{-1} s^{-1} (typical to pile driving). This is equivalent to a nine percent increase in the modulus value for every tenfold increase in the strain rate.

Dynamic Modulus from Crosshole Ultrasonic Testing

As discussed before, the properties of the concrete in a pile can be very different from those measured in a laboratory on cubes or cylinders taken from the same batch due to different environmental and curing conditions. Hence, a field method for measuring the dynamic modulus (E_d) of the pile material is highly desirable and the results will be representative of the actual conditions. This can be achieved by an innovative use of the results of conventional crosshole ultrasonic tests. The procedure is described as follows.

Due to the advent of modern electronics, in a crosshole ultrasonic test (ASTM, 2008b) the travel time of P-waves between the two access tubes is measured with high accuracy. By using the technique of oblique pulses (Amir et al. 2004), the P-wave speed (c_P) of the pile concrete can be accurately determined. The value of c_P depends only on the concrete properties and can be expressed in the following equation based on the theory of elasticity:

$$c_p = \sqrt{\frac{E}{\rho}} \sqrt{\frac{1 - v}{(1 + v)(1 - 2v)}} \qquad\qquad \text{Equation 4}$$

where ρ is the density and v is the Poisson's ratio of the material. The value of ρ is typically 2300 kg/m^3 and is relatively insensitive to the applied pressure (Justs et al., 2011). The value of v typically ranges from 0.15 to 0.22 (Neville, 1995), and thus the value of the second square root in Eq. 4 lies in the narrow range of 1.03 to 1.07 with a mean of 1.05. Substituting these typical ρ and v values into Eq. 4 and rearranging gives:

$$E_d \text{ (GPa)} \approx 2.1\, (c_P)^2 \qquad\qquad \text{Equation 5}$$

where c_P is expressed in km/s.

According to Miner (2013), crosshole ultrasonic tests were performed on three bored piles (P1 to P3) with a diameter of 2 m and a length of 73 m for a project in Vancouver BC. Each pile was fitted with five access tubes that enabled logging of ten profiles. Fig. 2a shows the average wave speed measured every meter along each of the pile. It can be seen that the wave speed increased from about 3900 m/s near the pile head to almost 4200 m/s near the pile toe – an increase of about 7.5%. The dynamic Young's modulus of the pile concrete has also been calculated using the measured wave speed and Eq. 5; the results are shown in Fig. 2b. It can be seen that the concrete modulus increased from about 32 GPa near the pile head to about 37 GPa near the pile toe (a 16% increase), or at an average rate of 70 MPa/m. Fortuitously, this compares rather well with the rate of 84 MPa/m calculated independently from compressive strength values for the other studies (Fig. 1b).
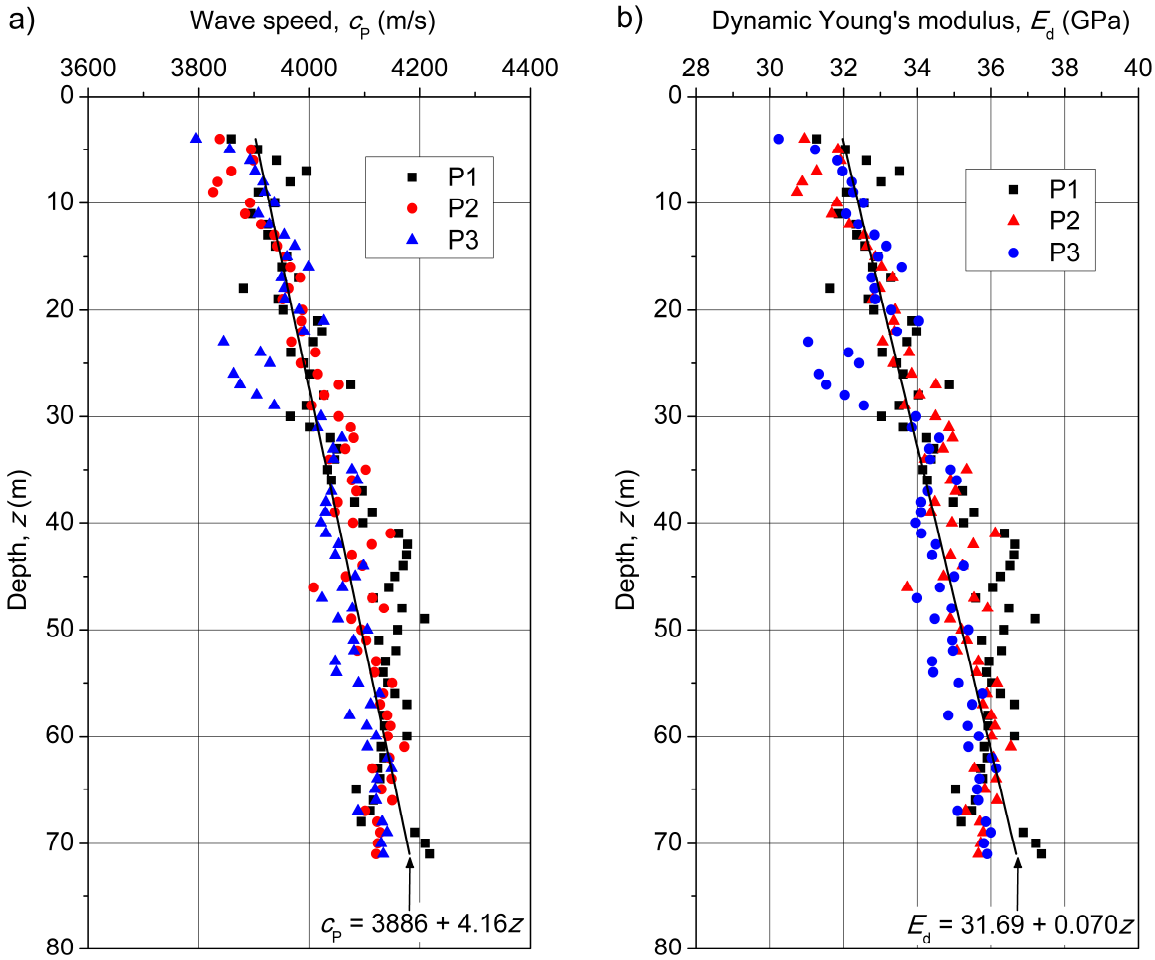

Fig. 1. Measured wave speed (left) and calculated dynamic modulus (right) against depth in three large-diameter bored piles (data after Miner, 2013)

Conclusions

Based on the case studies examined in this paper, the following conclusions can be made:

1. The concrete in a bored pile is not necessarily a homogeneous material and may vary with depth due to the chosen casting method and/or self-weight consolidation.

2. Based on the laboratory test results of core samples obtained from four different sources (Fig. 1a), the compressive strength of concrete in bored piles appears to increase with depth at a typical rate of 0.43 MPa/m. Further study of case histories will be required to confirm this value.

3. Based on the results shown in Figs. 1b and 2b, the Young's modulus of concrete in bored piles appears to increase with depth at a rate of about 70-85 MPa/m. Further study of case histories will be required to confirm this range.

4. If the increase in Young's modulus with depth is not taken into account during the interpretation of load test using tell-tale or strain gauge results, the axial load in the lower portion of a pile could be significantly underestimated.

5. Based on the results of a case history shown in Fig. 2, the non-destructive crosshole ultrasonic testing technique appears to be a suitable and convenient method for determining the profile of static Young's modulus (E_s). For the interpretation of pile load test results, the dynamic modulus may be correlated to the static value (E_s) using existing empirical relationships. The E_d/E_s ratio will depend on the difference in the strain rate and also the strain range over which the static value is determined. Further research will be required to quantify the effects of strain and strain rate on the E value of pile materials.

Acknowledgements

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