Diagnostics of condition of soil lying in the foundation of sewer collectors and metro tunnels by crosshole sounding method in urban underground space

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Abstract. Non-destructive geophysical crosshole sounding method can be used to control and monitoring the condition of natural and improved soils. This work studies the application of the crosshole sounding method to determine the condition of soils lying in the foundations of sewer collectors and tunnels. The investigation uses crosshole sounding apparatus APZ-1 developed by LLC “Geodiagnostika”. The study considered the results of crosshole sounding of soils at the site of the reconstruction of the Church of The Icon of the Mother of God “Joy of All Who Sorrow” and on the section of buried metro tunnels between “Lesnaya” and “Ploschad Muzhestva” stations in St. Petersburg (Russia). The author postulates that crosshole sounding provides the most accurate information about the foundation soils for making a decision on strengthening them for trouble-free operation of sewer collectors and tunnels.

Introduction

The conditions of underground construction in St. Petersburg (until 1991, Leningrad) are unique in the large volume of unstable soft soils occurring at depths of up to 100 meters below ground surface. The risks of the construction and operation of underground structures in soft saturated soils are associated with various construction incidents including disruption of the continuity of fences, breakthroughs of groundwater into the workings areas, decompaction of the soils of the bases. An huge accident occurred in St. Petersburg in 1995 between the metro stations “Lesnaya” and “Ploschad Muzhestva”, after which sections of the tunnels were flooded.

The urgency of the problem of control and monitoring conditions of soils, slurry walls, jet grouting and frozen ground and grout curtains in the underground space is determined by the requirements of accident-free policies for underground works as well as maintaining safety of buildings during their operations and service life. Since 1955 All-Russian Scientific Research Institute of exploration methods (VITR), and then from 2006 LLC “Geodiagnostika” (www.geodiagnostics.ru) investigated the relationship between the parameters of elastic waves distribution in soils and had performed tests to investigate continuity of different ground improvement measures including ground freezing and various types of grouting (jet grouting, compaction grouting, etc.) for purpose of ensuring their effectiveness. Results of the study had been used as a basis development of new control and monitoring technologies of the condition of natural and improved soils by geophysical crosshole sounding method.

The aim of research was to obtain the dependencies between the parameters of elastic waves and modulus of elasticity (deformation) of soil. The ultimate objective the research is arriving at the creation
the table of diagnostic characteristics to determine the condition of the soils at the foundations of sewer collectors and tunnels by crosshole sounding.

**1. Physical backgrounds of crosshole sounding method**
Soils (rocks) are different in their physical and mechanical properties. Elastic wave parameters (speed, sound pressure and spectrum) depend on properties of the environment they propagated in. Changing parameters of elastic waves during crosshole sounding is a physical background for determining the condition of natural and improved soils using grouting methods, jet-grouting, spoil freezing, etc. [1-4]. A lot of researches were carried out earlier proving a correlation between elastic wave parameters and strength and elasticity of materials [5-7].

Tunnels and sewer collectors are a “foreign” body embedded in the soil massif. Propagation of elastic waves in soil mass is defined by general acoustic rules. If there is a different body in the path of the elastic wave in the tested soil mass, then an “acoustic shadow” is observed in the form of a sharp decrease of speed, sound pressure and frequency of the elastic wave impulse. The physics of the acoustic shadow phenomenon is based on reflection of the elastic wave on the boundary between the tunnel surface and the soil mass and on the elastic wave’s rounding (diffraction) from the obstacle with extension of its propagation path. The occurrence of the “acoustic shadow” phenomenon when sounding between two holes is a physical background for determining the location of underground tunnels.

**2. Methodology for crosshole sounding from holes or embedded pipes**
The author has been working on developing a new scientific field “Seismoacoustic diagnostics of the condition of man-made and natural soil massifs” that considers soils and artificial objects arranged in the underground space (tunnels, fences, piles) as an object of diagnosis and elastic waves transmitted through or reflected from an object as carriers of a diagnostic information [2].

Research methods included crosshole sounding from observation holes drilled on both sides of sewer collector or tunnels and comparison of measured parameters of elastic wave with a table of diagnostic indications of different soil conditions (Figure 1). The distance between the observation holes was 10 – 50 m.

**Figure 1.** Scheme of study of soils in the base of the sewer collector by crosshole sounding method
1 — soil massif; 2 — sewer collector; 3, 11 — observation holes; 4 — downhole radiator of elastic waves; 5, 9 — cables; 6, 8 — cable guide roller; 7 — crosshole sounding apparatus APZ-1; 10 — downhole receiver of elastic waves; 12 — sound ray.
Diagnostic parameters showing the condition of materials are the speed of elastic wave (arrival time), the acoustic pressure range and the elastic wave pulse spectrum (Figure 2). The spectrum is calculated in a digital signal processing program using the fast Fourier transform (FFT) method. The FFT parameters are selected based on the recording parameters. The speed of the longitudinal elastic wave is the key diagnostic parameter. Additional advantages of the crosshole testing method are the following: a possibility to implement crosshole tomography due to the higher number of differently directed rays passing through the crosshole area.

![Figure 2. Diagnostic parameters of the crosshole sounding method](image)

At present, author has accumulated a fairly large amount of production data on the change in the parameters of an elastic wave during propagation in natural and artificial soils [1, 4]. The state of the soil is characterized by a certain combination of parameters (diagnostic feature) of the elastic wave impulse, which makes it possible to accurately diagnose the location of the soil in the section.

An increase in the speed of an elastic wave indicates a decrease in the plasticity of sandy-clayey soils (in the direction from fluid to solid) and an increase in the strength of artificial soils. The shift of the spectrum towards high frequencies indicates the presence of water saturation in sandy soils and an increase in fluidity and thixotropy of sandy-clayey soils (sandy loam, loam, clay). The decrease in the amplitude of the elastic wave is associated with the attenuation of the elastic wave and is caused by inhomogeneity, decompaction, porosity, lack of groundwater or stratification of soils.

3. Geophysical equipment

The studies used pulsed acoustic crosshole sounding apparatus APZ-1 (developer LLC "Geodiagnostika", Russia) with cable electric spark source of elastic wave [1].

Apparatus APZ-1 (Figure 3) is designed for measuring propagation time, amplitude and impulse frequency of elastic waves in formations between the source and receiver to determine elasticity characteristics of the area. The equipment received a metrological calibration certificate from the All-Russian Research Institute of Metrology named after D. I. Mendeleev (St. Petersburg). Basic relative error of time measurement is + 3 %.

Operation principle of hardware system consists of acoustic wave emitting, receiving impulse upon passing through the area (concrete, soil, soil-cement, etc.), registration of impulse on PC hard drive, measuring impulse parameters by the operator, processing the observation results and assessment of the state of propagation area according to impulse parameters. For excitation of elastic wave impulse, the sender enables the current impulse generator, cable and electric spark source by electrohydraulic shock.
The metering system consists of receivers of elastic waves, cables and PC based set of hardware and software tools. Software consists of WINDOWS Operational System, command mode software and WinPOS digital signals processing program. There can be additional software programs for digital processing of these measurements, including tomographic image of cross-hole space.

![Crosshole sounding apparatus APZ-1](image)

**Figure 3.** Crosshole sounding apparatus APZ-1
1 — cable with the electric spark radiator; 2 — current pulse generator; 3 — complex of software and hardware; 4 — downhole receiver cable; 5 — downhole receiver of elastic waves

Borehole devices are operating together with logging hoist equipped with cable or directly from the cables at shallow depth. The pulse repetition rate is 0.1-0.3 Hz. The sound pressure near the electric spark emitter of elastic waves reaches several MPa. The frequency range of the elastic wave impulse is 1-20000 Hz and higher. The minimum size of detected defects is 0.5 m.

The maximum sounding distance no less 100 m is achieved in hard monolithic rocks such as granite, silicified sandstone and quartzite.

4. Research results

4.1. The results of crosshole sounding of soils at the site of the reconstruction of the Church of The Icon of the Mother of God “Joy of All Who Sorrow”

The Church of The Icon of the Mother of God “Joy of All Who Sorrow” was built in St. Petersburg in the period 1893-1896. In 1933 the church was blown up and dismantled. On the site of the church, only the basement and the foundation had survived. In 2016, the reconstruction of the church began.

The problem of the construction of the new church building was the sewer collector, laid under the foundation of the church in 1973. To develop a design solution to strengthen the foundation of the church, it was necessary to examine the soils under the collector. Due to the presence of the collector and the foundation, it was impossible to take soil samples under the collector by drilling. To obtain information on the condition and deformations modulus of soil at the base of the collector in 2016, the crosshole sounding method was used.

Crosshole sounding was carried out between observation holes 1, 2, 3, 4 and 5, drilled from the ground surface to a depth of 15 m (Figure 4). The holes were encased with steel pipes and filled with technical water. The measuring interval via transducers along the hole was 0.5 - 1 m.
Figure 4. Crosshole sounding schemes of underground space at the site of the reconstruction of the Church of The Icon of the Mother of God “Joy of All Who Sorrow” in the horizontal plane (a) and in the vertical planes crossing (b, c, d) and not crossing (e) the sewer collector and church foundation

1, 2, 3, 4, 5 – observation holes; 6 – sounding direction; 7 – sewer collector; 8 – old church foundation

The sewer collector was found in the depth interval of 6 - 8 m by a sharp decrease in the speed of elastic wave and an increase in low frequency acoustic noise from the flow of sewage (Figure 5 and 6).

Figure 5. Oscillogram (a) and spectrum (b) of the elastic wave impulse recorded at a depth of 7 m with crosshole sounding between holes 4 and 5, distance 30.1 m
The geological section at the church construction site is divided by depth into the following parts according to the complex of seismoacoustic features (Figure 6):

- **0 - 4 m**: Not dense bulk soils (speed of elastic wave 749 - 1562 m/s).
- **4 - 12.5 m**: Loam from fluid to soft-plastic and plastic consistency (speed of elastic wave 1573-1737 m/s).
- **12.5 - 15 m**: Loam from plastic to hard-plastic consistency (speed of elastic wave 1743-1842 m/s).

The groundwater level is at a depth of 3 m.

**Figure 6.** The relationships between the speed of elastic wave and depth at the site of the reconstruction of the Church of The Icon of the Mother of God “Joy of All Who Sorrow” in St. Petersburg.

1 – in the vertical plane crossing soil massif (between holes 1 and 4); 2 – in the vertical plane crossing the old church foundation, sewer collector and soil massif (between holes 4 and 5); 3 – in vertical plane crossing the old church foundation and soil massif (between holes 3 and 5).

The depth of the preserved underground part of the church (basements and foundation) was determined at a depth of 5.5 m (Figure 6). The structure of the soil massif is the same over the entire area of the investigated site (under the collector and the foundation of the church). At the base of the collector and the foundation of the church there are weak soils (loams of predominantly soft-plastic consistency). No signs of disturbance in the natural composition of soils in the depth interval of 8.5 - 15 m were found. Soil with increased bearing capacity (hard-plastic loam) occurs in the interval of 12.5-15 m.
To study the relationship between the speed of elastic wave and the modulus of elasticity of soils, we used the data of laboratory studies of soils from the construction sites of mine shafts of the metro and sewage system in St. Petersburg, where crosshole sounding was carried out. The experimental calibration dependence "speed of elastic wave $v$ (m/s) - elastic modulus $E$ (MPa)" was approximated by a function of the form:

$$E = 0.025 \times v - 33.1 \quad \text{MPa.}$$

The calculated modulus of elasticity of soft loam at the base of the sewer collector is 6.2 MPa, plastic loam - 10.3 MPa, hard-plastic loam - 13 MPa.

4.2. Results of investigation of the geological structure and position of the buried tunnels on the section between "Lesnaya" and "Ploschad Muzhestva" metro stations

In St. Petersburg, near the square named "Ploschad Muzhestva" in the underground space, there are two buried metro tunnels. Tunnels with a diameter of 6 m were laid in 1974-1975 across the valley of the ancient bed of the river Neva and exploited for 20 years. In December 1995, the tunnel sections between “Lesnaya” and “Ploschad Muzhestva” stations were disconnected from the rest of the metro network and forcibly filled with water after sand and water penetrated inside the tunnels. In 2012, Geodiagnostika LLC performed crosshole sounding to determine the state of the soil and the position of the buried tunnels (Figure 7).

![Figure 7](image_url)

**Figure 7.** The relationship between the speed of elastic wave and depth in vertical planes crossing (1) and not crossing (2) the buried tunnels at the section PK183 between “Lesnaya” and “Ploschad Muzhestva” metro stations in St. Petersburg
The position of the tunnels in the underground space is established on the basis of the physical phenomenon of the “acoustic shadow” by a sharp decrease in the speed of the elastic wave (Figure 7), sound pressure and vibration frequency along the sound rays crossing the tunnel. The upper buried tunnel is located in the depth interval 64 - 70 m. The lower buried tunnel is located in the depth interval 76 - 82 m. Depth measurement error is ± 1 m. In vertical planes that do not intersect the tunnels, the values of the speed of elastic wave, sound pressure and vibration frequency along the acoustic rays correspond to natural soils.

The geological section according to the complex of acoustic features is divided in depth into the following parts (Figure 7). The groundwater level is at a depth of 5 m. Water-resistant soil layers occur at depths of 22 – 26 m (layered loams) and 32 – 46 m (solid consistency loams). Water-resistant interlayers differ in characteristics. Loams in the depth interval of 22 - 26 m are characterized by lower values of speed, sound pressure and frequency of elastic wave, which indicates layering and, mainly, plastic consistency. Loams in the depth interval of 32-46 m are characterized by an increase in speed of elastic wave, a decrease in the sound pressure and frequency of elastic wave, which indicates mainly a hard-plastic consistency. Water-filled and fluid soils (sand and sandy loam) occur in the depth intervals of 5-22, 26-32 and 46-86 m and stand out at a relatively low speed at high values of sound pressure and frequency (5000-7000 Hz) of elastic wave.

It is very strange that the lower tunnel was built in water-bearing sands that appear not to have sufficient bearing capacity. One of the causes of the discontinuity in the tunnel walls and the penetration of fluid soils into the tunnels in 1995 could be a decrease in density in the soils in the base of the tunnels.

Conclusions
A result of research made the following conclusions
1. Crosshole sounding technology provides diagnostics the condition of soils lying in the foundation of sewer collectors and metro tunnels.
2. The main diagnostic parameters in crosshole sounding method for determining the type and condition of soils are speed, sound pressure and spectrum of elastic waves.
3. Monitoring of the condition of the soils of the foundations of sewer collectors and tunnels in the most critical sections by crosshole sounding from observation holes would allow assessment of potential soil improvement measures application as needed to ensure continuity of facility operations.

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