RESEARCH PAPER / НАУЧНАЯ СТАТЬЯ
UDC 624
DOI: 10.22227/2305-5502.2025.1.15

Complex analysis of bored piles on light rail rapid transit system construction site in Astana, Kazakhstan

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ABSTRACT
Introduction. Light railway transport (LRT) is the name of the public transportation system that Astana is currently building. The LRT project on Astana's difficult soils is discussed in the article. Due to problematic foundation soils, both of these larger projects employed piled foundations.
Materials and methods. The bridge's foundation was built using bored piles that ranged in length from 8 to 55 m and had a cross-section diameter of 1.0 to 1.5 m. Every bored pile has a design bearing capacity ranging from 4,500 to 9,500 kN.
Results. The integrity test (ASTM D6760–08) and static load test (GOST 5686–94) findings for bored piles are presented in this study. Under those circumstances, maintaining the integrity of each bored pile's concrete body is crucial. Use the cross-hole sonic logging method to verify integrity. At the moment, the most trustworthy approach available for evaluating the integrity of a dug deep pile foundation on a building site is cross-hole acoustic logging, a non-destructive testing technique. After installation, integrity examinations are frequently the most practical way to evaluate the condition of the shaft.
Conclusions. The real site provided the results that were interpreted. Lastly, a few suggestions for testing procedures appropriate for Kazakhstan's challenging ground conditions are made.

KEYWORDS: deep foundation, instrumented test pile, cross-hole test, PIT

Acknowledgements. This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (AP13268718).

FOR CITATION: Zhussupbekov A.Zh., Shakirova N.U., Omarov A.R. Complex analysis of bored piles on light rail rapid transit system construction site in Astana, Kazakhstan. *Stroitel'stvo: nauka i obrazovanie* [Construction: Science and Education]. 2025; 15(1):15. URL: http://nso-journal.ru. DOI: 10.22227/2305-5502.2025.1.15

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Комплексный расчет буронабивных свай на участке строительства системы скоростного легкорельсового транспорта в Астане, Казахстан

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АННОТАЦИЯ
Введение. Легкорельсовый транспорт (ЛРТ) — система общественного транспорта, строительство которого ведется в г. Астане в настоящее время. Рассматривается проект ЛРТ на сложных грунтах Астаны. Из-за проблемных грунтов в обоих крупных проектах использовались свайные фундаменты.
Материалы и методы. Фундамент моста был построен с использованием буронабивных свай длиной от 8 до 55 м и диаметром сечения от 1,0 до 1,5 м. Каждая буронабивная свая имеет расчетную несущую способность от 4500 до 9500 кН.
Результаты. Представлены результаты испытаний буронабивных свай на сплошность (стандарт Американского общества испытания материалов D6760–08) и статическую нагрузку (ГОСТ 5686–94). В этих условиях обеспечение сплошности бетонной части каждой буронабивной сваи имеет решающее значение. Для проверки сплошности следует использовать метод межскважинного акустического каротажа. Сегодня наиболее надежным методом оценки сплошности глубокого свайного фундамента на строительной площадке является метод межскважинного акустиче-

ского каротажа, представляющий собой метод неразрушающего контроля. После установки обследование сплошности часто служит лучшим практическим способом оценки состояния ствола.
Выводы. Проанализированные результаты получены на реальном объекте. Приведены предложения по проведению испытаний в условиях сложных грунтов Казахстана.

КЛЮЧЕВЫЕ СЛОВА: глубокий фундамент, испытуемая свая с контрольно-измерительной аппаратурой, межскважинное испытание, испытание свай на сплошность

Благодарности. Данное исследование финансировалось Комитетом науки Министерства науки и высшего образования Республики Казахстан (AP13268718).

ДЛЯ ЦИТИРОВАНИЯ: *Жусупбеков А.Ж., Шакирова Н.У., Омаров А.Р.* Комплексный расчет буронабивных свай на уча-стке строительства системы скоростного легкорельсового транспорта в Астане, Казахстан // Строительство: наука и образование. 2025. Т. 15. Вып. 1. Ст. 15. URL: http://nso-journal.ru. DOI: 10.22227/2305-5502.2025.1.15

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INTRODUCTION

Timely quality control of the foundation ensures the safety of construction work and operation of the facility. One of the most popular control methods is non-destructive quality control of bored piles. The fact is that a violation of this continuity significantly reduces the bearing capacity of the pile as a whole. However, it is very difficult, sometimes even almost impossible, to detect discontinuities. Today, there are several methods for monitoring the integrity of piles; non-destructive testing methods are the most widely used.

Thus, an urgent task is to resolve the problem of using foundation bases that, on the one hand, have a high specific bearing capacity, and on the other, ensure the structural safety of buildings and structures throughout the entire standard service life. A package of application programmes allows you to determine the nature of the defect, as a result of working with which you can get the reduced pile profile and a table with the processing results.

The article used field tests of pile soils by non-destructive methods of Pile Integrity Testing (PIT method) and the cross-hole flaw detection method (Cross-hole method). The testing methods have been widely developed in America, China and Europe, and today it is one of the advanced methods of testing piles, assessing the quality of bored piles. The research work compared the PIT method and the cross-hole flaw detection method (Cross-hole method), used at the LRT (Light Rail Transport) construction sites in Astana with the aim of further adapting this method in Kazakhstan. The PIT method allows for an expert assessment of the actual condition of the pile, that is, to determine its length, as well as to analyze the integrity of the pile structure. This method is an express control and does not destroy the pile concrete. It can be used to test any type of pile, regardless of the technology used for its installation. The PIT method allows obtaining data on the bearing capacity of the pile with a significant degree of reliability in a relatively short time. The CSL method of monitoring the continuity of a concrete structure is based on the difference in the speed of ultrasonic waves in environments that differ in structure, mechanical and physical properties [1–10].

The aim of the work is to develop practical recommendations for the application of modern express methods for studying the performance of bored piles in complex soil conditions of Kazakhstan. To achieve this goal, the following tasks were solved: testing soils with piles using static load test methods (SLT); testing soils with piles using express methods (cross-hole flaw detection (Cross-hole method) and PIT method); analysis of experimental results of the bearing capacity of defective piles.

The first published report on defective piles described unusual piles in South Africa with loose sand beneath artesian water. Seki describes a project in Budapest where underwater piles were damaged and could not support the design loads. Since then, the issue of pile integrity has gradually become an increasingly important part of quality assurance programmes for construction projects. Pile integrity corresponds to the design requirements, in particular physical dimensions, material properties, and verticality. Failure to comply with the above requirements is a failure.

For a long time, piles were driven manually. The first description of a simple model with manual control dates back to 1,660. The invention of a frame with instructions and various devices for its lifting allowed to increase the power of the projectile. An undoubted achievement of the technological revolution is the invention of the steamship Nasmet (Great Britain). In 1889, this project was developed by the Russian engineer S.A. Artsish, which allowed to significantly increase its productivity. The first diesel floor devices appeared in the 30–40s of the last century, and in the 50s — electric vibrators. At the beginning of the XIX–XX centuries, the first monolithic piles appeared on the ground, in the scientific literature of that time about twenty. Today, the technology of making piles in the ground allows us to solve the most complex geotechnical problems: the construction of buildings and the development of underground structures in populated areas with existing infrastructure.

Currently, large-scale construction is being carried out everywhere, which is characterized by a significant increase in the number of floors in buildings and structures. Their uniqueness, the complexity of geological conditions and the need to resolve various issues related

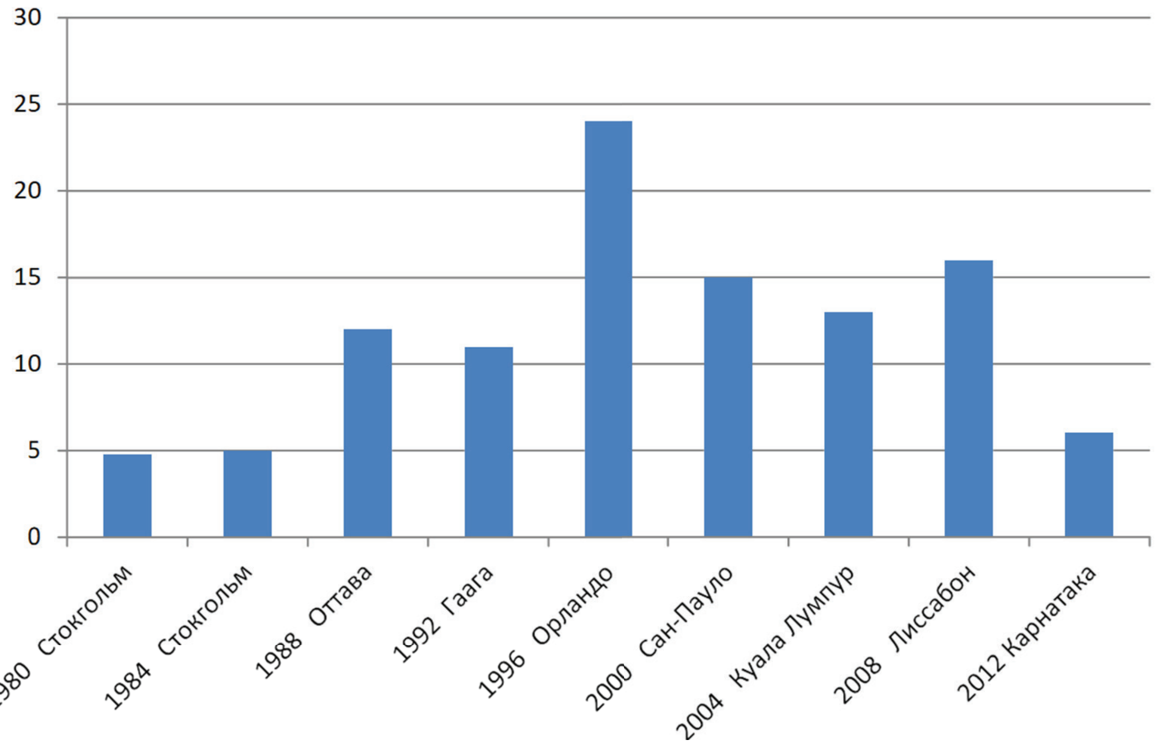


Fig. 1. Statistics of international geotechnical conferences "Stress – Wave"

Рис. 1. Статистика международных геотехнических конференций «Напряжение – Волна»

to compliance with existing norms and standards are also important. As a result, there is a significant increase in the load that must be transferred to the bearing layers of the soil.

The widespread use of bored piles in the construction of structures in confined urban areas has both advantages and disadvantages. One of the main disadvantages is the lack of sufficient information on the bearing capacity of defective bored piles.

At the same time, the normative recommendations continue to consider as the main task the maximally loaded single pile, the ultimate resistance of which is determined by experience or calculation, and the transition to the bearing capacity of the foundation is made by simply summing up the bearing capacity of the piles in the foundation. This approach is not always suitable for improving the reliability and cost-effectiveness of design solutions for pile foundations.

After more than fifty years of evolution, integrity inspections of deep piles has become commonplace. In addition, the industry is still looking for an experimental, cost-effective test method that can accurately create the internal and external geometry of a pile and determine its material characteristics. Unfortunately, pile integrity testing does not solve the problem, as evidenced by the statistics from the International Stress – Wave Geotechnical Conferences (Fig. 1). These events are probably the main forum for pile testing — the number of integrity testing activities grew steadily until 1996, and then there was a significant decline in production, a sign of stagnation [11–27].

The analysis of all existing non-intrusive methods is a classic inverse problem that still does not have a unique solution. To find a possible solution, you need to look at some assumptions and check them using a suitable model. For example, given a reflectometer trace, we usually make four main assumptions:

1. The tested element is a body.
2. The 1D wave equation is valid.
3. The wave velocity in the body is X, m/s.
4. The friction distribution on the surface is known (or ignored).

The first hypothesis is trivial, but the second is not. The 1D wave equation can be used for tested steel piles to check the integrity of all the assumptions on which it is based or incorrect. For example, imperfect piles are not prismatic and homogeneous, and the soil profile of a particular pile is approximately known. The best we can offer in these cases is to consciously estimate the pile length. It is clear that the wave equation method does not give results, and the most complex analysis is little more than an asymmetric pile profile, without directly affecting the construction properties of the pile (Fig. 2).

By definition, existing methods are more informative than non-intrusive ones, but they also have disadvantages. Therefore, the engineer determining the testing must evaluate the type of pile, the availability of equipment and the budget. In case of uncertainty, a prudent engineer has several advantages: to hire another laboratory

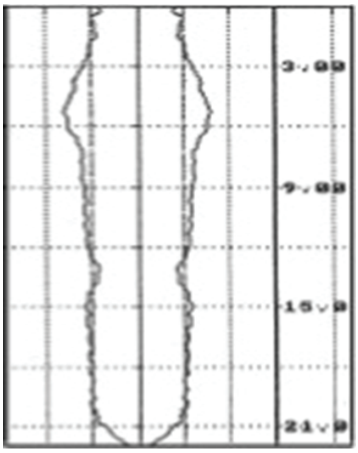


Fig. 2. Proposed pile profile

Рис. 2. Предлагаемое сечение сваи

to repeat the test (an experiment was adopted in Hong Kong in 1999) or to test with other methods. For example, the ultrasonic test can be supplemented by a single-hole test to check the outside of the pile. Fig. 3 shows the condition of a pile with a 15 % defect at a depth of 4 m, tested in a single borehole without anomalies and an ultrasonic echo, which clearly shows an increase in the first arrival velocity and attenuation rate. Of course, savings can lead to contradictory results when the correct technical solution is needed.

Occurrence of defects. The manufacturing process of compacted piles is not visible. It is therefore advisable to wait for a certain percentage of defective piles, especially when installing in difficult terrain and in the presence of groundwater. Fleming et al. describe many cases that lead to defects in driven and bored piles. A study of 49,000 piles tested in five countries showed that 1.85 % were found to be defective, with 6 % of very short ones being 20 % or more, with an overall defect of about 8 %. The defects are much higher, i.e. 76 %, with several areas below the norm. Such high error rates are inconvenient and can be prevented by checking the integrity as early as possible.

MATERIALS AND METHODS

Nowadays, non-destructive methods have become an effective technique for testing the integrity of deep concrete foundations. The results of non-destructive tests carried out using rapid method technology on bored piles located at 18 stations and sections were analyzed. In total, 1896 bored piles were tested between February and October 2018. Fig. 4–6 show some general characteristics of the tested piles in relation to each of the two groups (diameter and length of piles; number of piles and type of tests performed by PIT and CSL methods).

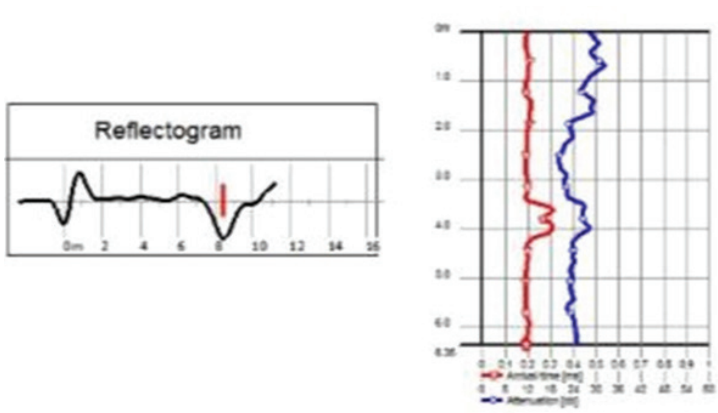
"Pile Integrity Testing — PIT" acoustic pile testing method

The following instruments are required for testing:

- a stock hammer to strike the impact;
- a transducer of the received signal (accelerometer) and a connecting element;
- instrument for data acquisition, visualization, recording and processing of fast signals;
- software for decoding the recorded and processed signals.

The work also uses highly sensitive sensors-accelerometers installed on the pile head, as well as a separate analog-digital instrument that includes a computer with a display and a programme that processes the information from the accelerometers.

The test instruments perform the functions of signal detection, filtering, amplification, reproduction, storage and processing and analysis. As for the exciter, a mechanical hammer, rod hammer or hand hammer with different sizes, lengths and weights and with different heads made of different material is selected, depending on the type of pile and the purpose of the test to meet the required excitation frequency and impact energy. The signal detection and processing instrument meets the regulatory requirements.



a *b*

Fig. 3. Pile with a 15 % defect at a depth of 4 m: *a* — impact echo; *b* — ultrasonic hole with one hole

Рис. 3. Свая с 15%-ным дефектом на глубине 4 м: *a* — ударное эхо; *b* — ультразвуковое отверстие с одним отверстием

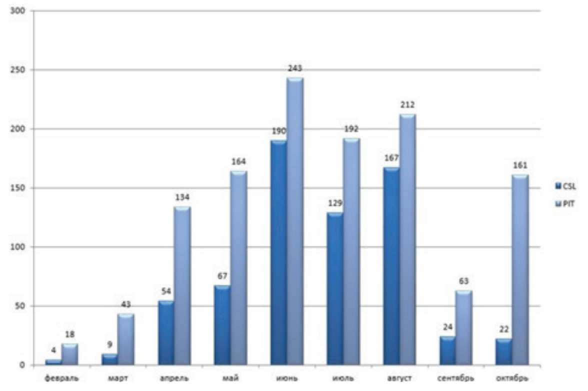


Fig. 4. Number of piles tested between February and October 2018 for Lot 1 and Lot 2.

Рис. 4. Количество свай в группах 1 и 2, испытанных в период с февраля по октябрь 2018 г.

Testing of piles by ultrasonic method "Ultrasonic Crosshole Testing — CSL"

Non-destructive testing of the continuity of concrete in deep foundations using the ultrasonic method (Ultrasonic, cross-hole ultrasonic flaw detection, ultrasonic diagnostics of piles, CSL (Fig. 7), ultrasonic testing of pile integrity, UT) is based on determining the parameters of ultrasonic waves (propagation velocity and attenuation) propagating between access pipes installed as part of the reinforcement cage, in order to obtain conclusions about the continuity of the concrete of the structure.

Defect zones, if any, in the tested pile are displayed on the above diagrams and described in the text of the report. Defect zones are determined by the increased first impulse arrival time (FAT) by more than 20 % depending on the first impulse arrival time in the nearby zone

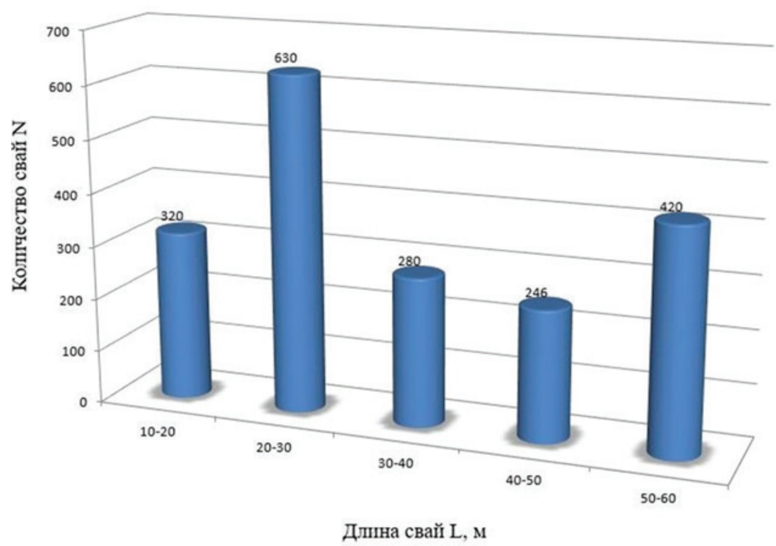


Fig. 5. Distribution of pile lengths

Рис. 5. Распределение свай по длине

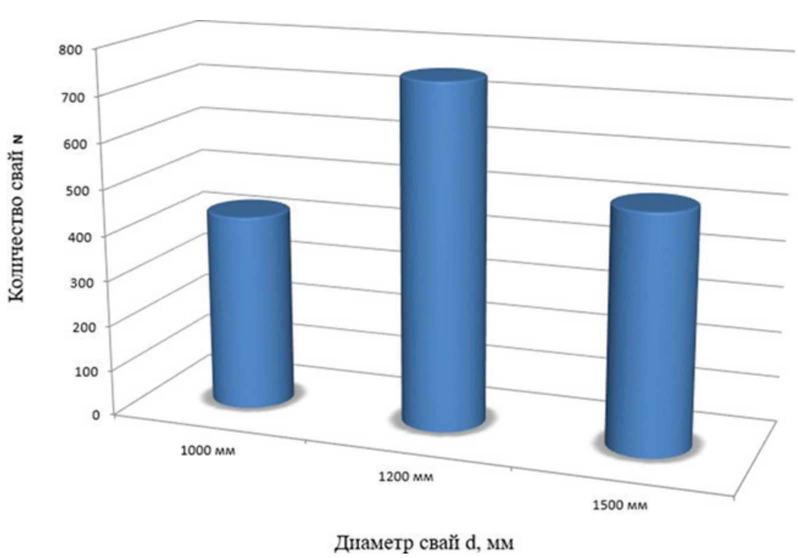


Fig. 6. Distribution of pile diameters

Рис. 6. Распределение свай по диаметру with normal concrete quality, and also in the defect zone the impulse energy and the speed of sound wave propagation are reduced.

The concrete of the tested pile is sounded in vertical planes passing through the geometric centers of the access pipes. To test the integrity of the pile, the ultrasonic wave source is immersed in one access pipe up to the lower mark, and the ultrasonic wave receiver is immersed in the other.

The source and receiver are synchronously raised and ultrasonic signals are excited and recorded at a given step. Analog signals recorded by the receiver (the dependence of the ultrasonic signal amplitude on time) are converted into a digital signal and stored in the device memory. Concrete integrity testing is performed from the lower elevation of the access pipes to the upper elevation of the structure concrete for each pair of access pipes installed in the structure.

After testing, the measurement results are analyzed, processed and interpreted. The measurement results are presented as graphs of the propagation velocity of ultrasonic waves and the attenuation of the recorded signals depending on the depth and, if necessary, as "waterfall" diagrams.

The tests are performed in accordance with GOST and the international standard ASTM D6760–16 Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing.

The crosshole ultrasonic flaw detection method allows for ultrasonic testing of the integrity of bored piles, diaphragm walls and other underground reinforced concrete structures.

RESULTS OF THE RESEARCH

Results of the analysis of the tested piles in the CHA-W programme

Testing of bored piles by the method of inter-borehole flaw detection at the construction site of the object: "New transport system of Astana. LRT. 1st stage" (section from the airport to the new railway station), sections 101–118 were carried out by KGS-Astana LLP in 2018 on the instructions of the Branch of China Railway Asia-Europe Construction Investment Co., LTD in the Republic of Kazakhstan. During the test work, 1896 bored piles were tested with the participation of the author. The work carried out on testing bored piles by the method of borehole flaw detection using the CHAMP device was carried out in accordance with the methodology set out in the TB 10218–2008 standard. The pile testing distance is less than the free length of the test tubes, since the tubes protrude above the surface of the pile concrete by 5 cm, and also due to the fact that the sensitive part of the receiving (recording) probe is located in its central part. The test tube data are presented in Table 1.

Table 2 summarizes the test results for each of the piles tested and each of the available pairs of test tubes to the probes' possible penetration depths.

The pile testing involved obtaining three depth measurement profiles and processing the results using the specialized programme CHA-W (Fig. 7) and

Table 1. Example of information about piles tested in 2018

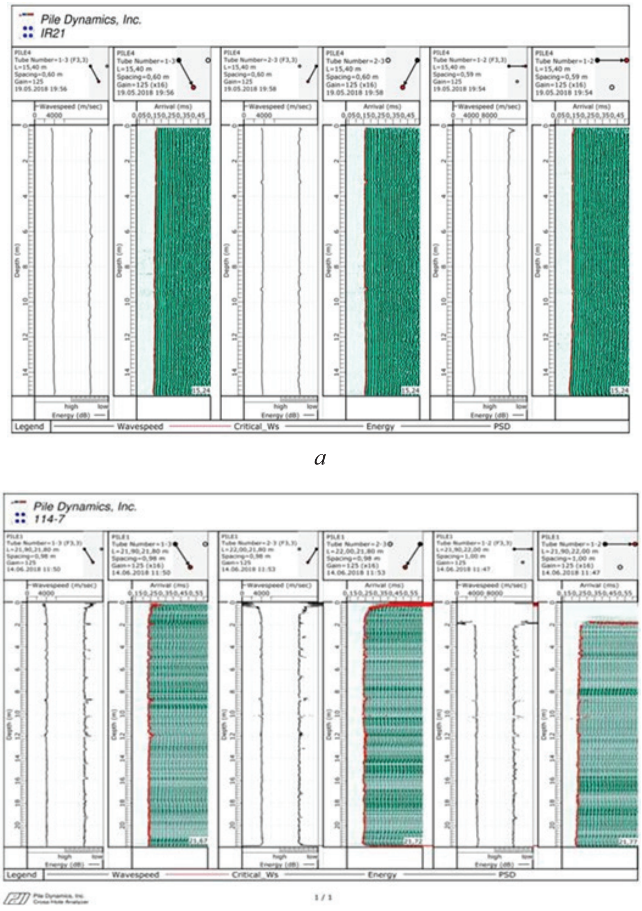
Табл. 1. Пример данных о сваях, испытанных в 2018 г.

Pile number	Date of manufacture of the pile	Length of pile, m	Diameter of the pile, m	Number of test tubes/diameter, –/mm	Height of test tubes above concrete piles, sm
Track 109-110, pillar IR-21, pile No. 4	5.10.2017	15.6	1.0	3/42	5

Table 2. Test results for each tested pile

Табл. 2. Результаты испытаний по каждой испытанной свае

Pile number	Test tube pair number, s	Distance between test tubes, m	Available test tube lengths, m	Pile type by continuity	Test results/comments
Track 109-110, pillar IR-20, pile No. 1	1–2	0.760	14,10/14,10	Type I	Homogeneous concrete, no anomalies detected
	2–3	0.800	14,10/14,10		
	3–1	0.730	14,10/14,10		
Track 109-110, pillar IR-20, pile No. 3	1–2	0.780	14,10/14,10	Type I	Homogeneous concrete, no anomalies detected
	2–3	0.720	14,10/14,10		
	3–1	0.790	14,10/14,10		
	3–1	0.490	15,90/16,10		

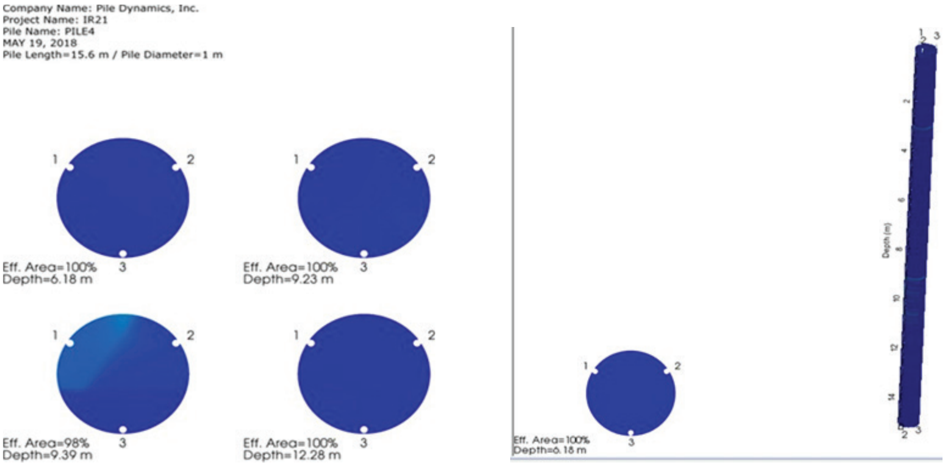


a

b

Fig. 7. Results of analysis of tested piles in the CHA-W programme: *a* — “good” piles; *b* — “bad” piles

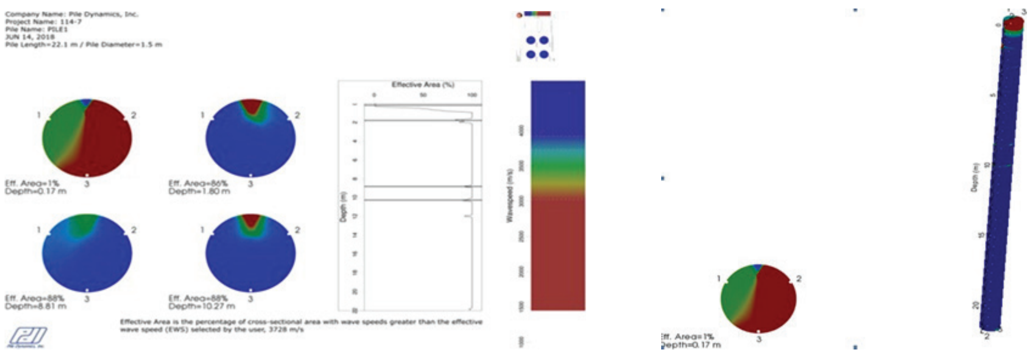
Рис. 7. Результаты анализа испытанных свай в программе CHA-W: *a* — «хорошие» сваи; *b* — «плохие» сваи



a *b*

Fig. 8. Results of analysis of tested piles in PDI-TOMO programme (“good” piles): *a* — cross-section of piles; *b* — 3D view of piles

Рис. 8. Результаты анализа испытанных свай в программе PDI-TOMO («хорошие» сваи): *a* — поперечное сечение свай; *b* — трехмерное изображение свай



a *b*

Fig. 9. Results of analysis of tested piles in PDI-TOMO programme (“bad” piles): *a* — cross-section of piles; *b* — 3D view of piles

Рис. 9. Результаты анализа испытанных свай в программе PDI-TOMO («плохие» сваи): *a* — поперечное сечение свай; *b* — трехмерное изображение свай

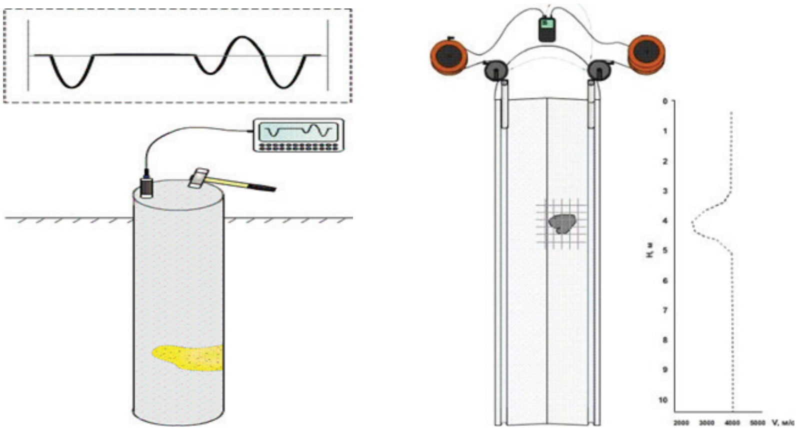


Fig. 10. Ultrasonic and Low Strain Test

Рис. 10. Ультразвуковое испытание при низкой деформации

PDI-TOMO (Fig. 8), the results of processing the obtained information are presented to this conclusion.

The test method identifies deviations in the propagation of ultrasonic waves in the homogeneous concrete of the piles under test. The defect zones are identified by an increased first impulse arrival time (FAT) of more than 20 %, relative to the first arrival time in a nearby zone of a pile with normal concrete quality, indicating a lower ultrasonic wave propagation velocity in the concrete of the pile. Direct interwall flaw detection tests were also performed in the pipes near the defects to better determine the position and nature of the defects (Fig. 9).

Acoustics in geotechnics is widely used in two types — Ultrasonic (Chum, Pulsar, Concrete) and Low Strain Test (PET, SIT, etc.), High Strain Test (DLT). They are used in construction geotechnics, from soil (bearing capacity) to

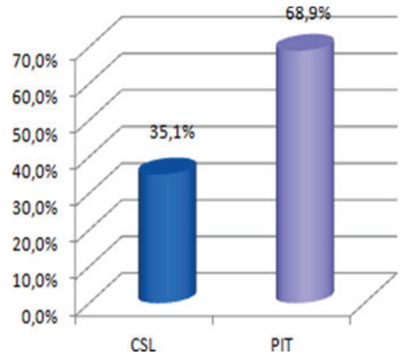


Fig. 11. Comparison of tested piles by number

Рис. 11. Сравнение испытанных свай по количеству

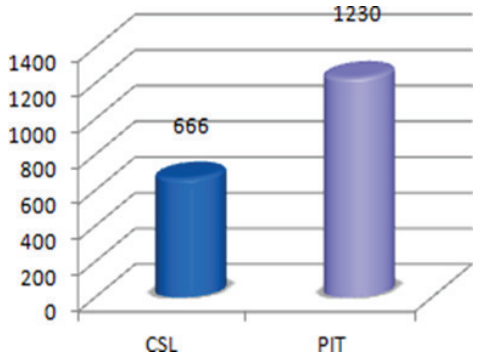


Fig. 12. Percentage comparison of tested piles

Рис. 12. Процентное сравнение испытанных свай

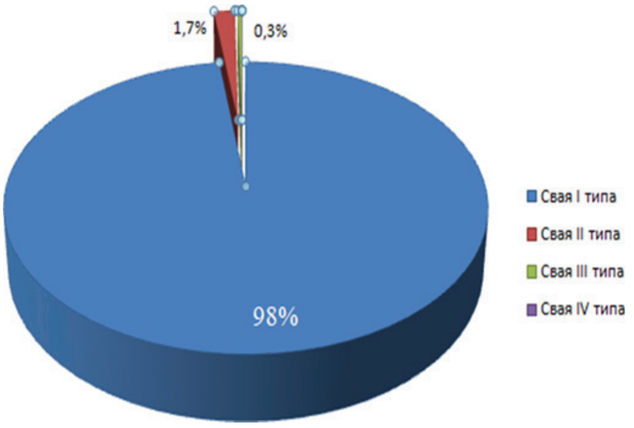


Fig. 13. Distribution by integrity classification of bored piles

Рис. 13. Распределение буронабивных свай по сплошности

foundation quality. Ultrasonic and Low Strain Test tests were conducted within the framework of one-dimensional wave theory, analytical and experimental studies that provide more detailed information about the integrity, strength and geometry of the foundation. Comparison of Ultrasonic and Low Strain Test results (Fig. 10) yields identical results with respect to the basic parameter C.

Comparison of test results obtained by the two methods. In 2018, more than 1,896 bored piles at the LRT Astana construction site were tested for integrity using two methods: 35.1 % by the inter-well flaw detection method and the other 68.9 % by the low strain test method (Fig. 11–13).

CONCLUSION AND DISCUSSION

The following conclusions can be drawn based on the results of continuity studies of bored piles using PIT and CSL methods:

1. Literature review has shown that the use of pile foundations is necessary in connection with the construction of industrial facilities and residential and civil buildings that transmit heavy loads, especially in areas composed of weak soils.

2. PIT method and CSL method allow to obtain data on the quality of piles with a significant degree of reliability in a relatively short time. This methodology is new for the domestic construction market. To date, there is no document regulating the use of this technology neither in Kazakhstan nor in the CIS countries.

3. In conclusion, the following diagrams are presented for each tested pile and each pair of test tubes:

• diagram of the dependence of the signal peak function on the depth;

• calculated pulse first arrival time (FAT) as a function of depth;

• calculated relative pulse energy as a function of depth.

Analysis of the test pile in the PDI-TOMO programme with geometric sections of the pile along its length and three-dimensional display of the pile with defects, if any.

The following data were obtained from the test results: defects due to various problems, as well as poor concrete quality (design strength is not possible), non-compliance with production technology or soil penetration into the concrete injected into the bored shaft. The condition of the soil at the construction site affects the test data. The cross-hole Sonic Logging method is the most accurate and qualitative test for field observation of deep pile foundations.

The defect zones, if present in the pile under test, are shown in the above diagrams and described in the text of the report. The defect zones are identified by an increased first impulse arrival time (FAT) of more than 20 %, depending on the first impulse arrival time in a nearby zone with normal concrete quality, and the pulse energy and sound wave velocity are reduced in the defect zone.

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Received August 28, 2024.
Adopted in revised form on September 20, 2024.
Approved for publication on September 25, 2024.

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The authors declare that there is no conflict of interest.

Поступила в редакцию 28 августа 2024 г.
Принята в доработанном виде 20 сентября 2024 г.
Одобрена для публикации 25 сентября 2024 г.

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Авторы заявляют об отсутствии конфликта интересов.