Uniformity Test of Bored Piles by Method of Ultrasonic Sensing

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Abstract. The article presents the existing methods of uniformity test of concrete bored piles. These methods include: testing of drilled cores, seismic tests, radioisotope or ultrasonic testing. The best method of these is the end-to-end testing with ultrasound. In this technique, there are no requirements for the rejection of the design. The article presents the accumulated results of tests of bored piles for continuity. Requirements of rejection for testing of bored piles are established. For the rejection of structures, we recommend using are coefficient of variation and the value of the relative deviation of the ultrasound velocity from the mean value.

1. Introduction

An integral part of the industry is the quality test of construction and installation works [1-3]. The test is carried out at all the stages: from the of materials production to the structures installation. In this case, both destructive and non-destructive research methods are used [4-6]. The reinforced concrete structures of bored piles of deep foundation are the most difficult inspection. Sufficient length and construction inaccessibility do not allow to perform its quality test by traditional methods.

The main requirements for the quality of piles erection are: compliance with geometric parameters, concrete continuity, and concrete strength compliance with the declared parameters. The worldwide practice proposes various methods for quality test for such structures [7-15]. Almost all of them are based on two methods: ultrasonic sounding and acoustic sounding.

In accordance with [16], during the pile foundation erection a continuous or selective quality test of the produced piles is carried out. The following types of tests are provided: full-length core punching with subsequent compression testing; the piles length test and the integrity assessment of their shafts using seismic acoustic tests; piles concrete quality assessment (homogeneity) at their full length using radioisotope or ultrasonic measurements. In coordination with the project organization it is allowed to use one of the specified test methods.

Each of these methods has several disadvantages. Thus, while testing the concrete strength of deep-laid piles, drilling cores over the entire length of the structure is time consuming and almost impossible. When conducting seismic tests, it is rather difficult to coordinate the discontinuities in the body of the pile. The latter method supposes number of mandatory preparatory activities at the stage of manufacturing structures without which it is impossible to carry out the inspection. Moreover, the last
two methods do not allow to reliably estimate the strength characteristics of concrete piles along its length.

The experience of engineering and laboratory support of construction shows that the most demanded test of the integrity of bored piles is in the construction of road and railway overpasses [17]. At the same time in Russia the ultrasonic testing is recommended by the existing regulatory documentation on the design and construction of such structures [18] for the concrete integrity test. And only if it is impossible to carry out it is allowed to use the seismic-acoustic method. Ultrasonic test method of concrete and reinforced concrete structures is widely used in Russian and global practice [19-24].

The essence of the method of end-to-end ultrasonic sounding consists in determining and analysing the change in the velocity of ultrasound propagation in the body of the pile along its entire length [14, 25]. To ensure the possibility of conducting a test before concreting the pile, two, three or four vertical channels made of steel pipes with a diameter of 50÷70 mm are usually installed in it. When testing, the radiator is installed in one of the channels, and the receiver of ultrasonic waves is installed in the other one. By parallel lowering of the converters, a continuous test of the concrete structure along its entire length is carried out. The pitch of the sounding horizons, as a rule, equals to 0.5 m. When detecting the areas with discontinuity, additional research is carried out to determine the size by reducing the scanning step, as well as performing sounding on inclined planes.

Notwithstanding the simplicity of this method, there is one but significant drawback. There are no rejection methods and standards in the current regulatory and technical documentation. Currently, Draft Amendment N 3 to SP (a set of rules) 79.13330.2012 “SNiP (building code and regulations) 3.06.07-86 Bridges and pipes. Inspection and Test Rules” is under consideration, which reflects the requirements for the preparation of structures for test and the procedure for conducting research. It is proposed to determine the continuity of piles concrete by experimentally found gradation dependencies “ultrasound propagation velocity - concrete continuity (strength)” for classes B15-B40, including the hardening in natural conditions. These rules of piles “culling”, as already mentioned, were obtained experimentally, apparently, by the authors of the draft change. Along with that by the document it is impossible to establish the amount of the experimental base, on the basis of which the indicated rejection values are given.

In [12], an analytical approach to establish rejection quantities by solving the wave equation was proposed. The authors give a calculation for heavy concrete classes from B20 to B45. So, for concrete class B35, the value of safe speed is obtained equal to 2485 m/s. Thus, if during the inspection the obtained speed values of the above mentioned, then with a probability of 0.9987 such a concrete can be attributed to the design class. Moreover, if the speed is below 2100 m/s, the concrete definitely has discontinuities.

Thus, it can be stated that at the moment in the practice of such a test there are no uniform requirements for the evaluation of concrete structures integrity. Each expert laboratory sets its own standards for grading, based on its own research experience. At the same time, after analysing the test reports carried out by various laboratories, the absence of any rejection values was noted. The protocols contain just conclusions and no results analysing.

2. Methods
This article provides an analysis of the accumulated results of the monitoring of the concrete piles integrity carried out by the authors on the infrastructure facilities under construction in recent years. The test was carried out by the staff of the ASA SamGTU in conjunction with the specialists of the Laboratory of Non-Destructive Testing NPO “ExpertSP” Ltd (Figure 1).
Figure 1. Pile testing

The ultrasonic flaw detector of bored piles PULSAR-1.2 version of DBS, developed by NPP Interpribor, in Chelyabinsk, served as a test device. This version of the device is equipped with a set of special technical tools allowing to test bored piles and foundations. Ultrasonic device transducers have a radial radiation pattern of signals and a hermetic design for operation in the aquatic environment. The movement of the transducers along the pile is tested by two position sensors (encoders). At the end of the test, the data is recorded in the instrument’s memory and imported into the software package, which allows sampling of the required results from the data set. The results are presented both in tabular form with an indication of the magnitude of the velocity in depth, and in graphic form in the form of a diagram (Table 1). An example of the representation of the test scheme is shown in Figure 2.

For the analysis of the accumulated test results of piles, a sample of 20 pieces was made (Table 2). The tests were carried out in conditions of real construction in different weather conditions, with different periods of hardening of concrete (no more than 7 days) and various mixture suppliers. The main criterion for the sampling is the design class of concrete structures for strength - B30.

The aim of the work was to process the results of studies obtained under repeatability conditions (on the same set of equipment, the same performers, identical test objects, concrete class for pile strength, etc.) to develop a unified approach to estimating the allowable speed deviations limits of ultrasound.
Table 1. Example of result of test of pile

| Measure number | Nominal immersion depth, m | Actual depth of immersion | The speed of ultrasound, m/s | Average speed, m/s | Deviation, % | Continuity chart |
|----------------|---------------------------|---------------------------|-----------------------------|-------------------|-------------|-----------------|
| 1              | 1.0                       | 1.008                     | 1.003                       | 3376              | -5.3        |                 |
| 2              | 1.4                       | 1.413                     | 1.402                       | 3541              | -3.8        |                 |
| 3              | 1.8                       | 1.824                     | 1.830                       | 3602              | -3.2        |                 |
| 4              | 2.2                       | 2.225                     | 2.222                       | 3517              | -3.5        |                 |
| 5              | 2.6                       | 2.633                     | 2.645                       | 3517              | -3.5        |                 |
| 6              | 3.0                       | 3.039                     | 3.045                       | 3610              | -3.2        |                 |
| 7              | 3.4                       | 3.461                     | 3.467                       | 3705              | 0.6         |                 |
| 8              | 3.8                       | 3.867                     | 3.859                       | 3603              | -2.4        |                 |
| 9              | 4.2                       | 4.277                     | 4.281                       | 3607              | -2.0        |                 |
| 10             | 4.6                       | 4.687                     | 4.680                       | 3477              | -5.6        |                 |
| 11             | 5.0                       | 5.096                     | 5.082                       | 3707              | +0.7        |                 |
| 12             | 5.4                       | 5.502                     | 5.511                       | 3706              | +0.7        |                 |
| 13             | 5.8                       | 5.908                     | 5.896                       | 3717              | +1.0        |                 |
| 14             | 6.2                       | 6.313                     | 6.309                       | 3762              | +2.1        |                 |
| 15             | 6.6                       | 6.718                     | 6.725                       | 3763              | +2.2        |                 |
| 16             | 7.0                       | 7.124                     | 7.133                       | 3665              | -0.4        |                 |
| 17             | 7.4                       | 7.528                     | 7.539                       | 3729              | +1.3        |                 |
| 18             | 7.8                       | 7.940                     | 7.932                       | 3670              | -0.3        |                 |
| 19             | 8.2                       | 8.340                     | 8.329                       | 3745              | +1.7        |                 |
| 20             | 8.6                       | 8.747                     | 8.748                       | 3789              | +2.8        |                 |
| 21             | 9.0                       | 9.157                     | 9.164                       | 3898              | +5.6        |                 |
| 22             | 9.4                       | 9.567                     | 9.574                       | 3784              | +2.7        |                 |
| 23             | 9.8                       | 9.974                     | 9.982                       | 3892              | +5.4        |                 |
| 24             | 10.2                      | 10.379                    | 10.392                      | 3759              | +2.1        |                 |
| 25             | 10.6                      | 10.789                    | 10.798                      | 3772              | +2.4        |                 |
| 26             | 11.0                      | 11.195                    | 11.203                      | 3873              | +4.9        |                 |
| 27             | 11.4                      | 11.606                    | 11.613                      | 3841              | +4.2        |                 |
| 28             | 11.8                      | 12.013                    | 11.995                      | 3811              | +3.4        |                 |
| 29             | 12.2                      | 12.418                    | 12.406                      | 3807              | +3.3        |                 |
| 30             | 12.6                      | 12.823                    | 12.808                      | 3780              | +2.6        |                 |
| 31             | 13.0                      | 13.236                    | 13.213                      | 3786              | +2.8        |                 |
| 32             | 13.4                      | 13.642                    | 13.626                      | 3713              | +0.8        |                 |
| 33             | 13.8                      | 14.049                    | 14.032                      | 3678              | -0.1        |                 |
| 34             | 14.2                      | 14.456                    | 14.466                      | 3623              | -1.6        |                 |
| 35             | 14.6                      | 14.866                    | 14.873                      | 3695              | +0.4        |                 |
| 36             | 15.0                      | 15.270                    | 15.280                      | 4035              | +8.8        |                 |
| 37             | 15.4                      | 15.681                    | 15.657                      | 3719              | +1.0        |                 |
| 38             | 15.8                      | 16.087                    | 16.072                      | 3739              | +1.5        |                 |
| 39             | 16.2                      | 16.498                    | 16.479                      | 3683              | 0.0         |                 |
| 40             | 16.6                      | 16.898                    | 16.885                      | 3744              | +1.7        |                 |
| 41             | 17.0                      | 17.309                    | 17.326                      | 3754              | +1.9        |                 |
| 42             | 17.4                      | 17.723                    | 17.737                      | 3554              | -3.5        |                 |
| 43             | 17.8                      | 18.130                    | 18.111                      | 3253              | -11.6       |                 |
| 44             | 18.2                      | 18.540                    | 18.547                      | 3330              | -9.5        |                 |
| 45             | 18.6                      | 18.954                    | 18.966                      | 3336              | -9.4        |                 |
Figure 2. Here is example representation of test circuitry of pile

3. Results and discussions
As can be seen from the test results, the average values of the speeds vary in the range from 3571 to 4053 m/s. In this case, the coefficients of variation in each test are different and lie in the range from 4 to 13%. The difference in average speeds is due to many factors. The main parameters affecting the speed of ultrasound propagation in concrete are its density, age, composition and aggregates characteristics [26, 27]. The concrete age at which the test of the structures was performed was different, and, as a result, the concrete density and strength at the time of testing differed. In addition, there were various concrete manufacturers, and hence there were different characteristics of coarse and fine aggregates. However, the difference in average speed values was not significant. So the standard deviation indicator is only 117 m/s with an average value of 3830 m/s, and the deviation of the extreme value does not exceed 7%. In draft Amendments N 3 to SP 79.13330.2012 “SNiP 3.06.07-86 Bridges and pipes. The rules for examinations and tests "the allowable minimum speed range for concrete class B30 with a curing time of 2 to 7 days is 2760 ÷ 3780 m/s. In this case, the range of values is wider than the range of values of the resulting average test rates.

The main indicator, determined during the testing, is the concrete homogeneity (continuity), not the average speed value and its comparison with the concrete class. The concrete continuity will characterize the magnitude of the relative deviation of the unit velocity values from the average value for a particular structure, as well as the magnitude of the coefficient of variation. The standards for ultrasonic testing of concrete [28] set the conditions for the use of the calibration dependence “ultrasound speed - concrete strength”, which specify the value of the allowable coefficient of variation equal to 15%. If the coefficient of variation exceeds this value, it is considered that the concrete of the tested structure is not homogeneous. In the previous edition of this document in 1987, this value was taken to be 12%.

To compare the requirements and recommendations of regulatory documents with actual test results obtained, an analysis of the obtained values was performed. We used the unit velocities values obtained
from tests № 2, 6, 9, 10, 11, 14, 15 (table 2) for processing. The criterion for the test data selection was concrete structure age at the time of testing, and it was equal to four days. The initial data for the analysis were the following parameters:

- number of values in the sample: 283;
- maximum unit speed: \( V_{\text{max}} = 4895 \text{ m/s} \);
- minimum unit speed: \( V_{\text{min}} = 2312 \text{ m/s} \);
- its average speed value in the sample: \( V_{\text{av}} = 3905 \text{ m/s} \);
- standard quadratic deviation: \( S = 319 \text{ m/s} \).

Variations coefficient of measured values was:

\[
K_v = \frac{V_{\text{av}}}{S} \cdot 100\% = 8\% \tag{1}
\]

| Test number | The age of the concrete, day | The value of ultrasonic velocity in concrete, m/s | Variations coefficient, % | Value of deviation of extreme values of speed, % |
|-------------|----------------------------|---------------------------------|-----------------|------------------|
|             |                            | Average | Maximum | Minimum       | Maximum | Minimum       |
| 1           | 2                          |         | 3839    | 4234          | 2943    | 10          |
| 2           | 4                          |         | 3855    | 4343          | 3346    | 7           |
| 3           | 2                          |         | 3571    | 3981          | 2115    | 8           |
| 4           | 3                          |         | 3771    | 4342          | 2105    | 11          |
| 5           | 3                          |         | 3743    | 4376          | 2950    | 8           |
| 6           | 4                          |         | 3735    | 4066          | 3122    | 6           |
| 7           | 5                          |         | 3878    | 4277          | 3411    | 6           |
| 8           | 3                          |         | 3935    | 4386          | 3001    | 8           |
| 9           | 4                          |         | 4053    | 4503          | 2312    | 11          |
| 10          | 4                          |         | 3968    | 4294          | 3295    | 4           |
| 11          | 4                          |         | 3896    | 4895          | 3154    | 8           |
| 12          | 2                          |         | 3159    | 3909          | 2105    | 13          |
| 13          | 3                          |         | 3697    | 4243          | 3131    | 5           |
| 14          | 4                          |         | 3957    | 4386          | 3201    | 7           |
| 15          | 4                          |         | 3756    | 4066          | 3124    | 5           |
| 16          | 7                          |         | 3897    | 4277          | 3628    | 6           |
| 17          | 5                          |         | 3659    | 4188          | 3213    | 10          |
| 18          | 7                          |         | 3923    | 4303          | 3584    | 6           |
| 19          | 5                          |         | 3800    | 4089          | 3588    | 4           |
| 20          | 5                          |         | 3843    | 4082          | 3543    | 5           |

Table 2. Test result

For clarity, the graphs of the normal (Gaussian) velocity value distribution are plotted, taking the average value, obtained experimentally (3905 m/s) as the expectation, mode and median. In this case, the standard deviations are taken based on the coefficients of variation: 15% according to [28]; 8%, calculated by experimental values and 10%, as the upper limit of a slight degree of dispersion (adopted in mathematical statistics). The points on the graph (Figure 3) indicate the quantitative values of the velocities in each interval. The interval spacing is assumed to be 100 m/s.

As a result of the data analysis, it was established that the graph of the normal distribution with the coefficient of variation equal to 16% does not have adequate convergence with the experimental values. The most optimal is the graph of the normal distribution with a coefficient of variation equal to 10%. The deviation of the minimum value of the speed of ultrasound from the average should not exceed 23%. With a coefficient of variation equal to 8%, the deviation should not exceed 19%. The graph shows that two unit speeds are below the maximum allowable, which can be characterized as a discontinuity.
of concrete in this area. To verify the findings, an additional static processing of the unit values of ultrasound velocities obtained during testing of piles on the third day after concreting was performed (tests No. 1, 4, 5, 8, 13 according to table 2). As a result of the analysis (Figure 4), it was established that the graph of the normal distribution with a coefficient of variation equal to 10% adequately describes the data obtained.

![Figure 3. Graphs of normal distribution of ultrasound velocities and test results](image)

![Figure 4. Graph of normal distribution of ultrasound velocities (K_v = 10%) and test results of piles on third day after concreting](image)
Thus, it is recommended to take the coefficient of variation, which should not exceed 10%, and the deviation of the minimum values of the ultrasound velocity in the structure which should not exceed 23%, as rejection criteria when monitoring the concrete integrity of the bored piles. Based on this, it can be claimed that in tests Nos. 3, 4, 9, 12 (Table 2) there were discontinuities in concrete. There is no doubt at analysing the test results, it is necessary to take into account not only the presence of discontinuity, which is characterized by a decrease in the speed of ultrasound, but also its location along the height of the pile, its dimensions. Thus, the discontinuities noted in the tests were located in the tips of the piles. The decrease in the ultrasound velocity values in these areas was due to the low strength of the concrete, caused by poor performance of concrete work. Defects were eliminated by sampling concrete on damaged areas with subsequent restoration.

When testing, it may be necessary not only to test the concrete homogeneity in the structure, but also to assess the compliance of the concrete strength set for the declared class. So, for example, the concrete continuity structure can be provided, however, the average value of the ultrasound velocity can be significantly lower for a given class of concrete at a certain age. In this case, when concreting the structure, it is necessary to prepare test samples of concrete from the same batch. Before conducting a continuity test, the speed of ultrasound propagation in a particular concrete of a certain age is determined by the reference samples. According to the established speed, one can draw a graph of the normal distribution with a variation coefficient of 10% and determine the minimum allowable value of the ultrasound velocity in a given pile. Cubes with dimensions of $150 \times 150 \times 150$ mm are recommended as the reference samples. Using the cubes with a face of 100 mm can lead to measurement errors. Test samples should be stored under the same conditions as the test pile before testing.

4. Conclusion
When testing the concrete homogeneity in bored piles the most optimal method is through ultrasonic sounding. However, the methods of such test available now in the normative literature do not include the norms of structures defects.

The test results analysis of piles in actual construction conditions showed satisfactory convergence of ultrasonic velocity values in concrete with various parameters (age, composition, manufacturer, etc.).

As a result of the analysis, defect criteria were established when testing bored piles. As such parameters, it is recommended to use a coefficient of variation equal to 10%, and the value of the limiting relative deviation of the ultrasound velocity on the defective area from the average value of the structure equal to 23%.

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