INTEGRATED SOLUTIONS IN STRUCTURAL STATE DIAGNOSTICS

Dr A Kirilenko & P Znajchenko
ZAO "Triada-Holding"
Scientific and Diagnostic Dept
Moscow
Russia

info@triadaholding.ru

Dr. V Kapustin,
Geophysical Dept
OOO "EngStrojIzyskanija"
Moscow
Russia

info@triadaholding.ru

KEYWORDS: Restoration, geophysical, rehabilitation, geo-radar, acoustic measurements.

ABSTRACT

Intensive restoration works of historic heritage buildings being performed in recent years in Russia need to be backed up by detailed construction documentation as well as reports on the current structural state.

It must be noted that – due to the "venerable age" of such buildings – quite often there is either no documentation at all or it must be specified in more detail which is a rather painstaking process.

Application of up-to-date geophysical and optical methods can be very effective in such situations.

The report contains a case history describing rehabilitation and restoration of an old bridge in one of the well-known historic park complexes in Moscow.

It describes in detail a combined application of geo-radar and acoustic measurements to investigate structural state of the bridge deck and abutments as well as to define foundation depth under the abutments. For this purpose special down-hole instruments were used. Rigid optical endoscopes were also used to define structural pattern and for structural state assessment.

The experience described could be useful to those engaged in structural state assessment and diagnostics.

INTRODUCTION

Restoring authentic appearance of historic heritage buildings according to modern techniques with modern materials requires detailed structural investigation and collecting full technical data. As a rule, original engineering documentation is missing.

Such tasks can be solved only when various inspection methods are used, both non-destructive and "invasive", i.e. interfering with structural integrity. Our experience in the field of historic heritage diagnostics shows that the most trustworthy results can be achieved only in case of integrated use of various methods.

EXAMPLE

A successful example of such an approach is our project "Tsaritsyno" which is one of the most beautiful parks in Moscow. This was planned to be a countryside residence of the Russian Empress Catherine II with a splendid palace surrounded by a spacious park. The construction started in 1776 but was stopped several years after because Catherine didn't like the palace. Since that time for almost 200 years it remained abandoned until the complete reconstruction and rebuilding works started in early 2000s.

By now the works have been finished, all the buildings and monuments being refurbished.

It must be said that one of the main attractions of the Tsaritsyno ensemble are the bridges which seem to blend skillfully with the surrounding hilly terrain. Several new bridges have been built at the main entrance to the park: they interconnect a number of picturesque ponds.

We inspected one of the oldest bridges in the park between the Upper and the Lower ponds. In old days it served not only as a bridge but also as a dam. That's why it is called the Tsaritsyno Dam. The bridge was built in the end of the XVIII century. It was made of bricks with lime mortar and dressed with limestone (called "white stone" at that time). Its piers and abutments were made of white stone too. During all the years that passed the bridge was reconstructed several times: from a 4-span bridge it was transformed into a 3-span one; a concrete dam was constructed with 3 gates for water passage and a downstream water inlet. At the time of the large-scale reconstruction of the whole complex the bridge was very close to an emergency state: brick arches deteriorated, stone cladding nearly damaged, many bricks missing, the brickwork detrimentally influenced by cyclic freezing-thawing.

As there was no documentation left from the time of construction we had to solve the following tasks:

- to find out the particular structural pattern of the piers, abutments, and bridge deck;
- to assess the actual structural state;
- to define the type and state of the foundation of the piers and abutments.

Our inspection involved both non-destructive methods and destructive techniques (such as drilling). Alongside with the traditional methods of flaw detection (such as ultrasonic, Schmidt hammer, testing machines) we also used acoustic probing, radar and endoscope.

Diagnostics of the foundations and underlying soil was accomplished with the help of geophysical surveying implying in-borehole measurements. Later all the results obtained by various techniques were processed and analyzed to increase data reliability.

The acoustic measurements were conducted in water-filled boreholes situated close to the bridge piers with the use of an elastic wave spark exciter "Sparker" (transmitter) and a single-channel acoustic system "GEONT_1_3" (receiver). The following measuring procedures were used:

- fixed position of the transmitter at the bottom of the borehole / continuous movement of the receiver along the borehole (potential logging);
- fixed position of both transmitter and receiver at the distance of 1 m / movement of the complete assembly along the borehole (differential logging);
- "inter-borehole" acoustic probing / parallel movement of the transmitter and the receiver.

Excitation of elastic waves was executed by an electric discharge of about 2kV coming from an excitation unit to electrodes located in boreholes filled with water. This is a brief description of the procedure. When the electric current runs off from an electrode, it warms up the surrounding liquid thus creating a cavity filled with vapor and gas. Acoustic waves originating during expanding/collapsing of the vapor-and-gas cavity move along the borehole in the form of pressure waves and hydro-waves. The rate of wave propagation depends on the strength of the surrounding soil. Hydro-waves are surface waves propagating along the borehole (their amplitude subsides exponentially from the borehole axis), that's why their propagation rate is determined mainly by the shearing behavior of the surrounding medium. The theory of elasticity [1] for linear-elastic waves of minor amplitude says that the rates of longitudinal and transverse wave propagation are related to the constants of elasticity in the following way:

$$V_p = \sqrt{E(1-\nu)\frac{1}{\rho(1+\nu)(1-2\nu)}} , \quad (1)$$

where E is E-modulus; ν is Poisson's ratio.

$$V_s = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2\rho(1+\nu)}} , \quad (2)$$

where μ is shear modulus; ρ is density.

The relationship $\frac{V_s}{V_p}=\sqrt{\frac{(1-2\nu)}{2(1-\nu)}}$ (3) in a uniform isotropic medium depends on the Poisson's ratio only.

The rate of hydro-wave propagation is mainly determined by the dynamic shearing modulus:

$$V_g=\frac{C_0}{\sqrt{1+\frac{\rho_0 c_0^2}{\mu}}}, \quad (4)$$

where ρ_0 is density of a borehole solution; C_0 is sound speed in a liquid medium.

The rate of transverse wave propagation can be defined from the following equation

$$V_s=C_0V_g\sqrt{\frac{\rho_0}{\rho(C_0^2-V_g^2)}}, \quad (5)$$

Thus, when the rates of longitudinal, transverse, and hydro-wave propagation are defined and the density is known the values of the basic dynamic constants E, μ, and ν can be obtained.

When the measurements were executed according to the potential logging procedure, close to the point of vertical interface (bridge pier) at $V_{pier}>V_{medium}$ refracted waves gliding along the bridge pier border were registered in first events (Fig.1), whereas in subsequent events we registered direct spatial waves and hydro-waves propagating in the surrounding medium.

When the measurements were conducted in accordance with the differential logging procedure provided that $d<X_0$ (where d is the distance between the exciter and the receiver; X_0 is an x-coordinate of the point where the head wave appeared as determined from the condition of its critical angle of incidence) first events were characterized by spatial waves propagating in the surrounding medium (Fig.2); in subsequent events hydro-waves' propagation in the surrounding medium was registered (Fig.3). It should be noted that spatial waves and hydro-waves excited by an electric spark source have big difference in amplitude: hydro-waves have high amplitude and low frequency, while spatial waves are low-amplitude and high-frequent. To be able to register a wave field measuring instruments with a wide dynamic range are needed; correlation of waves requires such methods of data processing as spatial filtering and wavelet analysis.

DATA PROCESSING

Processing of the data obtained allowed to define the rate of longitudinal wave propagation in the bridge abutments from the level of the concrete water inlet (ground surface level) to the deepest points of their underground parts. These values were inserted into a generalized regression equation [2] with a correlation factor of 0,89 to calculate limit values of compression strength of the material the abutments are made of:

$$\lg R_{\text{сж.}}[10^5\text{Pa}]=0{,}255\cdot V_p+1{,}708 \quad (6)$$

where V_p is the rate of a longitudinal wave in the investigated medium; V_s is the rate of a transverse wave.

The propagation rate of longitudinal waves in the concrete water inlet lies in the range of 3300-3400 m/s which corresponds to the concrete compression strength of 18 MPa.

Based on the data from in-borehole measurements and inter-borehole acoustic probing in the surrounding medium basic elastic properties of the medium were calculated, such as shear modulus, Poisson's ratio, deformation modulus (Fig.4). To calculate a modulus of deformation a universal relationship was used [3]:

$$E_d[10^5Pa]=0,099\cdot V_p+2,34\cdot V_s-332 \qquad (10)$$

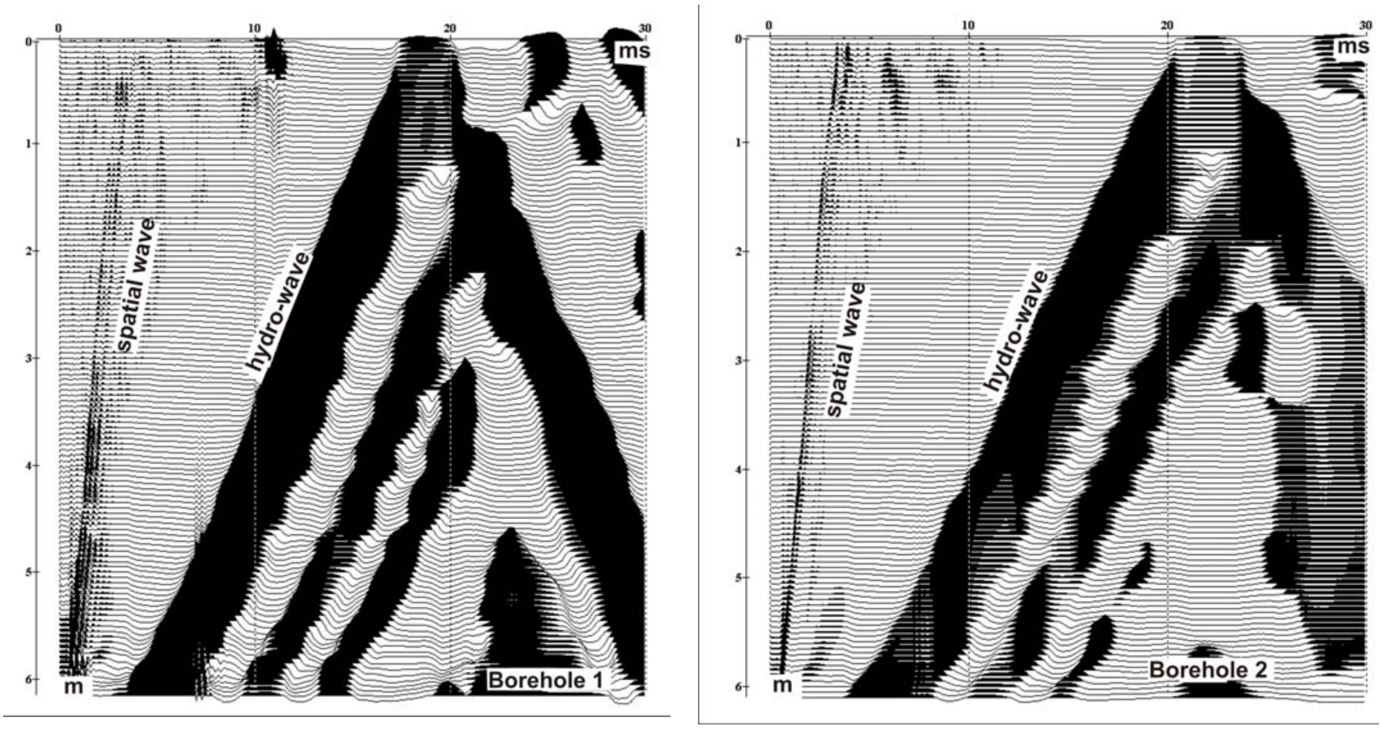

Fig.1. Acoustic probing in boreholes: first events show refracted wave gliding along the vertical interface; in subsequent events direct spatial wave and hydro-wave propagating in the surrounding medium are registered.

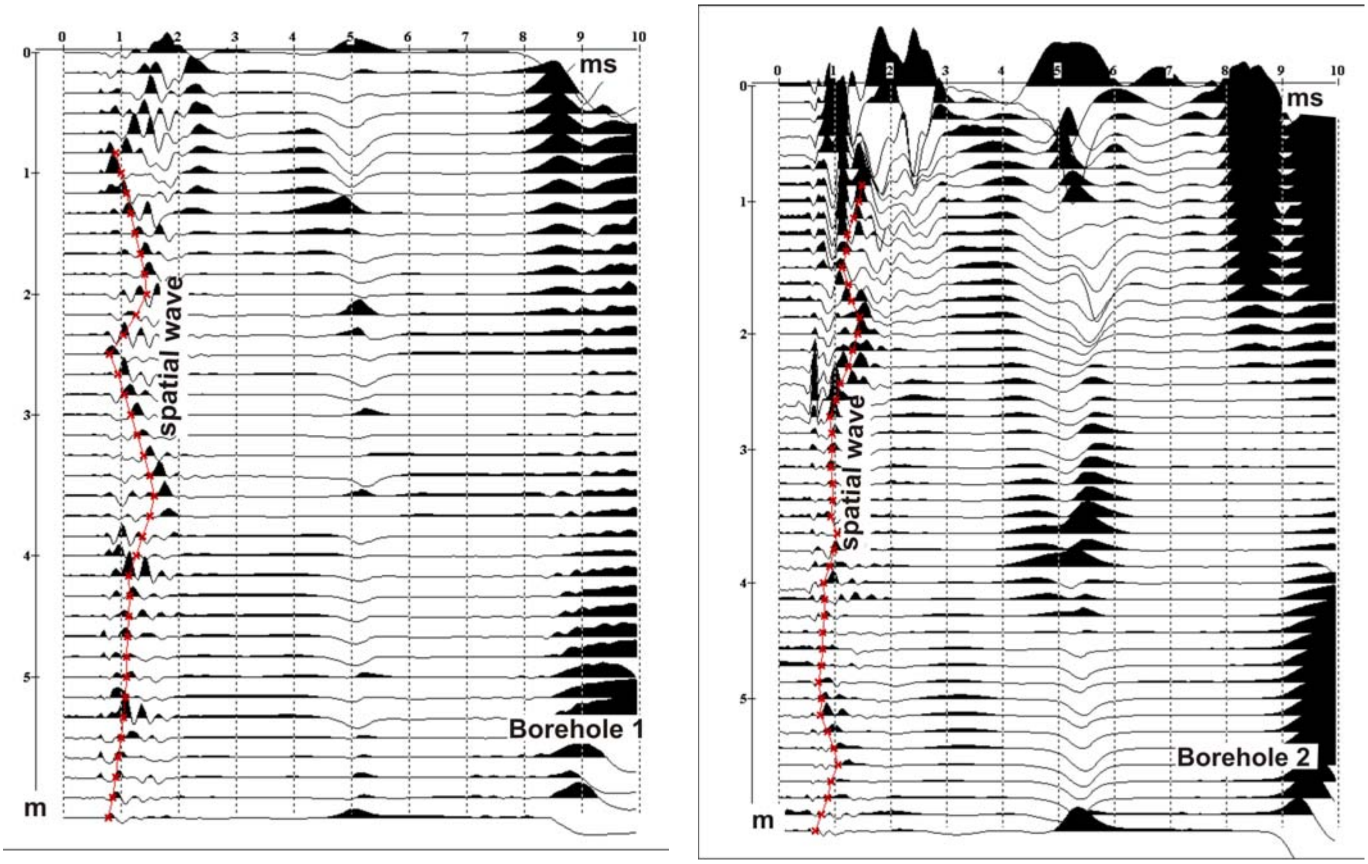

Fig.2. Acoustic probing in boreholes: first events show a spatial wave propagating in the surrounding medium

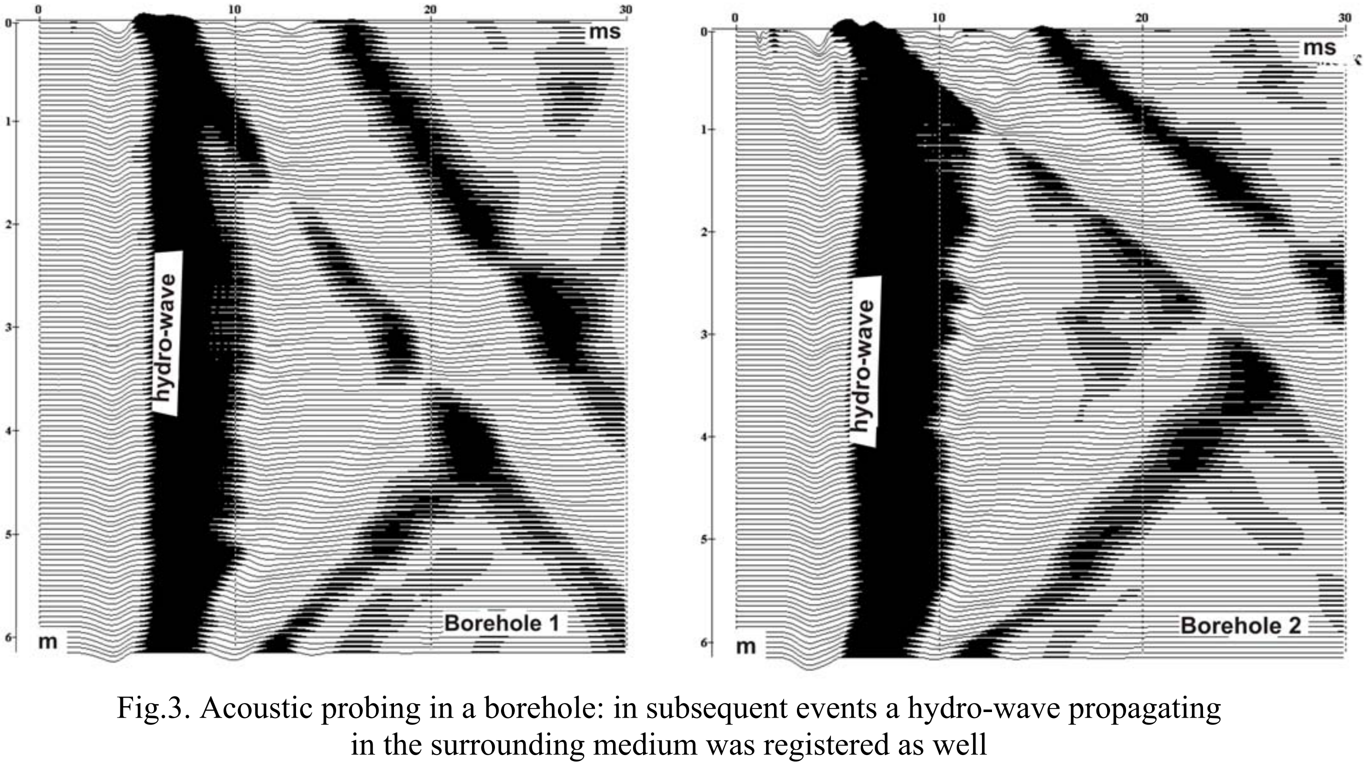

Fig.3. Acoustic probing in a borehole: in subsequent events a hydro-wave propagating in the surrounding medium was registered as well

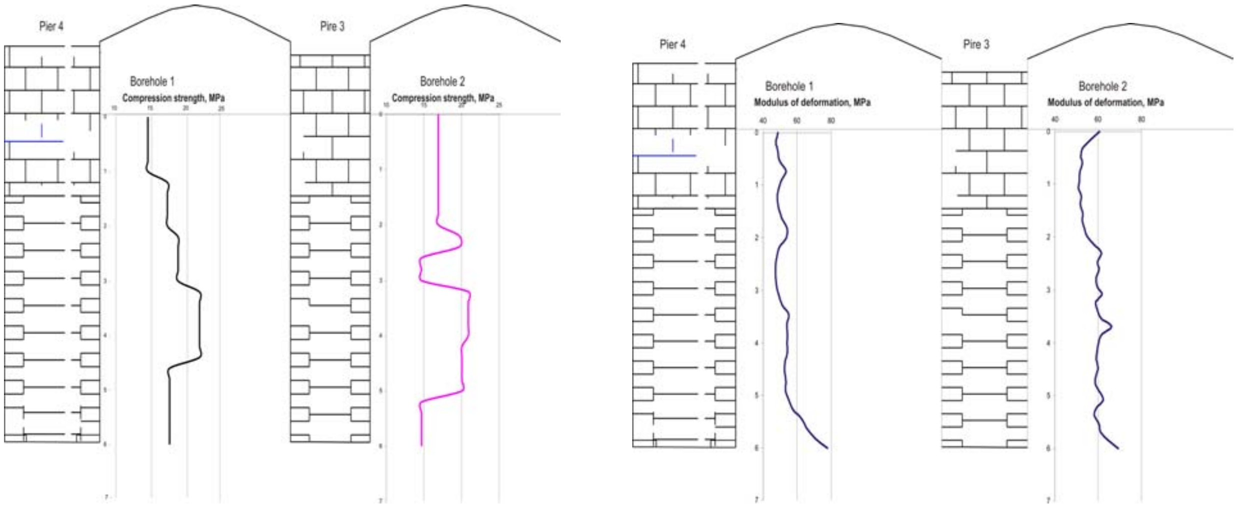

Fig.4. Distribution of the compression strength values along the depth of the piers (left)
Distribution of the modulus of deformation of the surrounding soil at various depths (right)

Radar method is based on emitting super wide-band (in nanoseconds) electromagnetic wave pulses of meter and micrometer ranges into the surrounding medium and subsequent receiving of signals diffracted from the interface between adjacent geological strata with different electro-physical properties as for example between dry and moist soil or between various soil types, etc. [4].

In-borehole radar probing was also used to define the depth of the below-grade parts of the bridge piers as well as to specify electro-physical properties of the surrounding soil. We used a special down-hole radar unit named «OKO» (“Eye”) equipped with a directional emitting-receiving antenna system (central frequency 700 MHz). Measurements were taken in accordance with two procedures:
- continuous radar profiling along the borehole axis with varying positioning of the antenna assembly;
- circular scanning at a fixed depth.

One of the boreholes was 6 m deep. It was profiled along the axis with the antenna directed to the bridge pier (Fig.5d) and vice versa (Fig.5e). In the first case the record clearly showed an interface between the below-grade part of the bridge pier and the surrounding soil. Quite a number of diffracting objects were also seen, major part of which was construction debris. Foreign objects at various depths (Fig.5f) were noticed in the record of the circular scanning as well. The average rate of electromagnetic wave propagation in soil as taken from a hodograph curve (curve of arrival time versus distance) was 6,5 cm/ns, due to high soil humidity.

The second borehole was 8 m deep. It was profiled in the same way. When probed according to the differential logging procedure diffraction was noted at the depth of 6 m (Fig.5b) which meant that it was the end of the pier. We also stated a diffracting interface (corresponding to the foundation/soil boundary) which was interrupted at the depth of 6 m. The pier end at the hodograph curve matched the time values less than the arrival of the wave diffracted from the pier; this might be explained by the presence a protrusion in the lower part of the pier.

At the depth from 6m to 8 m no interfaces or objects were recorded. There were objects higher than 6m, however most likely they were stones of the backfill. In the interval from 1,2m to 3,0 m an interface was recorded which might correspond to a vertical soil strengthening element, for example a wooden pile; similar elements could be seen clearly at a circular scan record.

The wave field obtained by acoustic logging showed an increase of spatial wave amplitude at the depth between 6m and 8 m (Fig.5a): this was another confirmation of the final depth of the foundation. Processing of the potential logging data allowed to define coherent lineups corresponding to the hodograph curves of direct and refracted spatial waves (Fig.5c); their average propagation rate was 1400 m/s in soil and 2000 m/s in the bridge pier, respectively. The break point of the curve corresponded to the depth of 6 m.

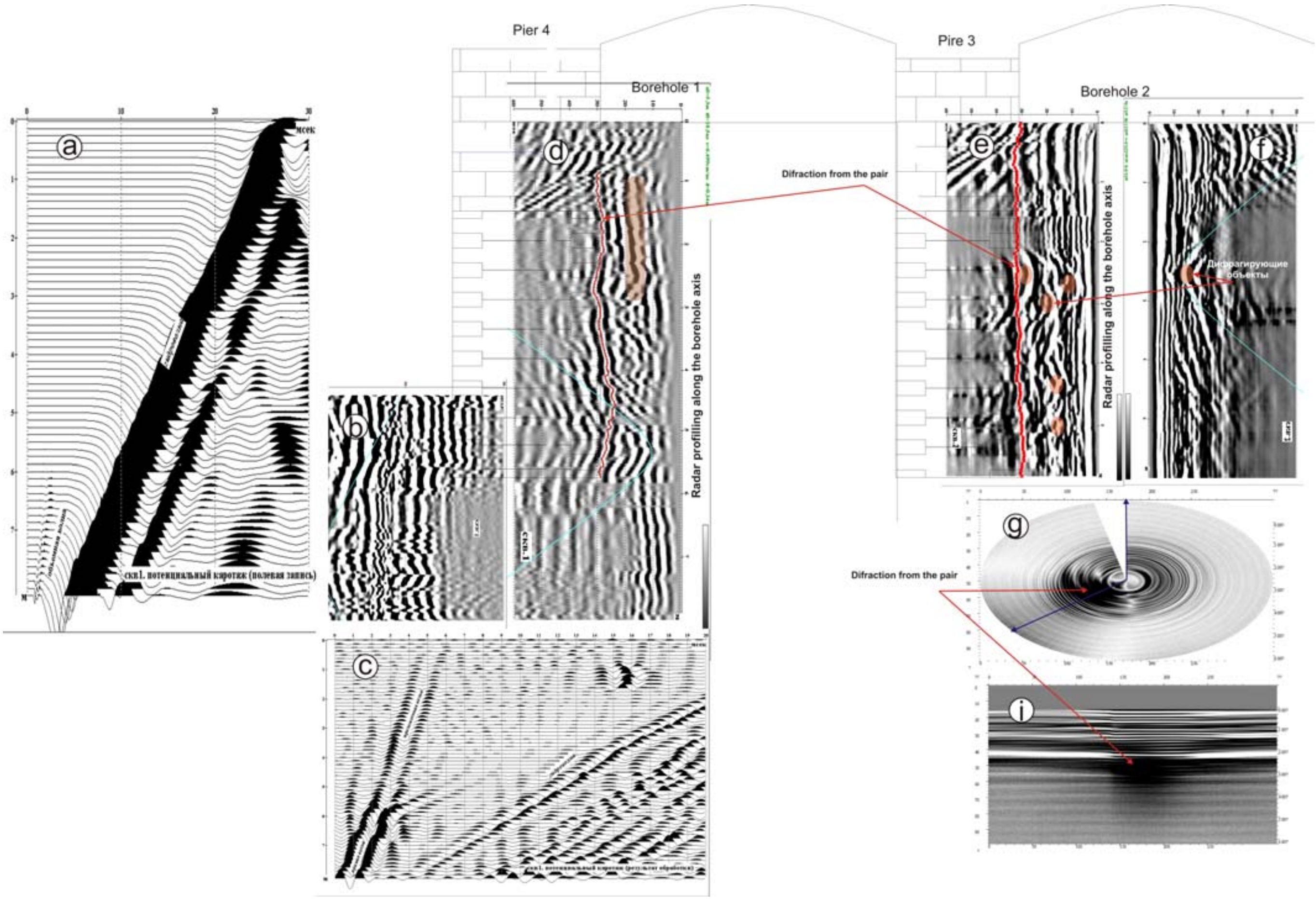

Fig.5. Results of the geophysical survey of the below-ground parts of the bridge piers and the surrounding soil

CONCLUSIONS

The results of our geophysical survey can be summarized as follows:

- the state of the below-grade parts of the bridge piers was assessed as satisfactory. The average compression strength of the masonry (up to 1,5 m deep) was 14-17 MPa, lower parts were even stronger up to 20-22 MPa. Maximum strength values were registered at the depth of 3,2-5,0 m; deeper than 5 m the strength went down (Fig.4);
- the soil between the piers showed high values the integral modulus of deformation which could be explained by the presence of some soil strengthening elements in that area. When cores were taken from the concrete water inlet, we ran into a wooden pile located under it. Later radar probing confirmed that there was quite a number of 2 m long piles there;
- under the central span of the bridge no piles were detected, though we discovered a cluster of stones at the depth of 2,5 -5,0 m (most probably of the backfill);
- the protrusions detected in the lower parts of the piers were 20-30 cm wider than the pier bodies;
- both acoustic and radar probing confirmed that there were no piles under the bridge piers.

The above mentioned results allowed us to formulate our conclusions.

The structures inspected were in a satisfactory state, though in need of repair and rehabilitation: removing stone cladding and all defective sections of stone- and brickwork; restoring the initial dimensions and cladding with modern materials resistant to moisture penetration. It must be said that the works should not change the authentic appearance of the bridge.

The results of our diagnostics gave basis to the subsequent reconstruction. At the moment the bridge looks exactly as it did 200 years ago enchanting the citizens and the tourists.

REFERENCES

1. L. Landau, E. Lifshits. The Theory of Elasticity. Moscow, 2003.
2. Acoustic Probing in Hydro- and Engineering Geology. Ed. by N. Gorjainov. Moscow, 1992.
3. Guidelines for Acoustic Probing in Engineering Survey. PCH 45-77. Moscow, 1977.
4. M. Vladov, A. Starovojtov. Acoustic Probing in Open-Cut Mines. Moscow, 1999.