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Peculiarities of Complex Engineering-geological Surveys on Subsidence Soil

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Abstract. *Paper presents the current problem of road construction on complex soils, the complexity of which lies in their subsidence properties. Insufficient study of soil conditions, in turn, poor preparation of subsidence ground bases during road construction, leads to a decrease in the quality of roads and a reduction in their service life. In order to prevent the consequences caused by these soils, it is necessary to carry out a comprehensive study. The object under consideration (ring road) is located in Almaty, Kazakhstan. According to engineering and geological surveys, the designed site has subsidence. Presented the methodology of field testing of soils, the results of static load tests of the bearing capacity of soil by piles, the results of testing the piles for integrity by the non-destructive vibroacoustic method. These studies are conducted in difficult soil conditions, which provides a high accuracy in determining the characteristics of the soil. The expediency of the selected measures is discussed, taking into account the results of the study and the peculiarities of the construction site.*

Keywords: *collapsing soil, physical and mechanical properties, reliability, static load test, PIT, design, bearing capacity, load, measure, road, pile, method.*

Introduction

Engineering-geological surveys are part of engineering surveys performed to prepare design documentation of the construction operation of buildings and structures. Construction engineering surveys include a comprehensive study of the condition of the territory of objects under construction [1-3].

As a result of conducting engineering-geological surveys, data on such undesirable properties of soil as subsidence. Soil subsidence arises as a result of soaking under a constant external load and the load from its own weight, which can give uneven settlements that can subsequently lead to the partial or complete destruction of buildings and structures [4-6].

In this regard, the need to study soils' deformation and strength properties and the construction of engineering structures on them today is an important and pressing issue. During engineering-geological surveys laboratory and field soil tests are used. Modern methods of field studies of soils, such as static, dynamic, drilling sounding allow obtaining continuous information on physical and mechanical properties of soils in depth [7-10]. Information systems for data transmission and processing, information and measurement systems that allow obtaining data at the construction site at once, one of which is the pile integrity testing, have also become widespread. The world's best practices testify to the importance of this type of work [11-13]. And comprehensive approach to geotechnical surveys allows ensuring the design reliability of the structure.

Materials and Methods

The projected road section with a length of 9.3 km is in the territory of Karasai and Iliysk districts of Almaty region (Figure 1).

In geomorphological terms, the construction site is located within the foothill sloping plain extending northward from the foothills of the Zailiisky Alatau.

The relief was formed as a result of debris flows and active river water activity and is a weakly hilly plain with river valleys, which are observed remnants of I and II above floodplain terraces.

In terms of hydrography, the researched site is located in the interfluve of the Kaskelen and Talgar rivers, crossing the Kargaly river.

The area's geological structure involves loose quaternary sediments deposited on bedrock rocks of the Paleozoic age.

Loess rocks of various ages and genesis lie in

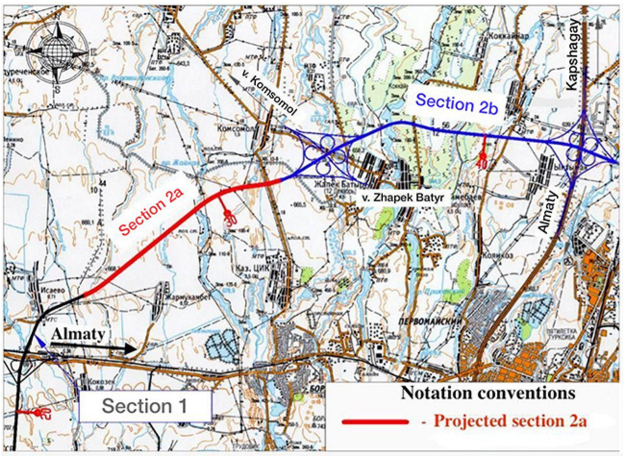

Figure 1 – Site location

patches on flat gentle slopes within the middle mountains, covering up to quaternary sediments with a thin thickness (up to 4-5 m). The loess rocks are dusty, pale-yellow, brown, and visible macropores. In some areas, the rocks have subsidence. Within the lowlands, the loess sequence lies on boulder and pebble deposits. Suffosion and subsidence processes are observed in loess strata containing a significant percentage of water-soluble salts.

To detail the geological-lithological section at the construction site were passed two exploratory wells to a depth of 25.0 m in each.

The following engineering-geological elements (EGE) were identified (Table 1):

- EGE – 2a – Semi-solid loam;

These soils have collapsible properties. The initial subsidence pressure is 0.636 – >3.0 kg/cm^2. The subsidence from its own weight does not exceed 5 cm. The type of ground conditions on subsidence is I (first).

- EGE – 2b – Tight plastic loam;
- EGE – 2v – Soft plastic loam;
- EGE – 4b – Fine water-saturated sand;
- EGE – 4v – Medium coarse water-saturated sand;
- EGE – 4g – Coarse water-saturated sand;
- EGE – 5b – Pebble soil water-saturated;

The groundwater was opened at a depth of 5.5-5.8 m and established at a depth of 4.0-4.1 m.

Normative and calculated values of the intercept cohesion (kPa), the angle of internal friction (deg), and the modulus of deformation (MPa) are shown in Table 2.

The calculated values of the characteristics are given, considering the coefficient of reliability on the ground.

The physical and geological processes and phenomena in the projected site are predicted erosion, seismicity of the area, salinization, frost swelling, subsidence.

When designing structures on subsidence soils, it is necessary to consider the possibility of increasing their moisture content due to soil soaking from external sources (rainwater, meltwater) from above. Taking this into account, it was to provide a set of measures, including the elimination of subsidence properties (water protection and structural measures).

Static load test was conducted to determine the bearing capacity and deformability of the pile on the ground and to determine the dependence of pile movement in the ground on the load [14]. For the tests, the bored pile No. 3 was identified as part of the foundations of the bridge support No. 3.

Control tests of pile bearing capacity with static

Table 1 – Physical and mechanical properties of soils

Parameter name	№						
	EGE-2a	EGE-2b	EGE-2v	EGE-4b	EGE-4v	EGE-4g	EGE-5b
Liquid limit, %	27.4	27.2	26.7	-	-	-	-
Plastic limit, %	17.8	17.9	17.7	-	-	-	-
Plasticity index, %	9.6	9.3	9.0	-	-	-	-
Index of liquidity, %	<0	0.33	0.56	-	-	-	-
Natural humidity, %	15.1	21.0	22.8	18.6	17.9	17.7	17.2
Soil particles density, g/sm^3	2.71	2.71	2.71	2.62	2.65	2.64	2.67
Soil density, g/sm^3	1.78	1.98	2.03	1.95	1.97	1.97	2.02
Dry soil density, g/sm^3	1.55	1.64	1.65	1.64	1.67	1.68	1.72
Void ratio	0.754	0.652	0.642	0.593	0.586	0.571	0.549
Degree of humidity	0.54	0.87	0.96	0.82	0.81	0.82	0.83
Coefficient of permeability, m/d	-	-	-	0.6	7.4	-	-
The natural angle of slope in the dry state, deg.	-	-	-	30	32	38	41
The natural angle of slope at water-saturated state, deg.	-	-	-	22	22	35	39
Soil resistance, kPa	334.2	191.6	98	147	245	343	980

load included: partial stripping of the working reinforcement of the anchored piles to attach to the stripped support of the power stand structures; manufacture, installation, and attachment of the anchoring device to the anchored piles; installing the loading device on the head of the pile to be tested, adjusting and aligning the position relative to the axis of the pilot pile and connecting the hydraulic power unit (Figure 2); setting and fixing the measuring equipment and instruments at the test points; testing the performance of the test system by test loading in the range 15-20% of the full load; testing by stage-by-stage control loading of the tested pile; control of settlement indicators and ground deformation by taking readings of recording devices; control of test load, according to pressure readings in the hydraulic system; obtaining and processing of test materials.

During the tests, to create a load force on the head of the pile being tested load-bearing equipment (power stand made of inventory structures, jack DG200P250, hydraulic pump, high-pressure hose system) and test recording devices (6PAO-0.01 deflectometer, 6PAO-0.1 deflectometer, WIKA manometer) was used. Types of equipment ate presented in Figure 3.

The design value of the load applied on the pile head is determined by the structure's design. The load safety factor for this test is defined as 1.5.

The maximum load on the tested pile was 239.0 Tf (the 9th stage of load application).

The tested pile was loaded evenly, without shocks,

Table 2 – Normative and calculated values of soil characteristics

№ EGE	Unit weight of soil, kN/m3			Intercept cohesion, kPa			Angle of internal friction, deg.			Modulus of deformation, MPa
	norm	PII	PI	norm	CII	CI	norm	γII	γI	
2a	17.8	17.8	16.9	25.0 / 20.0*	25.0 / 20.0*	23.0 / 18.0*	22.7 / 17.6*	22.7 / 17.6*	21.7 / 16.2*	26.6** / 19.2*
2b	19.8	19.8	19.7	27.0	27.0	26.0	21.8	21.8	21.5	28.5** / 26.7*
2v	20.3	20.3	20.1	26.0	26.0	24.0	18.9	18.9	18.5	26.8** / 20.6*
4b	19.5	19.5	19.3	4.0 / 1.0*	4.0 / 1.0*	2.6 / 0.7	30 / 22*	30 / 22*	27.3 / 20*	38.0 / 22.0*
4v	19.7	19.7	19.5	1.0	1.0	0.7	32 / 21*	32 / 21*	29 / 19.1*	30.0 / 25.0*
4g	19.7	19.7	19.5	1.0	1.0	0.7	38 / 35*	38 / 35*	34.5 / 31.8*	30.0
5b	20.2	20.2	20.0	1.0	1.0	0.7	41 / 39*	41 / 39*	37.2 / 35.4*	40.0

* – the denominator shows the characteristics of soils in the water-saturated state
** – modulus of deformation is given without taking into account the scale factor coefficient

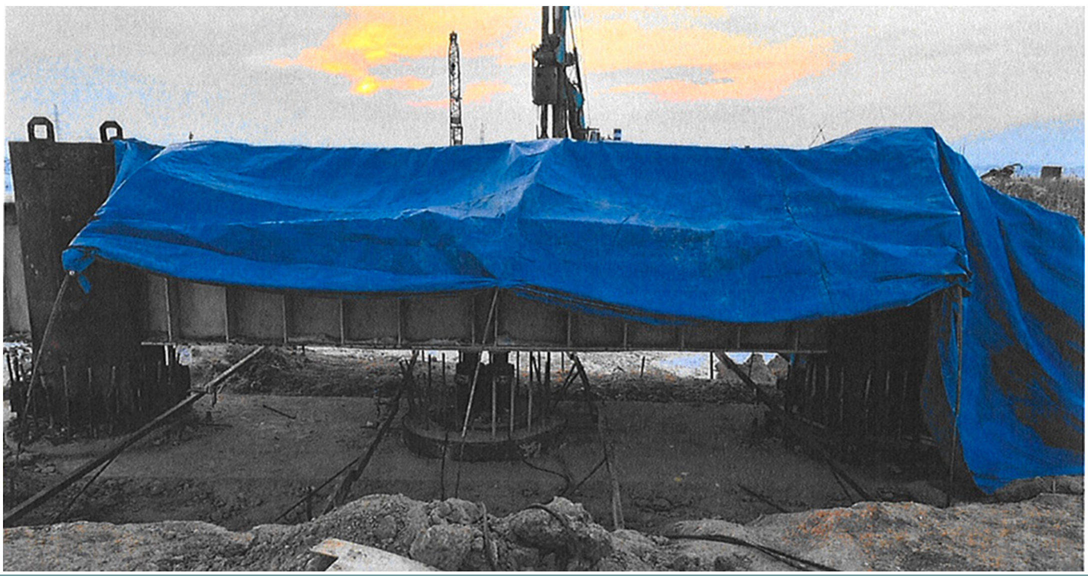

Figure 2 – General view of support No. 3 prepared for the test work

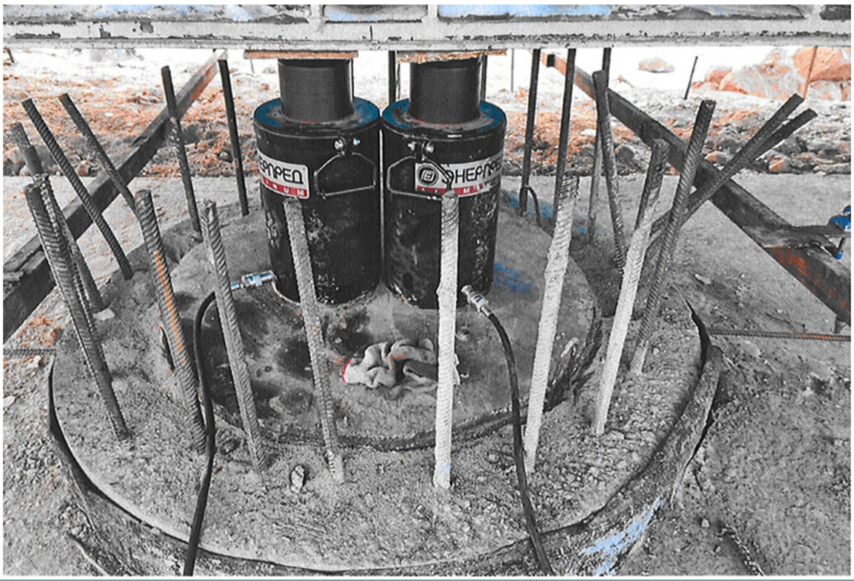

Figure 3 – Loading device with hydraulic jacks, girder system with anchored piles

in load steps, the value of which was not more than 1/10 of its estimated carrying capacity.

The force generated by the jacks on the first load stage was 27.0 Tf, with each successive load stage having an increase of 26.0 Tf.

At each stage of pile loading, readings were taken on all instruments, the first hour at 15-min intervals, then at 30-min intervals until the pile movement (settlement) decays, called its conditional stabilization. Conditional stabilization of pile settlement was accepted as no more than 0.1 mm for the last 60 min of observations at the given loading stage.

Zero readouts from the instruments were taken before the pile was loaded. The first reading was taken immediately after the load was applied.

The holding time of each stage, from the first to the eighth, under the pressurizing loads was 120 min for each stage.

At the ninth stage, the holding time was 210 min.

The maximum displacement of the pile when reaching the ninth stage of loading, when averaging the values of the control devices of the deflectometer when reaching the load – 239.0 Tf, at the 9th stage of loading on the tested pile was 1.48 mm.

Non-destructive vibroacoustic method, express control of pile integrity (continuity), is based on the principle of acoustic defectoscopy analysis of the passage and reflection in the studied structure of the acoustic wave, which is initiated by a calibrated impact on the pile head [15-16].

For test objects of control, excitation of waves is carried out by striking, with specialized equipment (hammer) with rubberized sides (of different softness). A vibration detector performs fixation of the bounced waves.

The number of sensors to be installed and their location and impact locations are set for each pile separately, based on local conditions. Sensors for several control points are used (at least 3 for each pile) to increase the reliability.

The sensor-accelerometer, depending on the design features of the object, conditions of access to the pile, as well as the design of the sensor itself, was installed on the pile head.

At the first stage, a series of impacts was applied, and at the second stage, the speed of the acoustic wave propagation of the rod in the concrete of the pile was determined. The average speed is in the range of 3600-4100 m/s, the third stage – cameral processing.

Sensor No.1 is a single-axis accelerometer with a wireless communication channel.

Sensor No.2 is an accelerometer of a similar type in a wired version, designed for installation on the lateral surface of the element.

A diamond nozzle angle grinder performed preparation of areas for the installation of the sensor and excitation of elastic vibrations on the pile head.

Cleaning the side surface of the piles to install the second sensor was carried out with the help of an angle grinder with a cord brush.

The installation of the sensors was carried out by means of adhesive. The general view of the tested piles is shown in Figure 4.

The primary processing of the digitized signals was performed in the «SPEKTR-4.3» software version 2020. This software package is universal and can solve several tasks of temporal amplitude analysis of oscillatory systems.

In the program, it is possible to measure the velocity in the time domain, integrate each signal, and perform filtering. A 6th order low-pass filter performs integration with a cut-off frequency of 0.1 of the sampling frequency.

Knowing the expected pile length (boundary conditions), the time area where the signal reflection was detected was determined. Timestamps are set on the graph, based on which the calculation of the pile

Figure 4 – General view of the tested piles

length is made.

Then the signals in the spectral domain were examined to determine the signals of anomalous spectrum changes.

After the primary processing, the detailed processing was performed in the specialized software «SPEKTR-2/SPEKTR-3» version 1.0.01.

Results and Discussion

The static pile test with indentation loads showed that the pile deformation stabilization was detected at the ninth load step with an indentation load of 239.0 Tf (which exceeds the design load with a reliability factor of 1.35), with an average settlement of 1.48 mm as measured by the last averaged test instrument measurement.

If these conditions arise, the ultimate resistance Fu of the pile under indentation loads, according to the results of the conducted tests, should be taken as a load of 239.0 Tf.

The test results showed that the bearing capacity of pile No. 3 on supporting the ground is sufficient to withstand the maximum design indentation load (Figures 5-6).

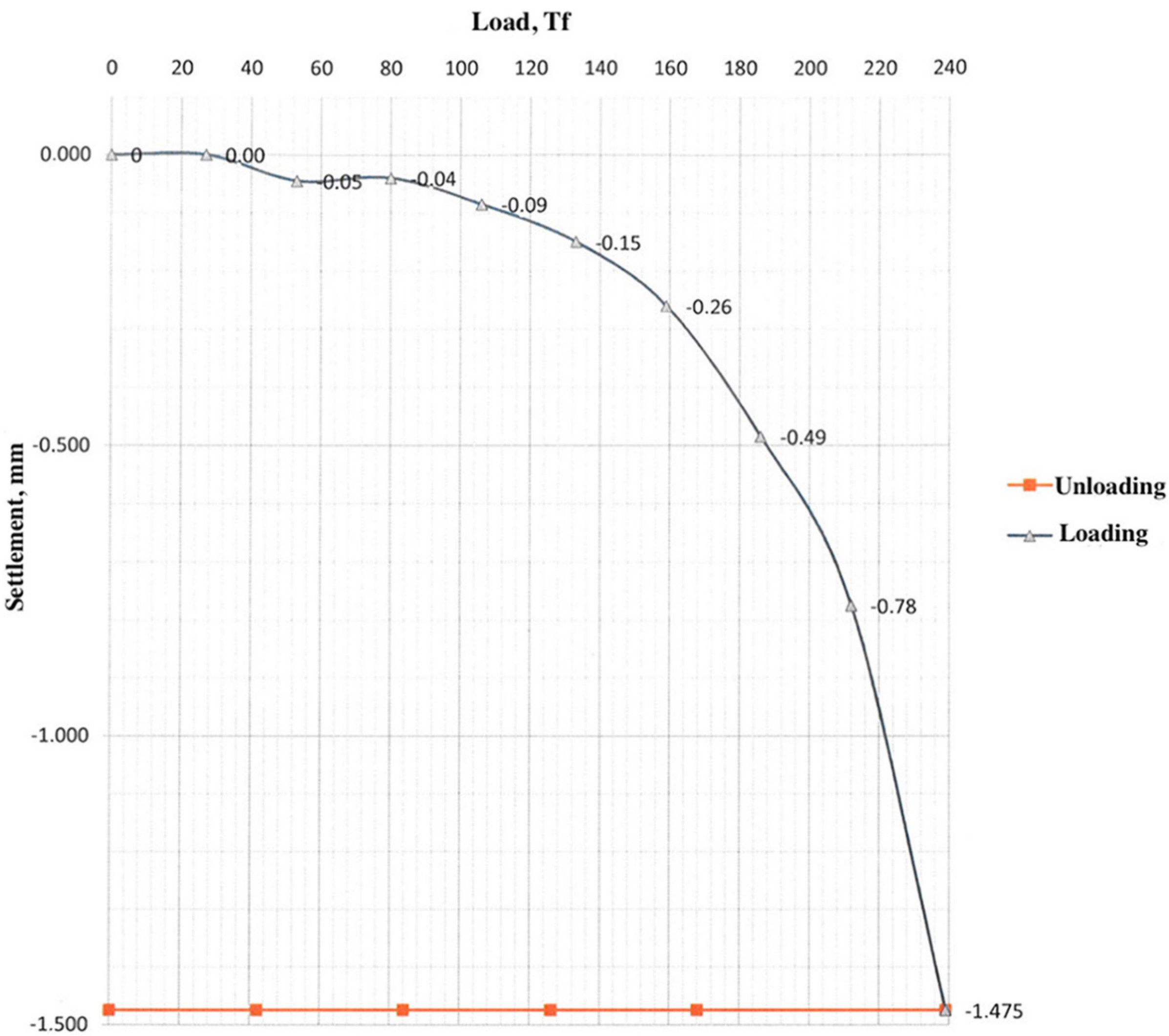

Figure 5 – Graph of total pile settlement results for all test phases

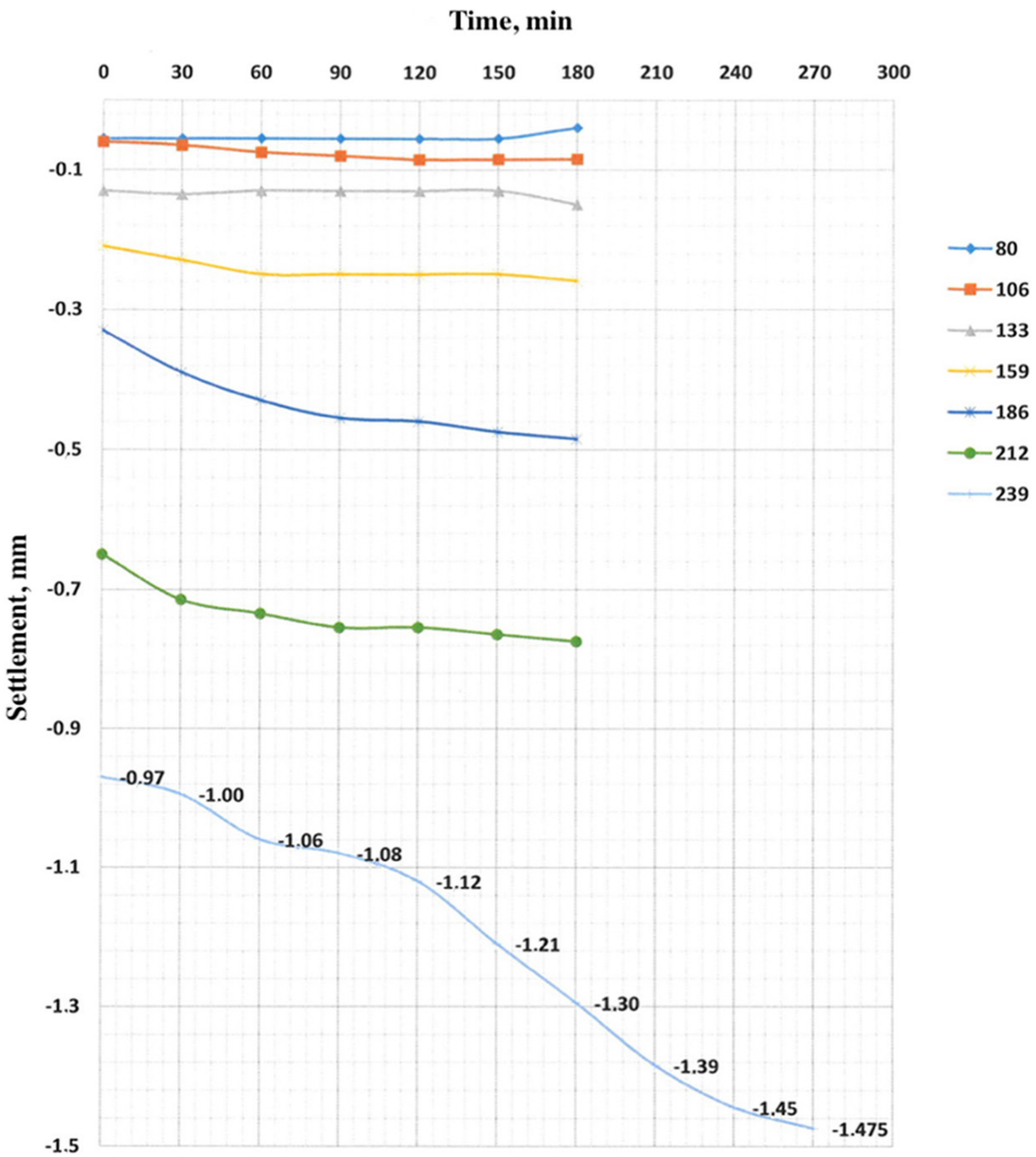

Figure 6 – Diagram of the results of pile settlement by loading stages

According to the results of testing of 10 bored piles of support No.1 at the «Bridge» site, after processing and interpretation of the obtained spectrograms (reflectograms of responses) for the 10 tested piles, no significant changes in the pile cross-section downward were detected. Zones of discontinuity and decompaction of concrete in the section of the bored pile were not detected. Stable signals from different soil layers and non-systematic «acoustic» roughness are observed. The test results of the 10 piles are shown in Table 3 and Figures 7-10.

Table 3 – Results of pile length measurements

Pile No.	Pile length, m	Test result
1	21.4	satisfactorily
2	21.6	satisfactorily
3	21.0	satisfactorily
4	21.3	satisfactorily
5	21.6	satisfactorily
6	21.6	satisfactorily
7	21.0	satisfactorily
8	21.6	satisfactorily
9	21.3	satisfactorily
10	21.5	satisfactorily

Conclusion

Construction of roads with consideration of subsidence deformations leads to an inevitable increase in construction costs, but at the same time, the cost of road maintenance in subsequent years is reduced because it is the design for safe operation that is the most important factor. The complex investigation allowed to take into account complex conditions of the designed section. The following conclusions can be made in the course of the research work:

1. The physical and geological processes and phenomena in the projected site are predicted erosion, seismicity of the area, salinization, frost swelling, subsidence;

2. When designing structures on subsidence soils, it is necessary to consider the possibility of increasing their moisture content due to soil soaking from external sources (rainwater, meltwater) from above. Taking this into account, it was to provide a set of measures, including the elimination of subsidence properties (water protection and structural measures);

3. Satisfactory results were obtained from the static and integrity tests. The latter allowed us to check the homogeneity of the piles and identify the possibility of hidden defects.

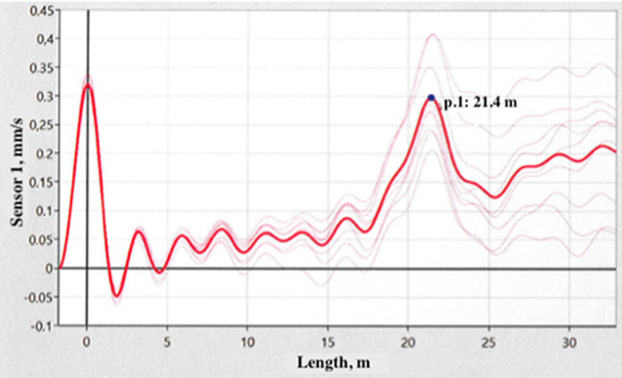

Figure 7 – Analysis of the wave passing through the body of pile No. 1

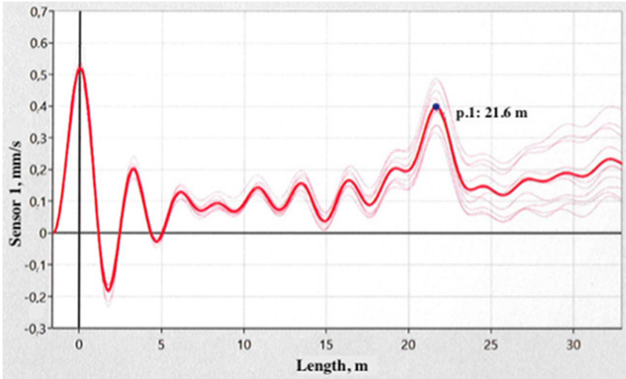

Figure 8 – Analysis of the wave passing through the body of pile No. 2

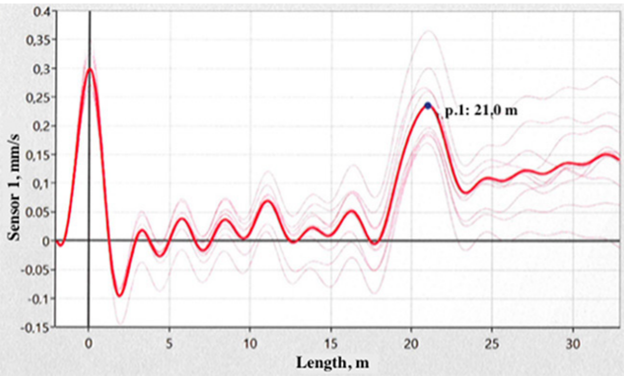

Figure 9 – Analysis of the wave passing through the body of pile No. 3

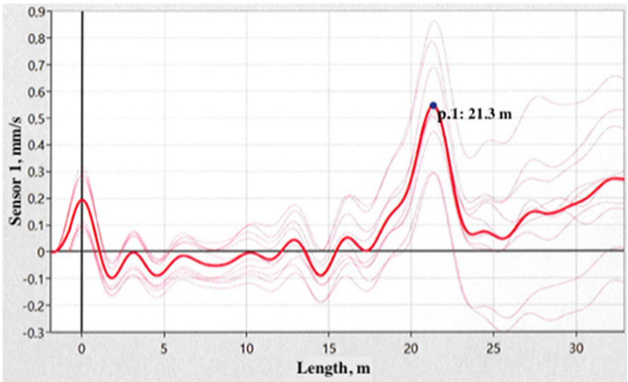

Figure 10 – Analysis of the wave passing through the body of pile No. 4

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Шөгінді топырақтардағы кешенді инженерлік-геологиялық ізденістердің ерекшеліктері

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Аңдатпа. *Күрделі топырақтарда жол салудың қазіргі кездегі өзекті мәселесі ұсынылған. Бұл топырақтардың күрделілігі олардың шөгу қасиеттерінде жатыр. Топырақ жағдайларын жеткіліксіз зерттеу, өз кезегінде, жол салу кезінде шөгетін топырақ негіздерін сапасыз дайындау – жол сапасының төмендеуі мен олардың пайдаланылу мерзімінің қысқаруына әкеледі. Осы топырақтардан туындаған салдардың алдын алу үшін кешенді зерттеулер жүргізу қажет. Қарастырылып отырған нысан (айналма автомобиль жолы) Алматы қаласында орналасқан (Қазақстан). Инженерлік-геологиялық ізденістерге сәйкес, жобаланатын учаскенің шөгуі бар. Топырақты далалық сынау әдістемесі, топырақтың көтергіш қабілетін қадалармен статикалық сынау нәтижелері, қадаларды бұзбайтын виброакустикалық әдіспен тұтастығын сынау нәтижелері ұсынылған. Күрделі топырақ жағдайларында жүргізілетін бұл зерттеулер топырақтың сипаттамаларын анықтаудың жоғары дәлдігін қамтамасыз етеді. Зерттеу нәтижелері мен құрылыс алаңының жағдайларын ескере отырып, таңдалған іс-шаралардың орындылығы талқыланып келтірілген.*

Кілт сөздер: *шөгінді топырақ, физика-механикалық қасиеттер, сенімділік, статикалық жүктемемен сынау, қадалардың тұтастығын сынау, жобалау, көтергіш қабілеттілік, жүктеме, өлшеу, жол, қада, әдіс.*

Особенности комплексных инженерно-геологических изысканий на просадочных грунтах

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Аннотация. *В работе представлена актуальная на сегодняшний день проблема строительства дорог на сложных грунтах, сложность которых заключается в их просадочных свойствах. Недостаточное исследование грунтовых условий, в свою очередь, некачественная подготовка просадочных грунтовых оснований при строительстве дорог приводят к снижению как качества дорог, так и сокращению срока их эксплуатации. Для того чтобы предотвратить последствия, вызываемые данными грунтами необходимо проводить комплексные исследования. Рассматриваемый объект (кольцевая автомобильная дорога) расположен в г. Алматы, Казахстан. Согласно инженерно-геологическим изысканиям проектируемый участок имеет просадочность. Представлена методика полевых испытаний грунтов, результаты статических испытаний несущей способности грунта сваями, результаты тестирования свай на сплошность неразрушающим виброакустическим методом. Эти исследования проводятся в сложных грунтовых условиях, что обеспечивает высокую точность определения характеристик почвы. Приведено обсуждение целесообразности выбранных мероприятий с учетом полученных результатов исследования и условий строительной площадки.*

Ключевые слова: *просадочный грунт, физико-механические свойства, надежность, испытание статической нагрузкой, испытание свай на сплошность, проектирование, несущая способность, нагрузка, измерение, дорога, свая, метод.*

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