Manuscript

Elizaveta Loseva

INCREASING THE RELIABILITY OF LOW-STRAIN PILE INTEGRITY TESTS FOR PILE FOUNDATIONS IN SOFT WATER-SATURATED SOILS

Specialty 2.2.8. Methods and devices for monitoring and diagnostics of materials, products, substances and the natural environment

Extended abstract of the dissertation for the Degree of Ph.D. in Engineering

Saint Petersburg, 2023

The dissertation was carried out at the Saint Petersburg Mining University.

Academic supervisor:

Associate professor ***Vladimir Syasko,*** Dr.Sc. in Engineering.

Potential official reviewers:

Professor ***Konstantin Abbakumov,*** Dr.Sc. in Engineering, Professor of the Department of Electroacoustics and Ultrasonic Engineering, Saint Petersburg Electrotechnical University;

Igor Kinzhagulov, Ph.D. in Engineering, Lecturer of the Faculty of Control Systems and Robotics, ITMO University.

Potential external reviewer organization: Acoustic Control Systems (ACS Group), Moscow.

The dissertation defense will take place at the meeting of the Dissertation council, Saint Petersburg Mining University, 2, 21st line, Saint Petersburg, 199106 Russia.

The dissertation is available in the library of the Saint Petersburg Mining University and on the website https://spmi.ru/obyavleniya-o-zaschitakh-2023-goda

Scientific secretary
of the Dissertation council **Denis Ustinov**

AN OVERVIEW OF THE WORK

Topic relevance

The conditions for constructing buildings in St. Petersburg are complex due to the unique characteristics of the geological cross-section, which sets them apart from those of other regions in the country. A specific feature of the city's territory is the presence of soft, water-saturated, thixotropic soils that can change their physical, mechanical, strength, and deformation characteristics under different dynamic conditions. If the local cross-section contains such soil types and strong bearing layers are situated at depths of 20 meters or more, piles are used as foundations for constructing buildings. Based on their construction methods, these piles can be classified into two groups: precast and cast-in-place piles. When driving precast piles, defects may occur in the pile shaft due to imperfections in the production process. When cast-in-place piles are used, boreholes are drilled into the ground and then filled with concrete, which contacts the soil before hardening and is exposed to a variety of factors that can affect the quality of the structure, potentially leading to defects in the pile shaft.

Today's regulatory documents define the basic requirements for assessing the length and integrity of piles, including core drilling and the use of non-destructive testing methods. One of these methods is low-strain pile integrity testing. However, despite its widespread use, this method has a number of limitations. Also, there are currently no regulatory documents formulating the fundamental principles of pile foundation quality control performed with the use of this method.

Prior research on the topic

The features of the geology of St. Petersburg have been studied by G.F. Strangways, H.G. Pandera, E.I. Eichwald, R. Murchinson, G.P. Gelmersen, P.A. Kropotkin, N.F. Pogrebova, K.K. Markova, M.A. Lavrova, L.G. Zavarzina, R.E. Dashko and other scientists. Various aspects related to the origin and formation of defects in piles have been studied by such scientists as K. Fleming, A. Weltman, M. Randolph, K. Elson, and others. The features of pile defect formation in soft water-saturated soils have been analyzed by researchers such as A.I. Osokin, R.A. Mangushev, A.N. Gaido, and I.P. Dyakonov. The development and application of methods for testing pile foundations are associated with the names of specialists such as J.M. Amir, N. Massoudi, F. Rausche, G. Likins, and G. Goble. In Russia, I.N. Lozovsky, A.A. Churkin, V.V. Kapustin, A.Yu. Khmelnitsky and various specialized companies have contributed to this field.

Despite its advantages, low-strain pile integrity testing also has several limitations. For example, in most cases, the method fails to correctly determine pile length or locate defects when the first significant signal anomaly has been detected. As a result, there is a need to develop a methodology, as well as a set of hardware and software tools, to enhance the reliability of interpreting data obtained through low-strain pile integrity testing.

The subject and object of the research

The subject of the research is the processes of excitation, propagation, and recording of elastic waves and the algorithms used for processing and analyzing signals recorded during low-strain pile integrity tests.

The object of the research is the method of low-strain pile integrity testing for precast or cast-in-place piles installed in soft water-saturated soils.

The goal of the research is to expand the list of defects that form in precast and cast-in-place piles installed in soft water-saturated soils and to enhance the reliability of their detection by improving the principles and methods for recording and processing signals in low-strain pile integrity tests.

The idea of the research is that the reliability of defect detection during the construction and operation of piles in soft water-saturated soils can be increased by means of multi-frequency impulse excitation in the pile shaft and the subsequent complex continuous wavelet transform of the recorded signals provided that artificial neural network classifiers are used.

The thesis aims to achieve its goal by addressing the following objectives:

1. Conducting an analysis of the processes involved in the formation of defects in piles constructed and operated in soft water-saturated soils, as well as evaluating the methods used for assessing their integrity and length.
2. Designing artificial defects and carrying out numerical simulations to study the processes of signal reception and processing during low-strain pile integrity testing in soft water-saturated soil conditions.
3. Developing a technology for manufacturing and certifying pile test samples with artificial defects to be used at a test site for the verification of testing methods.
4. Developing and validating a methodology for pile foundations testing in soft water-saturated soils that increases the reliability of data obtained using low-strain pile integrity testing by using the complex continuous wavelet transform and artificial neural network classifiers.
5. Conducting an experimental study of the proposed methodology using pile test samples with artificial defects and precast spliced piles.
6. Applying and validating the proposed methodology in real settings.

The scientific novelty of the research

1. Numerical simulation models of the multi-frequency impulse excitation and propagation of elastic waves and the reception of signals from piezoacoustic transducers have been developed and experimentally confirmed for piles installed in the conditions of the soft water-saturated soils of St. Petersburg.

2. The principles of phase analysis of the recorded signals in the frequency-time domain have been developed and implemented during the testing of cast-in-place piles and precast piles installed in soft water-saturated soils, which provide an increase in the resolution of low-strain pile integrity tests.

3. It is shown that the multi-frequency impulse excitation of elastic waves in the head of the pile installed in soft water-saturated soils and the subsequent time-frequency analysis of the recorded signals increase the reliability of defect detection provided that artificial neural network classifiers are used.

4. A methodology has been developed and experimentally substantiated for multi-frequency impulse excitation during the low-strain pile integrity testing of pile foundations constructed and operated in soft water-saturated soils.

The theoretical and practical significance of the research

1. A methodology has been developed and substantiated for analyzing the signals recorded during low-strain pile integrity tests in the frequency-time domain using the complex continuous wavelet transform and phase-shift analysis and their subsequent classification using artificial neural networks, which makes it possible to increase the reliability of defect detection in the shafts of piles constructed and operated in soft water-saturated soils.

2. A technology has been substantiated and developed for manufacturing and certifying pile test samples with artificial defects to be used at a test site for the verification of testing techniques and tools.

3. A program has been developed for verifying the methodology of low-strain pile integrity testing for piles constructed and operated in soft water-saturated soils.

4. The results of the thesis were used in non-destructive testing of pile foundations of the Geostroy LLC activity in the form of a methodology for monitoring the integrity and estimating the

length of pile foundations, which is confirmed by the implementation certificate.

5. Based on the results of field tests, a computer program was developed to detect defects in pile foundations.

Methodology and research methods. The analysis of the propagation of elastic waves during low-strain pile integrity tests was carried out using the finite element method in the COMSOL Multiphysics software. The method of low-strain pile integrity testing using pile test samples with artificial defects was designed and tested using Spektr-4.0, a certified instrument for assessing pile length and integrity.

The following are the key arguments to be defended:

1. The multi-frequency impulse excitation of elastic waves in the pile shaft, followed by an analysis of the signals recorded in the frequency-time domain using the complex continuous wavelet transform, phase-shift analysis, and classifiers based on artificial neural network, makes it possible to expand the list of defects detected in piles constructed and operated in soft water-saturated soils and increase the reliability of their detection.

2. The use of numerical simulations of the multi-frequency impulse excitation and propagation of elastic waves in pile shafts based on the complex continuous wavelet transform, phase-shift analysis, and an artificial neural network for parameter analysis, along with the use of pile test samples with artificial defects, made it possible to verify the proposed methodology of low-strain pile integrity testing for piles constructed in soft water-saturated soils.

Validity of the research results

The key arguments, conclusions, and recommendations developed in the thesis are based on rigorous theoretical approaches and numerical models that have been theoretically and experimentally substantiated. They are confirmed by the theoretical justification of the processes of elastic wave excitation and propagation in inhomogeneous media and by the results of processing the recorded signals and comparing them with the results demonstrated by other research works.

Evaluation of the research results. The key arguments and findings of the research have been presented at the following seminars and conferences: the 1st All-Russian Interuniversity Scientific and Practical Conference of Young Scientists dedicated to the 80th anniversary of the founding of the Department of Construction Production (St. Petersburg, 2020); International Conference on Complex Equipment and Quality Control Laboratories (CEQCL) (St. Petersburg, 2020); LXXV Science-to-Practice Conference for undergraduates, graduate students, and young researchers "Topical Issues in Modern Construction" (St. Petersburg, 2022); St. Petersburg Congress "Professional Education, Science and Innovation in the XXI century" (St. Petersburg, 2022).

The author's personal contribution lies in setting research objectives, analyzing the processes of formation of defects during the construction and operation of piles in soft water-saturated soils and methods for assessing their integrity and length, developing artificial defects and numerical simulations of obtaining and processing signals during low-strain pile integrity testing in soft water-saturated soils, development of technology for manufacturing and certification of pile test samples with artificial defects in the composition of the test site for verification of control methods, development and verification of methods for testing pile foundations in soft water-saturated soils, which increases the reliability of data obtained using low-strain pile integrity testing, based on complex continuous wavelet transform and classifiers with using artificial neural network classifier, experimental study of the developed methodology using pile test samples with artificial defects and precast spliced piles, practical application and validation of the methodology in real conditions of using piles.

Publications. The findings of this research have been covered in detail in four publications, including two articles published in leading Russian peer-reviewed journals approved by the Higher Attestation Committee for publishing postgraduate research results. Two more articles have been published in journals indexed in the Scopus citation database. The author has also received a certificate of state registration for a computer program.

Thesis layout. The thesis consists of a table of contents, an introduction, five chapters with conclusions, a general conclusion, and a list of references that includes 107 titles. The thesis contains 63 figures and 4 tables and is 146 pages in length.

Acknowledgments. The author expresses her deep gratitude and sincere appreciation to Professor Anatoly Potapov for his help in formulating and substantiating the research objectives.

The author expresses special gratitude to Ilya Lozovsky for the opportunity to work together, constructive criticism and significant assistance in the formation of the general structure and main idea of the dissertation research.

The author is sincerely grateful to Anatoly Osokin, Ph.D. in Engineering, for invaluable production experience and the opportunity to collect field and experimental data.

THE KEY POINTS OF THE RESEARCH

The introduction justifies the relevance of the topic, formulates the goal and objectives of the research, highlights its scientific novelty, and reveals its theoretical and practical significance. Also, the key arguments to be defended are outlined.

The first chapter analyzes the geology of St. Petersburg and the technologies traditionally used in the construction of pile foundations in soft water-saturated soils.

The chapter identifies the most common defects that occur during the construction of piles in soft water-saturated soils, such as necking, soil inclusions, water erosion, etc.

The chapter analyzes changes in the physical and mechanical characteristics of the concrete mixture during hardening in soil and shows how soft water-saturated soils influence pile formation in a soil mass and cause defects.

Also, the chapter reviews methodologies used to assess the length and integrity of pile shafts and identifies several limitations of the most popular low-strain pile integrity testing methods.

Based on the results of the analysis, the first chapter concludes by formulating the goal and objectives of the experimental study.

The second chapter presents the theoretical foundations of low-strain pile integrity testing. In order to increase its resolution, numerical simulations were conducted to study the propagation of elastic waves in piles with artificial defects. Based on the results, conclusions were drawn about the impossibility of detecting defects using the standard methodology. To improve the reliability of data interpretation, a draft methodology for low-strain pile integrity testing of pile foundations in soft water-saturated soils was developed. This methodology is based on time-frequency and phase-shift analyses of the recorded signal.

At the end of the second chapter, conclusions are formulated, and recommendations for using the results are given.

The third chapter details the development of pile test samples and a test site for the verification of the proposed methodology. The results of the experiments using the methodology to analyze pile test samples with artificial defects are presented, which confirm the main results of the numerical simulations.

The fourth chapter presents the main results of applying the proposed methodology for low-strain pile integrity testing in soft water-saturated soils using time-frequency and phase-shift analyses of the recorded signal and classifiers based on artificial neural networks. It is shown that the application of the draft methodology made it possible to localize artificial defects in pile test samples, thereby increasing the reliability of the interpretation of signals recorded using low-strain pile integrity testing.

The fifth chapter reports on the validation of the proposed methodology under real-world conditions in which pile foundations are used. It also formulates proposals for adjusting regulatory documents.

The conclusion presents the key findings aligned with the goal and objectives of the research.

The main results are reflected in the following key arguments:

1. The multi-frequency impulse excitation of elastic waves in the pile shaft, followed by an analysis of the signals recorded in the frequency-time domain using the complex continuous wavelet transform, phase-shift analysis, and classifiers based on artificial neural network, makes it possible to expand the list of defects detected in piles constructed and operated in soft water-saturated soils and increase the reliability of their detection.

Low strain impact integrity testing (also referred to as sonic, pulse-echo, PIT, SIT) is one of the most widely spread techniques for indirect evaluation of pile integrity. The test procedure is covered with ASTM D5882 standard and other international codes. The method is based on the analysis of propagation of elastic waves in a pile body. The elastic waves are generated with a handheld hammer impact on a pile top. The excited waves travel downwards along the pile body and reflect upward from the pile toe or non-uniformities such as cross-section changes, variations of elastic modulus, or density of the pile material (Figure 1). The pile head particle acceleration is recorded as a function of time by a sensor attached to the top of the structure. Next, the recorded signals are processed and prepared for the interpretation procedure.

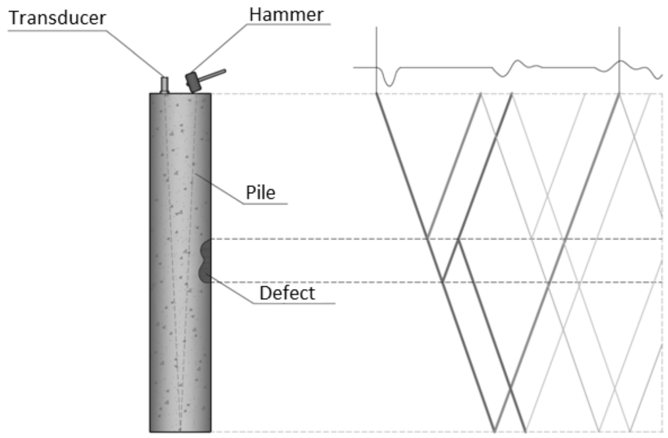

Figure 1 – Scheme of low-strain pile integrity testing. The red and blue lines conditionally show the wave propagation trajectories

Due to the fact that natural defects (Figures 2-5) can have varying shapes and acoustic characteristics, it can be technically and technologically challenging to replicate them. Therefore, in experiments and studies, real defects are often substituted with artificial ones.

To improve the resolution of low-strain pile integrity testing for detecting defects, multi-frequency impulse excitation is used with different input pulse durations. Shorter pulses emulate the work of light metal hammers, while longer pulses emulate that of heavy-duty mallets.

The numerical simulations of elastic wave propagation in piles with defects were performed in the axisymmetric formulation using the finite element methodology and the COMSOL Multiphysics 5.3 software (COMSOL Inc., Stockholm, Sweden).

To generate elastic waves, an external vertical force *F* in the form of a Gaussian pulse modulated by a Hanning window was applied at the center of the pile head to an impact area 30 mm in diameter (1):

$$F = -A\mathrm{e}^{-\left(2\pi\frac{(t-0.5T)}{T}\right)^2} \cdot \begin{cases} \left(0.5 - 0.5\cos\left(2\pi\frac{t}{T}\right)\right), & \text{if } t < T \\ 0, & \text{if } t \geq T \end{cases} \quad (1),$$

where *A* is the maximum force, t is the time, *T* is the input pulse duration.

The acoustic waves were registered with a 25 mm synthetic acceleration sensor offset from the pile axis by 75 mm.

Preliminary calculations were carried out for four types of artificial defects in cast-in-place piles. The first model represents a flawless pile (Figure 6a). The second model represents a pile with an artificial defect made of polystyrene with a diameter of 250 mm (Figure 6b), which covers 30% of the cross-sectional area of the pile. The third model (Figure 6c) represents a pile with a vertical artificial defect made of polystyrene with dimensions of 150 × 300 mm. The fourth model (Figure 6d) represents a pile with an artificial defect made of polystyrene with dimensions of 150 × 150 mm. The height (thickness) of each artificial defect was 100 mm, the pile diameter was 450 mm, and the total length of the pile was 3 m.

Figure 7 shows the results of the numerical simulations of elastic wave propagation for all four models with input pulse durations of 0.5, 0.75, and 1 ms. Although each synthetic signal shows a clear reflection from the pile toe, the resolution of different input pulses varies significantly. Low-frequency signals are insensitive to artificial defects in the pile shaft, while high-frequency signals lead to noticeable reflections from artificial defects if they cover 30% of the pile cross-section (Model 2). Defects with dimensions of 150×300 mm and 150×150 mm are not detected when using low-frequency signals. When using high-frequency signals, a subtle reflection appears in the area of the defect, which cannot be unambiguously interpreted.

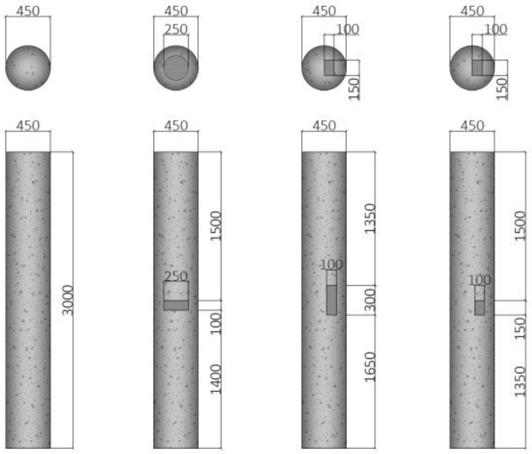

Figure 6 – Geometric parameters of cast-in-place pile models: a – a flawless pile (Model 1), b – pile with an artificial defect 250 mm in diameter and 100 mm thick (Model 2), c – pile with an artificial defect with dimensions of 100x150x300 mm (Model 3), d – pile with an artificial defect with dimensions of 100x150x150 mm (Model 4)

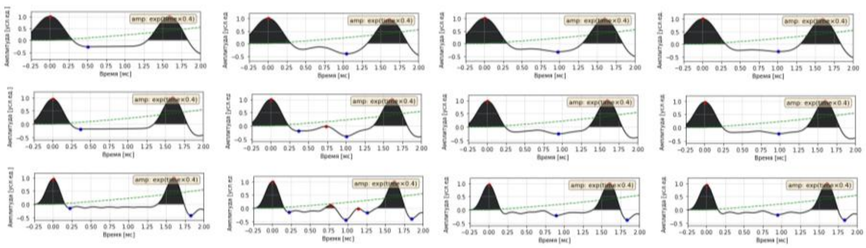
Figure 7 – Numerical simulation results of low-strain pile integrity tests for four types of artificial defects in cast-in-place piles: a – flawless pile (Model 1), b – pile with an artificial defect 250 mm in diameter and 100 mm thick (Model 2), c – pile with an artificial defect with dimensions of 100x150x300 mm (Model 3), d – pile with an artificial defect with dimensions of 100x150x150 mm (Model 4)

To improve the reliability of the signals recorded in low-strain pile integrity tests, it is proposed to use the complex continuous wavelet transform for time-frequency analysis. The complex continuous wavelet transform converts the signal under study $f(t) \in L^2(R)$ into a function of two variables a , $b \in R$, $a > 0$ (2):

$$W(a,b) = \int_{-\infty}^{+\infty} f(t) \frac{1}{\sqrt{a}} \psi^* \left(\frac{t-b}{a} \right) dt \ , \quad (2)$$

where function $\psi(t)$ is the mother wavelet;
* represents the complex conjugation operation;
a is the scale parameter of the mother wavelet;
b *i*s the time shift that determines the location of the wavelet.

To apply the wavelet transform successfully, it is important to select an appropriate mother wavelet. In our case, it is proposed to use the complex Morlet wavelet as the mother function (3):

$$\psi(t) = \frac{1}{\sqrt{\pi B}} exp^{-\frac{t^2}{B}} exp^{i2\pi Ct} \ , \quad (3)$$

where B is the bandwidth;
C is the center frequency.

By changing the bandwidth and center frequency parameters, we can adjust both the mother wavelet depending on the signal and the time-frequency resolution of the wavelet transform.

One of the key distinctions of the complex continuous wavelet transform is its imaginary and real parts. Using the real part, one can get can information on the amplitude in a single region, whereas the imaginary part also provides information on the phase, enhancing signal interpretation accuracy (4):

$$\phi(a,b) = arctan \left(\frac{W_I(a,b)}{W_R(a,b)} \right) \quad (4),$$

where $\phi(a,b)$ is the phase angle;
$W_I(a,b)$ is the imaginary part;

$W_R(a, b)$ is the real part.

If there are anomalies (defects) in the pile shaft, the amplitude of the recorded signal changes, which can be observed in the amplitude spectrum. Also, if there are anomalies in the test object, phase changes occur, which are tracked on the phase spectrum. By analyzing the moment of phase change, one can draw a conclusion about the integrity of the pile, accurately localize the anomaly, or estimate the length of the pile.

The following are the results of using the complex continuous wavelet transform methodology to perform low-strain pile integrity tests on reinforced concrete piles. Figures 8 and 9 show the results of applying the methodology to Models 1 and 2. The phase shift at any input pulse duration is clearly visible at 0 ms and 1.6 ms, which corresponds to the input pulse and the wave being reflected from the pile toe at a depth of 3 meters.

On the phase spectrum of Model 2 (Figure 9), the phase shift also occurs at 0.75 ms, which corresponds to the location of the defect.

2. The use of numerical simulations of the multi-frequency impulse excitation and propagation of elastic waves in pile shafts based on the complex continuous wavelet transform, phase-shift analysis, and an artificial neural network for parameter analysis, along with the use of pile test samples with artificial defects, made it possible to verify the proposed methodology of low-strain pile integrity testing for piles constructed in soft water-saturated soils.

To validate the proposed methodology, a test site was set up with pile test samples containing artificial defects. The water erosion defect was represented by samples with a diameter of 250 mm and a thickness of 100 mm represented, and the soil inclusion defect was represented by samples with dimensions of 100x150x300 mm and 100x150x150. Three pile test samples were made for each type of defect, along with one flawless pile test sample.

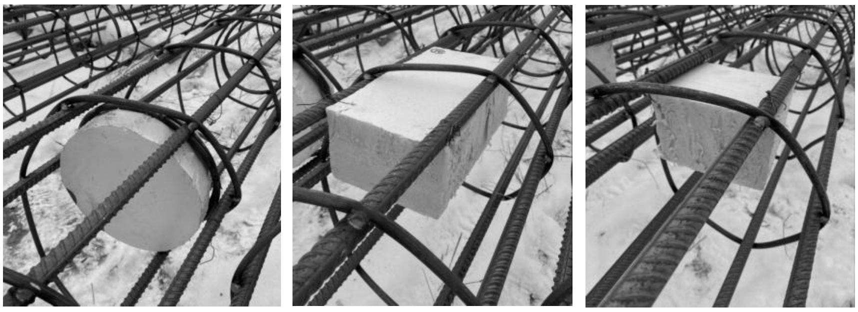

Figure 10 – Test site with pile test samples containing artificial defects

Figures 11 and 12 show the results of low-strain pile integrity tests performed on the pile test samples and the results of subsequent signal processing using the complex continuous wavelet transform.

Also, it is proposed to interpret the results and identify pile defects by means of a cluster analysis method called ANN classifier (artificial neural network classifier) with the characteristic points of the spectrum of the recorded signal used as the input vector of the ANN classifier and the type of pile defect used as the output vector. The results of the study led to the conclusion that the ANN classifier can serve as the primary tool for the automatic interpretation of the results of low-strain pile integrity tests.

Based on the findings, recommendations are proposed for adjusting the documents regulating the monitoring of pile foundations in the process of their construction and operation.

CONCLUSION

This thesis represents a complete study that proposes a new solution to an urgent issue in science problem, namely the necessity to expand the list of defects developing in pile foundations during their construction in soft water-saturated soils and to increase the reliability of defect detection by improving the principles and techniques of signal processing in low-strain pile integrity tests.

The research led to the following conclusions and recommendations:

1. The analysis of St. Petersburg soil characteristics and pile construction technologies made it possible to classify pile shaft defects and identify the processes leading to their occurrence during the construction of pile foundations in soft water-saturated soils.

2. Numerical simulations of elastic wave excitation and propagation in pile foundations revealed the limitations of low-strain pile integrity tests in estimating the length and integrity of piles constructed in soft water-saturated soils. Also, a solution was proposed based on the phase analysis of multi-frequency signals in the time-frequency domain to improve the resolution of the method.

3. The use of the complex continuous wavelet transform for the phase-shift analysis of recorded signals in the time-frequency domain was substantiated, which makes it possible to detect defects in piles constructed in soft water-saturated soils, localize splices in precast piles, and assess their total length.

4. A methodology was substantiated and developed for manufacturing and certifying pile test samples with artificial defects to test piles constructed in soft water-saturated soils.

5. A methodology was developed for monitoring pile foundations in soft water-saturated soils based on multi-frequency impulse excitation in the pile shaft and the subsequent analysis of the recorded signals in the time-frequency domain using the phase-shift analysis and classifiers based on artificial neural networks. This allows for expanding the list of defects and increasing the reliability of defect detection in piles constructed in soft water-saturated soils or regions with similar soil characteristics.

6. Pile test samples and real piles were used in experiments to ensure that the principles and processes of pile testing resulted in identifying pile defects and making pile length assessments with the required metrological characteristics. Based on this, recommendations were formulated for adjusting relevant regulations and using

them in the construction of pile foundations in St. Petersburg and other regions with similar soil characteristics.

KEY PUBLICATIONS REFLECTING THE RESEARCH FINDINGS

Articles:

1. Lozovsky, I.N. Wavelet denoising for low strain pile integrity testing / I.N. Lozovsky, E.S. Loseva, V.A. Syasko // Testing. Diagnostics. - 2022. - No. 9. - P. 36-45.

2. Churkin, A.A. Increasing The Reliability Of The Low Strain Integrity Testing Of Piles Under Existing Structures / A.A. Churkin, E.S. Loseva, I.N. Lozovsky, V.A. Syasko // Testing. Diagnostics. - 2022. - No. 10. - P. 24-32.

3. Loseva, E.S. Wavelet Analysis for Evaluating the Length of Precast Spliced Piles Using Low strain pile integrity testing // Loseva E.S., Lozovsky I.N., Zhostkov R.A., Syasko V.A. // Applied Sciences. - 2022. - No. 12. - P. 1-12. https://doi.org/10.3390/app122110901.

4. Loseva, E.S. Identifying Small Defects in Cast-in-Place Piles Using Low strain pile integrity testing / Loseva E.S., Lozovsky I.N., Zhostkov R.A. // Indian Geotechnical Journal. - 2022. - No. 52. - P. 270-279. https://doi.org/10.1007/s40098-021-00583-y.

Patent:

5. Koteleva N.I., Loseva E.S., Syasko V.A. Computer program No. 2023610021 (Russian Federation). A program for defect detection in bored and cast-in-place piles based on field data obtained by low-strain pile integrity testing. Application date: December 15, 2022. Published on January 9, 2023. Applied by St. Petersburg Mining University. Applicant of SPGU. 1 page.

Defects that occur during the construction of piles in soft water-saturated soils:

Figure 2 – Necking

Figure 3 – Washout of concrete mixture

Figure 4 – Soil inclusions

Figure 5 – Caverns

Results of applying complex continuous wavelet transform to the results of numerical simulation of low-strain pile integrity testing:

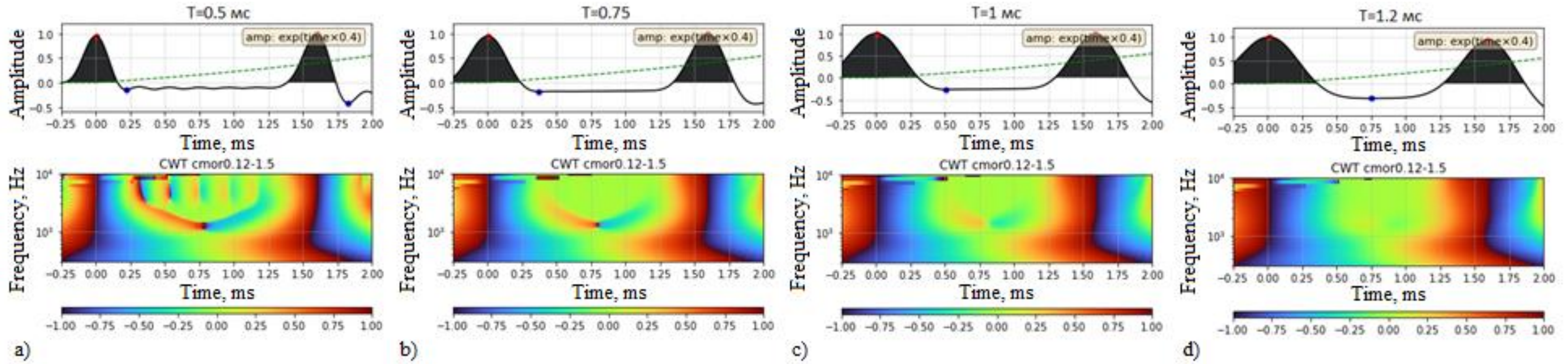

Figure 8 – Representation of signals in time domain and distribution of phase angles for flawless pile (Model 1) with input force pulses: *a*) 0.5 ms; *b*) 0.75 ms; *c*) 1 ms; *d*) 1.2 ms

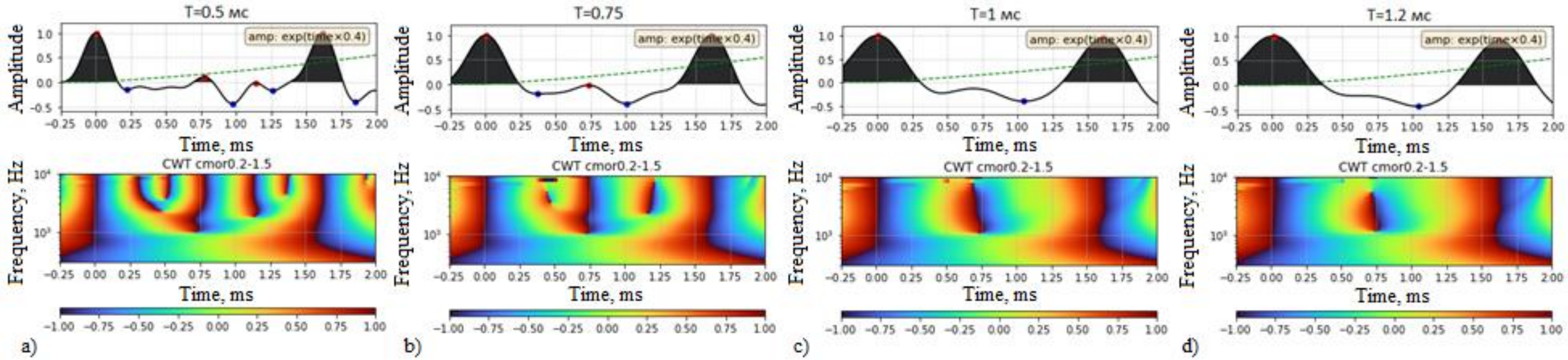

Figure 9 – Representation of signals in time domain and distribution of phase angles for pile with an artificial defect 250 mm in diameter and 100 mm thick (Model 2) with input force pulses: *a*) 0.5 ms; *b*) 0.75 ms; *c*) 1 ms; *d*) 1.2 ms

Results of applying low-strain pile integrity testing to pile test samples and subsequent signal processing using complex continuous wavelet transform:

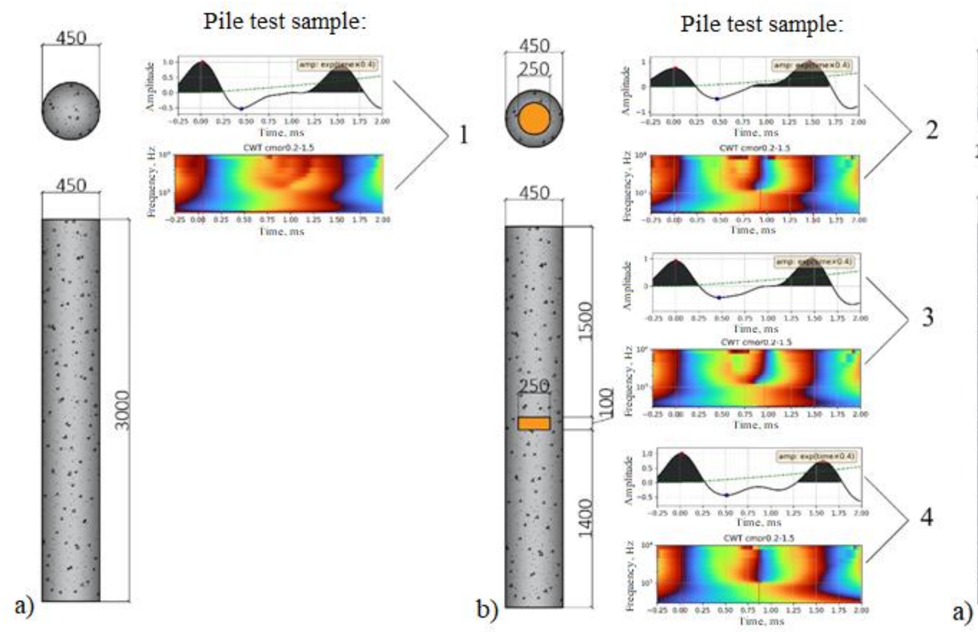

Figure 10 – Representation of signals in time domain and distribution of phase angles for: a) flawless pile test sample 1; b) pile test sample 2-4 with an artificial defect 250 mm in diameter and 100 mm thick

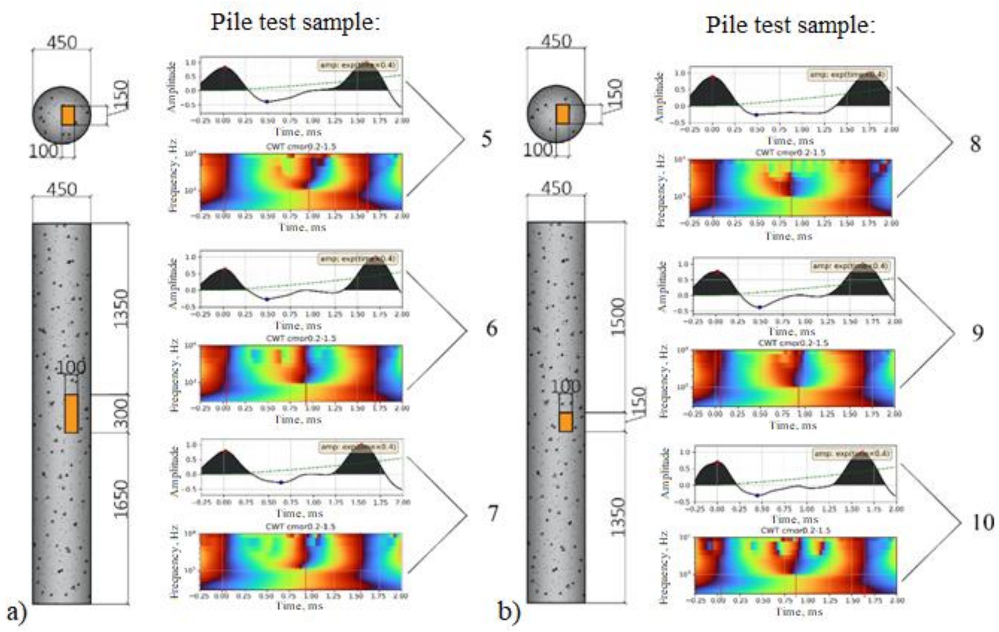

Figure 11 – Representation of signals in time domain and distribution of phase angles for: a) pile test sample 5-7 with an artificial defect with dimensions of 100x150x300; b) pile test sample 8-10 with an artificial defect with dimensions of 100x150x150