Ultrasonic testing of concrete hardening in pile foundations

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Abstract. This article discusses the ultrasonic method for monitoring the strength of concrete in piles. Geotechnical conditions of the city territory are indicated. The conditions of hardening of the concrete mixture in the pile shaft and the normal conditions of hardening of concrete samples are described. A detailed description of the control technique is given. The dependence of the ultrasonic wave propagation velocity on the age of concrete in piles and concrete samples is established. Based on the results of the work, it was concluded that it is possible to control the strength of concrete in-situ.

1. Introduction

Pile foundations are most widely used in construction of buildings and structures of various applications in Saint Petersburg. This is due to the specific features of the engineering and geological structure of the city area attributable to the location in the Neva River Delta with a large thickness of weak soils, which lies to a great depth over almost the entire area of the city. One of the most used and common types of such foundations are piles made in soil.

2. Applicability

The pile foundations made in soil are constructed in boreholes that are drilled using special-purpose drilling rigs with various types of equipment and based on various technologies. Therefore, most notably common are piles made according to the continuous flight hollow stem auger technology and piles made by means of compacting/reaming the soil. Regardless of the type of equipment used, the piles of the above-mentioned types require that the preliminarily drilled boreholes should be filled with concrete mix and a reinforcing cage lowered into the borehole. As these works are carried out mainly at great depths in a thickness of soft soils, the question arises regarding the concreting quality of borehole shaft. It is also important to understand the time of concrete strength gain in the pile body due to the fact that the concrete hardening conditions in the soil differ significantly from normal conditions.

Concrete hardening at depth and under normal conditions. As a control of the concrete strength along the length of the pile body, core drilling and testing of concrete specimens are used. Core drilling is a rather laborious process. Testing the strength of concrete by this method, according to the standards, is no more than 2% of the total number of piles. The use of this method does not fully reflect reality due to the small amount of sampling. The method of sampling concrete specimens is also not accurate, since specimens are taken from the concrete mixture delivered to the building site, but not from the structure itself, respectively, according to the results of their tests, it is impossible to correctly interpret the set of
Concrete strength in the pile body. Nevertheless, this control method is used at all sites during the zero-cycle period.

Storage conditions for witness specimens in the form of cubes with dimensions of 100×100×100 mm are established by the regulatory document, which states that the specimens intended for hardening under normal conditions, are stored, after they have been produced and before the formwork has been removed, in the forms covered with a damp cloth or other material that prevents moisture from evaporating from them in a room at the air temperature of (20±5) °C.

After the formwork has been removed, the specimens are placed in a chamber with the normal hardening conditions: at a temperature of (20±2) °C and the relative air humidity of (95±5) %. In the chamber, the specimens are stored under a layer of wet sand, sawdust or other materials wetted on a regular basis (GOST 10180-2012 “Concretes. Methods for determining of strength by reference specimens”, Item 4.3.2) [1].

The hardening conditions in the pile shaft vary along its length and differ from the normal conditions. For instance, the construction site where trial piles were constructed was represented by soils, whose natural moisture content was within a range of 10% to 40%. The soil temperature should also be taken into account. A depth of seasonal freezing is 1.5 to 2 m in Saint Petersburg. Accordingly, the concrete temperature from the level of the pile top to a depth of about 5 m depends on the season, then the temperature varies from 5 °C to 9 °C depending on the pile depth.

The methods used. To control the process of concrete strength gain in the shaft of a concreted borehole, the method of seismic acoustic flaw detection was considered. On piles of various types made in the soil, a series of tests were conducted at concrete ages of 3, 7, 14, 21, and 28 days using instrument Spektr-4.0, whose principle of operation is based on recording the parameters of elastic waves by means of impact pulse that occurs at the time of impact with a dedicated hammer on the pile head. The wave propagates along the pile shaft at certain velocity V reflecting from the interfaces of the media. The reflected wave returns to the pile head and is recorded by an accelerometer, which, in turn, records the required time interval Δt for the wave to pass twice through the pile body of length L. Then, the received signal is digitized, and the processed results are presented in the form of oscillograms. At the concrete-soil interface, a characteristic jump appears on the oscillogram, which indicates that the wave was reflected from the pile foot [2]. At this point, the time is recorded and the wave propagation velocity is measured according to the formula:

\[ c = \frac{2 \cdot L}{\Delta t}, \]

where \( c \) - wave propagation velocity; \( h \) - length of pile; \( \Delta t \) - time interval. The wave velocity was determined for the piles at the different ages of concrete.

Figure 1. Pile reflectogram
Table 1. Relationship of propagation velocity of longitudinal ultrasonic wave in pile body versus age of concrete

| Pile No. | Pile length L, m | Concrete age in pile body, days | Velocity C, m/s |
|----------|------------------|---------------------------------|----------------|
| 1        | 3                | 3715.51                         | 3762.65        |
|          | 7                | 3818.53                         | 3876.96        |
|          | 14               | 3903.8                          |                |
| 2        | 22.3             | 3758.25                         | 3787.97        |
|          | 7                | 3796.97                         | 3915.62        |
|          | 14               | 3930.75                         |                |
| 3        | 3691.31          | 3769.25                         | 3841.55        |
|          | 14               | 3905.55                         | 3924.98        |
| 4        | 3737.63          | 3686.62                         | 3862.5         |
|          | 14               | 3936.95                         | 3934.1         |
| 5        | 3778.44          | 3793.49                         | 3910.31        |
|          | 14               | 3905.55                         |                |

*Average velocity: 3736.23 3760 3814.47 3898.45 3921.85*

As a result of the analysis, a direct relationship was established between the age of concrete and the propagation velocity of ultrasonic wave. The “older” the concrete, the higher the wave propagation velocity, which indicates that concrete is gaining its strength.

Tests were also made on reference specimens in the form of concrete cubes measuring 100×100×100 mm. The measurements were taken according to the end-to-end sounding method using instrument Pulsar. During the tests, it was found that the wave propagation velocity was higher when measured in the concrete cubes of the same age of concrete as in the piles.

Table 2. Relationship of propagation velocity of longitudinal ultrasonic wave in specimens versus age of concrete

| Measurement base, mm | Concrete age in specimen, days | Velocity C, m/s |
|----------------------|--------------------------------|----------------|
| 100×100×100          | 3                              | 3976.14        |
|                      | 7                              | 4016.06        |
|                      | 14                             | 4065.04        |
|                      | 21                             | 4123.71        |
|                      | 28                             | 4166.67        |

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Using the universal calibration graph from GOST 17624-2012 “Concretes. Ultrasonic method for strength test” (Figure G.1), the strength of concrete in piles was determined. This value should be considered as averaged along the pile shaft. In different areas, the speed may vary.

**Table 3. Concrete strength in pile shafts**

| Pile No. | Pile length L, m | Concrete age in pile body, days | Concrete strength, MPa |
|----------|------------------|---------------------------------|------------------------|
| 1        | 22.3             | 3                              | 31.76                  |
| 2        | 22.3             | 7                              | 33.01                  |
| 3        | 22.3             | 14                             | 33.13                  |
| 4        | 22.3             | 21                             | 34.12                  |
| 5        | 22.3             | 28                             | 35.26                  |
|          |                  | *Average strength:*            | **32.48**              |

Strength in concrete samples was also measured.

**Table 4. Concrete strength in concrete specimens**

| Measurement base, mm | Concrete age in specimen, days | Concrete strength, MPa |
|----------------------|-------------------------------|------------------------|
| 100×100×100          | 3                             | 36.32                  |
|                      | 7                             | 36.96                  |
|                      | 14                            | 37.74                  |
|                      | 21                            | 38.68                  |
|                      | 28                            | 39.37                  |

**Figure 2. Relationship of propagation velocity of longitudinal waves versus age of concrete in piles and concrete specimens**

**Figure 3. Relationship of concrete strength versus age of concrete in piles and concrete specimens**
3. Conclusion
Having further established a relationship between the propagation velocity of longitudinal ultrasonic wave and the concrete strength in witness specimens, it is possible to determine the concrete strength in the pile body at a given time. Thus, it is possible to control the concrete strength gain in the pile foundations by the non-destructive method directly in the field conditions.

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