JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
ISSN 1392-3730 print/ISSN 1822-3605 online
2012 Volume 18(4): 512–518
doi:10.3846/13923730.2012.709958

EXPERIMENTAL STUDY ON TECHNOLOGICAL INDICATORS OF PILE-COLUMNS AT A CONSTRUCTION SITE

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Received 20 Dec. 2010; accepted 04 Nov. 2011

Abstract. Decision making is a vital component of success in construction management. All construction businesses recognize the painful necessity of technology choice. Good decisions mean good business. Decisions that are based on knowledge and sound reasoning can lead a company into long-term prosperity.
The mandate of a construction management researcher is to use rational, systematic, science-based techniques to inform and improve decisions of all kinds. The paper presents results of an experimental study on technological indicators of pile-columns at a construction site. Based on in-situ investigation of natural soil conditions, regression equations have been determined, which can be very useful when planning similar works at a construction site. Besides, they allow determining duration and energy consumption of construction works.

Keywords: pile-columns, technology, indicators, construction site, regression analysis.

1. Introduction

Rationality of construction works is one of the most challenging tasks in real life. In terms of construction, only well-reasoned decisions should be taken. Thus, choosing technologies is just as important as deciding on an effective design. Construction technologies are highly dependent on *in-situ* conditions, e.g. soil conditions are particularly important for foundation. Besides, there is a growing need for well-reasoned methods that would ensure a more effective scheduling of construction works to forecast the project duration and related energy consumption. Numerous investigations deal with the impact of soil conditions on construction works.

The experimental programme was developed based on previous work and, among others, on a study conducted by Lambert *et al.* (2006) on the assessment of coarse granular pavement foundation materials.

Unforeseen site conditions have been named by Minchin *et al.* (2011) as the greatest challenge in pile construction. A full understanding of the mechanical behaviour of soils is of major importance in construction engineering, including construction of bridges and roads as well as pile-columns. In engineering (e.g. in case of foundations), soil is usually treated as a continuum (Amšiejus *et al.* 2010). As required by designers and constructors, information on soil properties is obtained at each construction site by examining the physical and mechanical properties of soils (Amšiejus *et al.* 2009).

Lithuania belongs to the group of countries experiencing an extensive effect of climatic conditions on road design, construction and repair. Climatic conditions encompass the amplitude and speed of temperature change, max and min temperatures, precipitation, wind direction and speed, thickness of snow cover, and freezing depth. The latter – freezing depth – is one of the most important climatic factors in winter (Juknevičiūtė, Laurinavičius 2008). It must be underlined that the paper does not investigate these climatic conditions and their impact on soil. Ždankus and Stelmokaitis (2008) presented new ideas about the possibilities to increase the reliability of soil stability computation method. Sušinskas *et al.* (2011) presented the process for selection of the most fitting and effective pile-column instalment alternative. The selection is based on a set of criteria: Mass, Cost of Instalment, Labour Costs, Machinery Costs, Scope of Earthwork and Instalment Tolerance. The solution to the problem was found using MCDM methods (Sušinskas *et al.* 2011).

Boutet *et al.* (2011) developed models that relate the strength properties of soils (undrained shear strength obtained with a vane tester) on one hand, the resilient properties (back-calculated modulus obtained with deflection tests) on the other hand, and the penetration index values.

Fam and Rizkalla (2003) provided an experimental programme and investigated the behaviour of concrete-filled FRP tubes as flexural members, axial members and beam-column members using large-scale concrete-filled

FRP tubes as well as analytical modelling and parametric studies.

Cai *et al.* (2011) developed T-shaped bidirectional soil-cement deep-mixing column as part of quality improvement of soft soil for low-volume roads and proved it to be effective and economical. Yoon *et al.* (2011) presented the evaluation of load test results and the rationale used for the selection of the resistance factor. An instrumented pile load tests – both static and dynamic – were performed as part of the foundation design for the bridge project. The load–transfer curve of the test pile was obtained from strain measurements by using "sister bar" strain gauges at six locations along the pile shaft.

Abu-Farsakh *et al.* (2011) investigated batter pile foundations and conducted a full-scale lateral load test on an eastbound pier of a new bridge to evaluate their performance under lateral loading. The investigation results were as the soils' high-order polynomial curves at different depths.

Kačianauskas *et al.* (2010) presented simulation methodology to imitate the dynamic behaviour of the non-cohesive frictional visco-elastic particle system.

In their study, Roling *et al.* (2011) targeted such specific topics as current foundation practice; the extent of timber pile use; pile analysis and design; and pile drivability, pile design verification, and quality control.

There are lots of different applications of piles in construction. In urban areas, many high-rise buildings and viaducts are supported by pile foundations (Zhang *et al.* 2011b). The way the designed and actual founding depths of foundations correspond to variability of geological conditions has long been a concern. Zgang and Dasaka (2010) evaluated the spatial variability characteristics of as-built and estimated founding depths of driven steel H piles with reference to the spatial variability characteristics of geologic profiles at a weathered soil site in Hong Kong. Spatial variability characteristics were evaluated in terms of variance and scale of fluctuation. Zhang *et al.* (2011a) proposed a two-stage analysis method to study the behaviour of pile groups with rigid elevated caps subjected to tunnelling-induced ground movements, in which the pile-pile interaction, coupling of longitudinal and lateral deformation, and influence of working loads were considered. The results of a series of parametric studies showed that the influence of working load on tunnelling-induced pile responses was significant.

Pile-columns and wood polypropylene composite sheet piling are one of the most interesting types; various authors (Tamrakar, Lopez-Anido 2011; Tomlinson, Woodward 2008; Tonias, Zhao 2007) provided a series of simple examples of the design of piles. Zhao *et al.* (2007) presented a catastrophic model for stability analysis of high pile-column bridge pear and described a pile-column calculation model (Zhao *et al.* 2009).

Selection of the most suitable technology is a multiple criteria problem. From among feasible alternatives, the choice should be made basing on the set of significant criteria. There are numerous methods, which could be applied for multiple criteria evaluation and selection of feasible alternatives (Zavadskas, Turskis 2011), which could be applied (Antucheviciene *et al.* 2011).

The aim of the study was to select the best technology for mounting the driven pile-columns, based on the investigation of soil conditions. The main criteria under consideration are the duration of ring driving and the related energy consumption, which are interrelated with soil conditions.

2. Investigation of soil conditions

The design and construction of foundations and earth structures require good knowledge of mechanical behaviour of soils and their spatial variability. Such information can be best obtained from appropriately planned laboratory and *in-situ* tests. However, *in-situ* tests can often be preferred to laboratory tests due to cost and time efficiency, the ability to assess the soil in its natural environment and the possibility to estimate the spatial variability of the deposit. Among the vast number of *in-situ* devices, the static cone penetrometer (CPT) represents the most versatile tool currently available for soil exploration (Lunne *et al.* 1997). In terms of the study, soil conditions have been investigated at a specific construction site. Cone Penetration Testing (CPT) was used to identify ground conditions in the upper 12 m of the subsurface. The CPT device consisted of a cylindrical probe with a cone-shaped tip with different sensors that allowed a real time continuous measurement of soil strength and characteristics by pushing it into the ground at a speed of 2 cm/s. The typical CPT probe measures the force on the cone, the sleeve friction and the pore water pressure.

The reference test equipment consisted of a 60° cone with 10 cm^2 base area (Fig. 1).The 36 mm diameter cone had a 60° apex at the tip, 150 cm^2 sleeve surface area, and a shoulder position (u_2) pore water pressure

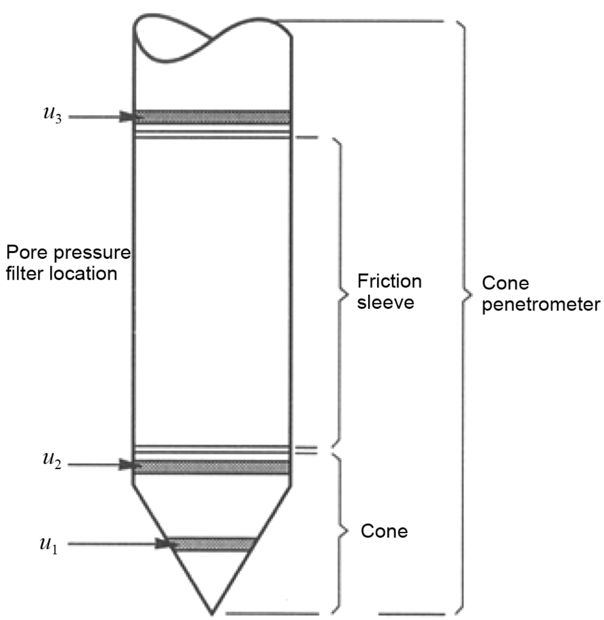

Fig. 1. 36 mm (top) diameter penetrometer and terminology for cone penetrometers (Lunne *et al.* 1997)

element. A velocity of penetration was measured by geophone and inclinometer was used to control the vertical position. The cone had an u_2 pore water pressure element. The cone was vertically advanced at the standard rate of 2 cm/s (Lunne *et al.* 1997) while readings of the cone resistance (q_c), cone sleeve friction (f_s), inclination (i), and pore pressure (u_2) were taken every 5 cm.

Cone resistance, q_c, and sleeve friction, f_s, were usually derived from measurements on electrical strain gauge load cells. The pushing equipment consisted of push rods, a trust mechanism and a reaction system. The hydraulic jack drilling rig was used as the pushing equipment for the cone. The "tip resistance" was determined by the force required to push the tip of the cone and the "sleeve friction" was determined by the force required to push the sleeve through the soil. The "friction ratio" is the ratio between the sleeve friction and the tip resistance, measured as a percentage. Soil type and thereby soil resistance could be inferred from these measurements.

3. The constructional types of pile-columns under investigation

The columns with piles were interconnected by three types of joints (Fig. 2). Investigations were performed in three different towns of Lithuania: Marijampolė, Klaipėda and Šiauliai.

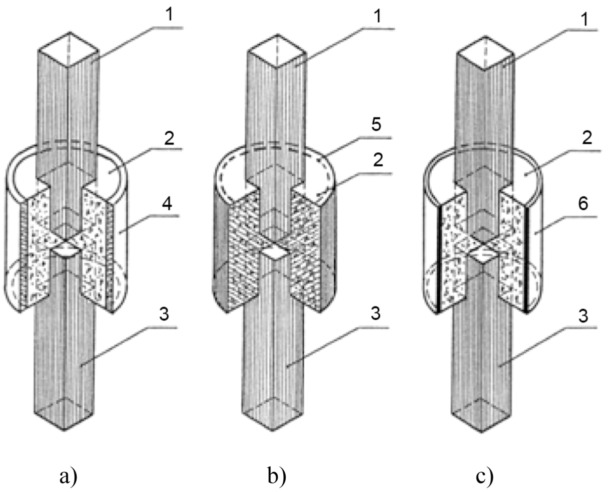

Fig. 2. Constructional types of joints for pile-columns under investigation: a) pile-column with a driven reinforced concrete ring; b) pile-column with a removable steel ring; c) pile-column with a steel ring left in place; 1 – column; 2 – concrete placed *in-situ*; 3 – pile; 4 – reinforced concrete ring; 5 – reinforcing steel frame; 6 – steel ring

Technology for construction of pile-columns is illustrated in Figs 3 and 4.

Two different ways for installing foundation over the pile were considered:

a) drilling a borehole (0.80 m diameter, and 1.0 m deep);

b) hammering the ring (in the middle of the ring adding the punch) (Figs 3 and 4).

Fig. 3. The punch for ring driving

Fig. 4. Driving the ring with the use of the punch

4. Technological alternatives for installing the pile-columns

5 technological alternatives for installing the pile-columns were considered (Table 1).

These alternatives were constructed with the help of three different weight hammers: for alternative A_3 – 1250 kg; for A_1, A_4 and A_5 – 1800 kg; and for A_2, A_4 – 2500 kg.

The arithmetic mean value $\overline{t}$ of 23 operations for the first alternative A_1 varies from 95 seconds (the 7th operation) to 2017 seconds (the 22nd operation). The standard deviation s_t – varies from 36 seconds (the 7th operation) to 426 seconds (the 1st operation). The coefficient of variation V_t – varies from 11% (the 4th operation) to 60% (the 17th operation).

Table 1. Considered technological alternatives for installing the pile-columns (driving of rings)

Alternative	Short description of the alternative
A_1	Driving the reinforced concrete ring with the use of the punch; driving the pile; constructing, positioning and adjusting the mounting jig for the column; placing *in-situ* concrete; and column mounting.
A_2	Driving the reinforced concrete ring with the use of the punch; driving the pile; placing *in-situ* concrete mixture foundation with the nest for column mounting; and column mounting.
A_3	Driving the steel ring with the use of the punch; driving the pile; placing *in-situ* concrete mixture foundation with the nest for column mounting; and column mounting.
A_4	Driving the steel ring with the use of the punch; driving the pile; placing *in-situ* concrete foundation with the nest for column mounting; removing the steel ring; and column mounting.
A_5	Drilling the leader bore diameter of 0.8 m and 1.0 m in height; driving the reinforced concrete ring; driving the pile; positioning and adjusting the mounting jig for the column; placing *in-situ* concrete mixture; and column mounting.
Remark	*The inner diameter of all driven rings equals to 1.0 m.*

Table 2. The workflow statistics of installed pile-columns, when reinforced concrete ring is driven (alternative A_1), for warehouse construction in Marijampolė

Process number, in sequence	Technological process	Mean value $\bar{t}$, (s)	Standard deviation s_t, (s)	Coefficient of variation V_t, (%)
1	Preparation works	912	426	47
2	Adjustment of axis delineation	838	140	17
3	Installation of the piling rig to the operating position	561	117	21
4	Positioning and adjusting of the mounting jig for the reinforced concrete ring	1517	166	11
5	Slinging of the reinforced concrete ring and siting on the place	601	190	32
6	Slinging of the punch and siting onto the reinforced concrete ring	553	131	24
7	Adjusting the diesel hammer onto punch	95	36	38
8	Starting a diesel hammer	323	141	44
9	Punching of the reinforced concrete ring	730	150	21
10	Removing the punch	248	69	28
11	Marking the axis onto the reinforced concrete ring	582	81	14
12	Positioning and adjusting the mounting jig for the column onto the reinforced concrete ring	602	99	16
13	Slinging, lifting and adjusting of the pile to the hammering position	501	91	18
14	Vertical positioning of the pile	382	73	19
15	Positioning of the diesel hammer onto the pile	96	44	46
16	Driving of the pile supervising the vertical position	1055	365	35
17	Recreation of workers	549	329	60
18	Mounting of the extension	275	41	15
19	Pile driving by applying the extension until the required altitude	601	121	20
20	Removing the mounting jig	264	54	20
21	Removing the extension	267	49	18
22	Placing *in-situ* concrete mixture foundation with the nest for column mounting	2017	252	12
23	Removing form from the nest	366	89	24

The statistical data were determined for all alternatives (A_1, …, A_5) and for all operations for each alternative (Table 2).

Investigation of statistical data revealed that durations of almost all operations were subject to the normal distribution law or were approximately normally distributed. The punching duration distribution of A_1 alternative's 9th operation is demonstrated in Fig. 5.

Normal distribution law allows applying the arithmetic mean for determining the position of data while the standard deviation could be used to determine dispersion.

The arithmetic mean $\bar{t}$, the standard deviation s_t and the coefficient of variation of duration V_t for each operation of alternatives A_1–A_5 were determined as follows (Table 2):

$$\bar{t} = \frac{\sum_{i=1}^{n} t_i}{n}, \tag{1}$$

$$s_t = \left[\frac{\sum_{i=1}^{n} \left(t_i - \bar{t} \right)^2}{n-1} \right]^{0.5}, \tag{2}$$

$$V_t = \frac{s_t}{t} 100, \tag{3}$$

where t_i is value of each measurement for each operation's duration, and n is the sample size (the number of measurements).

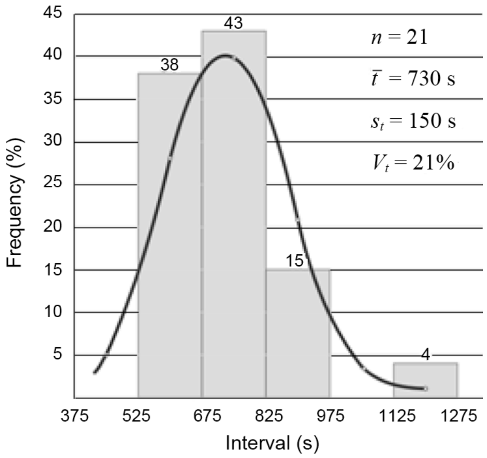

Fig. 5. The punching duration histogram, normal distribution curve and statistical data of the reinforced concrete ring

The types of operations and real site conditions (qualification and the number of workers, organisation of works, soil conditions, weather conditions, conditions of constructions storage and facilities for construction) have a certain influence on the statistical data.

5. Dependence of technological parameters on soil conditions

The main attention of the case study was given to the investigation of the influence soil conditions have on the punching duration of the ring as well as the amount of energy for ring punching. Based on the experimental data, linear and exponential dependence equations for punching duration of ring t and the average cone resistance $\bar{q}_c$ (MPa) were determined (Figs 6 and 7). The coefficient of determination R^2 varies from 0.70 to 0.99. It is obvious that the punching duration of the ring varied by 70–99% dependent on the average cone tip resistance $\bar{q}_c$ variation.

Energy consumed for ring punching E (kJ) was determined for each alternative. Interrelation of the average cone tip resistance and consumption of energy were determined using linear (Fig. 8) and exponential (Fig. 9) regression equations. According to the test results, lines (Fig. 8) and curves (Fig. 9) for each alternative were obtained.

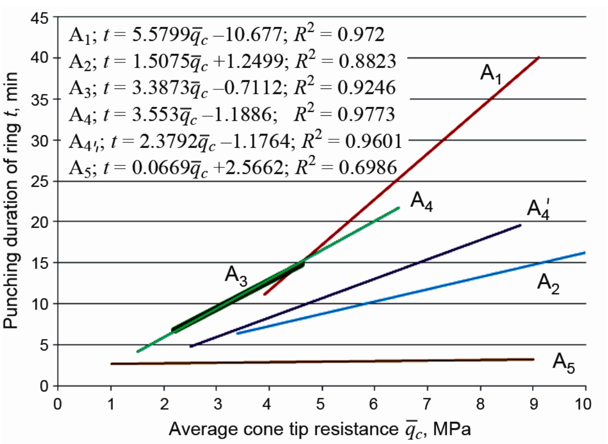

Fig. 6. Influence of soil conditions on the ring punching time, using the linear dependence regression equation

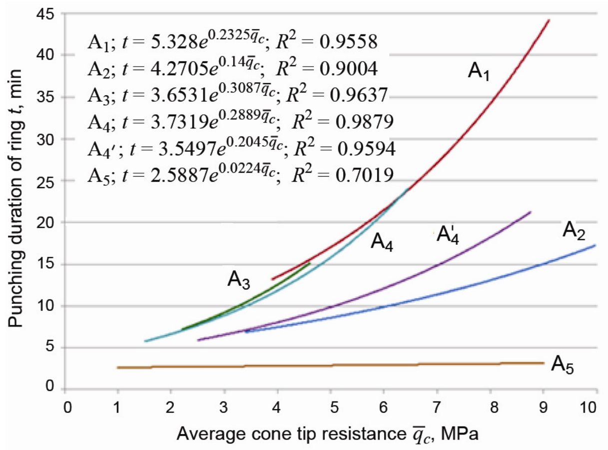

Fig. 7. Influence of soil conditions on the ring punching time, using the exponential dependence regression equation

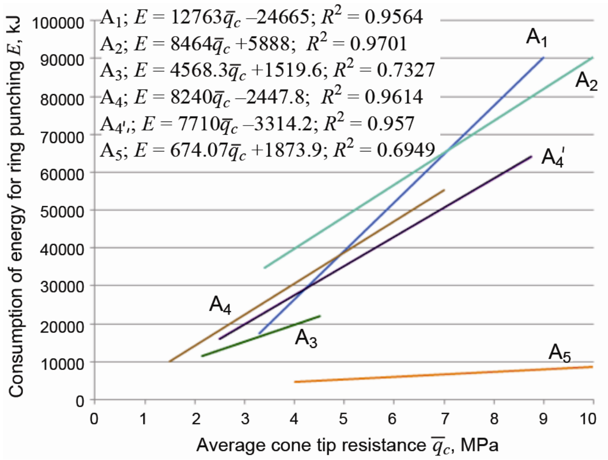

Fig. 8. Influence of soil conditions on the consumption of energy for ring punching, using the linear dependence regression equation

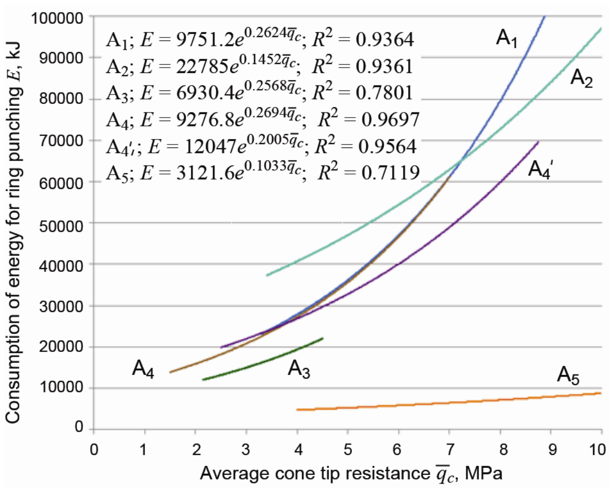

Fig. 9. Influence of soil conditions on the consumption of energy for ring punching, using the exponential dependence regression equation

The coefficient of determination R^2 for linear equations varies from 0.69 to 0.97. The coefficient of determination R^2 for exponential equations varies from 0.71 to 0.97. It is obvious that the regression equations of punching energy consumption are strongly dependent on soil conditions, which are determined by the average cone resistance $\bar{q}_c$.

The model of the investigated and solved problem is based on the single criterion. In real life, selection from among a set of feasible alternatives should be made basing on the set of significant criteria set. This material and results of other investigations will be used for multiple criteria assessment and selection of pile-column alternatives. The problem will be solved by applying several-multiple criteria decision-making methods: ARAS (Zavadskas, Turskis 2010; Zavadskas *et al.* 2010b; Tupenaite *et al.* 2010), TOPSIS (Kalibatas *et al.* 2011), and COPRAS (Zavadskas *et al.* 2010a; Medineckienė, Björk 2011). The criteria weights will be established using expert judgement (Kendall, Gibbons 1970; Zavadskas *et al.* 2011) and AHP (Sivilevičius 2011a, b; Podvezko *et al.* 2010) methods.

6. Conclusions

Rationality of construction works is one of the most challenging tasks in real life. Soil conditions are one of the most important criteria for construction of building foundations.

The main value of this research is that experiments were made at different construction sites and dealt with natural soil conditions (*in-situ*). Three types of column and pile joints were used. Consumption of materials, construction technology and duration for each alternative were different. The average cone tip resistance $\bar{q}_c$ varied from 2 MPa to 10 MPa. The punching duration of rings was predetermined by soil conditions. Based on experimental data, linear and exponential dependence equations for punching duration of ring t were determined; the average cone tip resistance $\bar{q}_c$ (MPa) was very close while the coefficients of determination R^2 were very similar and varied from 0.70 to 0.99. The similar conclusion could be made regarding the energy consumption results. In this case, the coefficient of determination R^2 was very similar and varied from 0.69 to 0.97.

Construction of pile-columns encompasses more than 23 technological operations. The duration of construction works as well as the arithmetic mean, the standard deviation and the coefficient of variation varies in wide intervals and are dependent not only on to soil conditions.

Investigation of statistical data revealed that durations of almost all operations were subject to the normal distribution law or were approximately normally distributed. The determined regression equations will be very useful when planning similar construction works. According to the equations, the duration of construction works and energy consumption could to be planned.

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