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Research article

Normalized impulse response testing in underground constructions monitoring

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Abstract

Impulse Response testing is a widespread geophysical technique of monolithic plate-like structures (foundation slabs, tunnel lining, and supports for vertical, inclined and horizontal mine shafts, retaining walls) contact state and grouting quality evaluation. Novel approach to data processing based on normalized response attributes analysis is presented. It is proposed to use the energy of the normalized signal calculated in the time domain and the normalized spectrum area and the average-weighted frequency calculated in the frequency domain as informative parameters of the signal. The proposed technique allows users a rapid and robust evaluation of underground structure's grouting or contact state quality. The advantage of this approach is the possibility of using geophysical equipment designed for low strain impact testing of piles length and integrity to collect data. Experimental study has been carried out on the application of the technique in examining a tunnel lining physical model with a known position of the loose contact area. As examples of the application of the methodology, the results of the several monolitic structures of operating municipal and transport infrastructure underground structures survey are presented. The applicability of the technique for examining the grouting of the tunnel lining and the control of injection under the foundation slabs is confirmed. For data interpretation the modified three-sigma criteria and the joint analysis of the attribute's behavior were successfully used. The features of the field work methodology, data collection and analysis are discussed in detail. Approaches to the techniques' development and its application in the framework of underground constructions monitoring are outlined. The issues arising during acoustic examination of reinforced concrete plate-like structures are outlined.

Keywords
nondestructive testing; technical geophysics; impulse response testing; underground constructions; soil-structure contact state; grouting quality; void detection; attribute analysis

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Introduction.

Reinforced concrete structures like tunnel lining, shaft support, foundation slabs, etc. (so-called plate-like structures) are widespread in underground construction. Many of them are operated in difficult conditions, characterized by great depths, high stress values, dynamic manifestations of rock pressure, intense water inflows, disturbance of the enclosing soils, etc. [1]. Those factors have a negative effect on the structures technical condition and lead to a significant growth of costs for their current maintenance and overhaul [2]. Another aspect of the urban underground construction is an excluding of the negative impact on the surrounding environment. In tunneling this is achieved by using modern shield systems with active face loading and the construction of lining immediately after the shield is moving [3, 4]. Grouting injection improves the distribution of the static loads, reduces material deformations, prevents the settlements, increases water tightness, and, as a result, increases the durability of construction [5-7].

Quality control of soil-structure's contact state and performed grouting should be carried out systematically. To survey massive monolithic constructions of significant linear dimensions, geophysical techniques are often used due to their ability to indirectly assess the state of the structure and its interaction with soils [8-11]. To fulfil the task of underground structures state evaluation, a few non-destructive methods are mainly used:

- Ground-penetrating radar (GPR) profiling allows determining the reinforcement state and presence of defects in structure [12, 13], assessing the state of the lining-soil contact [14, 15] and even evaluation of grout layer thickness is possible [16].
- Ultrasonic tomography [17, 18] mainly used to assess the strength of concrete lining, the crack opening depth, presence of inner defects and the determination of the reinforcement step.
- Acoustic survey carried out by Impact-echo (IE) or Impulse Response (IR) techniques [19-21], makes it possible to evaluate the integral characteristics of the structure in different scales [22-24] and localize the zones of anomalous contact or grouting state [25, 26].
- Some techniques such as Infrared Thermometry profiling [27], Resistivity survey [28] or Surface Waves analysis [29-31], also used for examination of plate-like structures, but less often.

In this paper, we present a technique of normalized impulse response processing and analyzing (described in [26]), that allows to get rapid and robust assessment of the contact state or grouting quality for various types of underground structures. The advantage of this technique in comparison with the mobility response testing method, which is widely used in foreign practice, is that there is no need to use a calibrated signal source (a striker with a force sensor). The acoustic response is described by parameters whose behavior is determined by signal features that are stable to small changes in the impact force (the duration of the oscillation train and their distribution over a characteristic frequency range). In addition, the behavior of the response is sensitive to the presence of air-filled voids at the soil-structure interface, which allows the technique to be used in combination with GPR profiling (which makes it possible to successfully localize flooded zones, but does not allow air voids to be confidently identified) to increase the reliability of conclusions based on the results of a geophysical survey.

We use physical model of segmental liner with grout behind to make sure that proposed approach works. Based on the model results, some features of signal processing are described. Some examples of technique's application on surveying underground structures are given. Finally, we enlist some of leaks and gaps of our study and suggested directions for future investigations.

Methods.

In terms of acoustic survey, the grouted media may be described as multi-layered (structure-grout-soil) system. Thus, the tasks of grouting quality control and evaluation of soil-structure (two-layered system) contact conditions can be considered jointly. A complex wave field can be excited in that kind of media.

Impulse Response and Impact-echo techniques are based on the phenomenon of the occurrence of low-frequency and high-frequency resonant oscillations, respectively (Fig.1, *a*). Inducing free oscillations in a soil-structure system and analyzing of response in different frequency ranges therefore have different resolution capability. Selection of frequency ranges involves a "scale factor" – the higher frequencies are selected, the smaller the discontinuities affect the recorded data [22].

IE method is based on the "thickness resonance" phenomenon caused by the standing waves formation because of multiple reflections from the upper and lower surfaces of the structure. Data processing can be carried out both in the frequency and in the time domains (for thick slabs, when direct and reflected pulses are resolved in time). Spectral attributes analysis is actively used for data interpretation [20, 32-34]. IE testing allows detecting defects with size of tens of centimeters and therefore can be used for detailed inspection of a selected section of a structure.

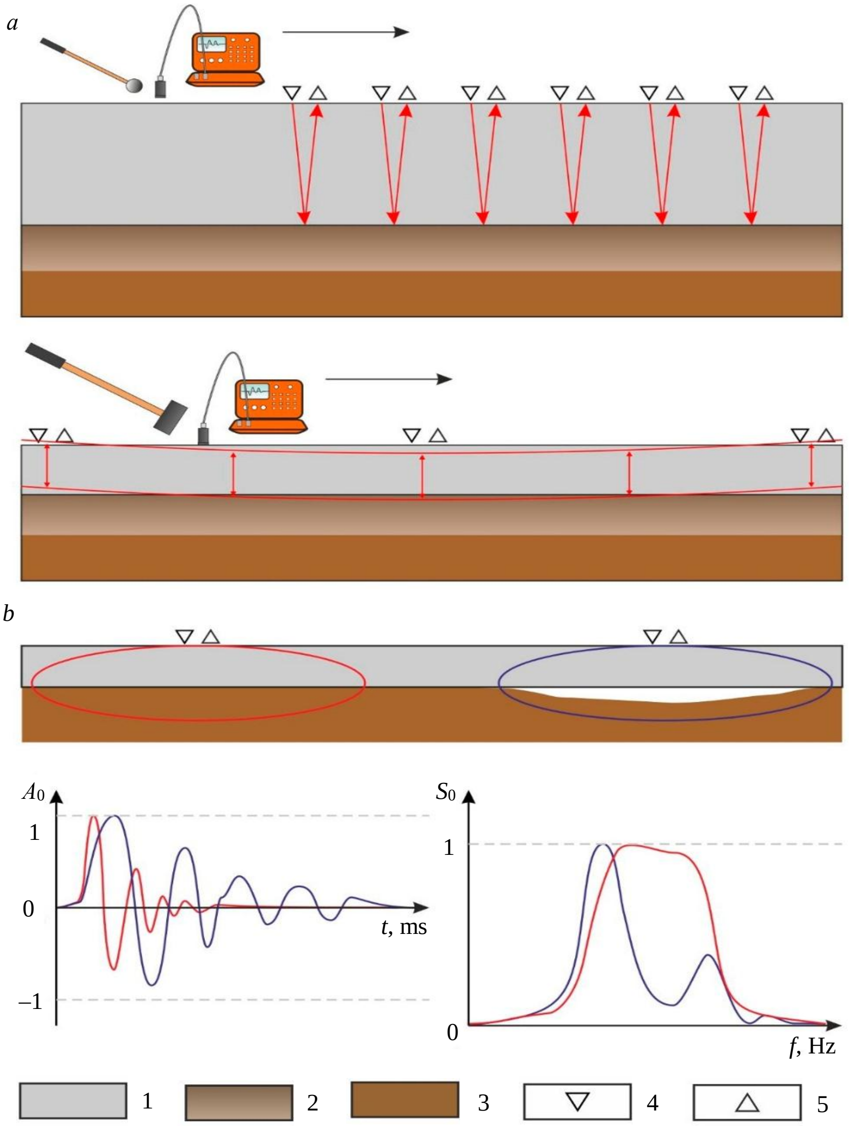

Fig.1. acoustic testing of plate-like structures
by impact-echo and impulse response (*a*) and the principle of a normalized
impulse response formation (the volume of the medium involved in the oscillation
and the idealized response in the time and frequency domains) (*b*)
1 – reinforced concrete; 2 – grouting; 3 – soil; 4 – source; 5 – receiver

IR method is based on the phenomenon of the low bending oscillations emergence of the medium volume between the defect (loose contact or grouting failure) and the free surface (plate-air interface). The idea of the technique itself is very similar to the “local defect resonance” concept in nonlinear ultrasonic testing [35]: bending oscillations in multi-layered structures cause harmonic resonance in zones of delamination. For linear-elastic body model wave-defect interaction manifests itself in amplitude and phase variations of the input signal. The technique has enough modifications, differing both in the type of oscillations induction (vibration or pulsed) and in the data processing [9, 26, 36, 37]. Low frequency IR testing is used to detect large contact state or grouting failures (from first meters in plan and more).

Bending oscillations of the massive plate-like structure lie in the low-frequency range of the Fourier spectrum. For a preliminary assessment of their frequency range, the hinged plate model may be used. The fundamental mode frequency of hinged plates oscillations may be determined by well-known analytical solutions for different shapes of plates:

$$\omega_1 \cong \pi^2 \left\{\frac{a^2+b^2}{a^2b^2}\right\}\sqrt{\frac{Eh^2}{12\rho\left(1-\mu^2\right)}};$$

$$\omega_1 \cong \frac{3.2h}{2r^2}\sqrt{\frac{E}{12\rho\left(1-\mu^2\right)}},$$

where a and b – length and width of rectangular plate respectively; r – radius of circular plate; h – plate thickness; E and μ – Young's modulus and Poisson's ratio of the plate; ρ – plate density.

There is a theoretically unsolved problem with a rigorous description of the occurrence of an anomalous response in zones of disturbed contact conditions [26, 36, 37]. For significant contact breaches (large areas of material removal under plate or zones of rock destruction behind the lining), the bending vibrations approach looks correct: the wavelength of the excited pulse is less than the linear dimensions of the structure section involved in the vibration. For small contact violations (local voids in rock massif or areas of weakened soils), the formation of an anomalous response occurs in a complex way, in the near zone of the impact source (and includes various nonlinear effects, dispersion of surface waves, etc.). However, the occurrence of an anomalous acoustic response can be clarified at the stage of geotechnical interpretation of the survey result.

Application of IR method makes it possible to obtain a qualitative assessment of the contact conditions of the plate-soil system. When free oscillations are induced in a layered structure, the efficiency of the grouting mortar or enclosing soils as a damper manifest itself in comparative response changes in the time and frequency domains. In case of contact failure (presence of delamination, void, cavity behind plate), there follows a noticeable increase in the duration and amplitude of the main oscillation train (Fig.1, *б*). The standard approaches of data interpreting are to analyze the response energy and the peak spectrum frequencies, calculate signal attributes such as Q-factor, use of numerical modeling and a priori information as supporting tools [38].

The principal questions, which are usually assigned to the qualification of a specialist, are data interpretation and final decision on contact state. This is, first of all, the choice of the criterion for the allocation of voids, i.e., set of parameters for quantitative classification of anomalous response areas.

The proposed approach to rapid data analysis were briefly described in [26] and provides an alternative view on data processing. It consists of analyzing the set of dynamic attributes of the normalized response. Technique allows avoiding the need to use a calibrated source with force sensor (which is required for the mobility analysis techniques [36]) by the analysis of the normalized response parameters that are more resistant to the signal excitation's conditions. Previously, the attributes were adapted for signal processing in vibration diagnostics of geotechnical structures, piles low strain integrity testing and parallel seismic survey [11, 39, 40].

Due to the approximation of concrete structure as the ideal linear elastic body under the low-amplitude dynamic impact, the response behavior in the time and frequency ranges does not depend on the applied force but depends on the working conditions and properties of the body itself. For real reinforced concrete structures, this property is fulfilled approximately, but this turns out to be sufficient for solving practical tasks. It was shown that signal reception conditions affect normalized response more than varying impact force in the usual field-testing range.

With this approach, the recorded acoustic trace $V(t)$ and its Fourier spectrum $S(j\omega)$ are represented a:

$$V(t) = A_{\max}V_0(t); \quad S(j\omega) = A_{\max}S_0(j\omega),$$

where $A_{\max}$ – maximum signal amplitude; $V_0(t)$ – signal value normalized to the maximum amplitude; $S_0(j\omega)$ – signal spectrum, normalized to the maximum spectral amplitude.

The attributes of the normalized signal energy E_n, the normalized spectrum area S_n and the average-weighted frequency f_s allows us to characterize the absorption nature of the oscillation energy, excited in the studied linear-elastic body, and are determined by the following formulas:

$$E_n = \sum_0^T V_0(t) V_0(t);$$

$$S_n = \sum_i \left| S_0(i) \right| df;$$

$$f_s = \frac{\sum_i \left(S(i) f(i) \right)}{\sum_i S(i)},$$

where V_0 (t) – normalized signal's value, $t = 0, \dots T$, $df = \frac{\Delta f}{2(n-1)}$, Δf – sampling frequency; n – number of samples in the spectrum; $i = 1, 2 \dots n$; $S_0(i)$ – the value of the normalized spectrum at the i-th point; $f(i)$ – frequency value at i-th point.

According to Parseval equality, the response energy can be determined as follows:

$$E = \int_0^T V(t)^2 dt = \int_0^{\omega} \left| S(j\omega) \right|^2 d\omega. \tag{1}$$

The signal energy, as can be seen from (1), is determined in the time domain by the signal amplitude $V(t)$ and the time interval (0; T), i.e., signal duration. In the frequency domain, the energy is determined by the spectral amplitude $|S(j\omega)|$ and frequency interval (0; ω). When using E_n attribute, its value is determined mainly by the duration of the signal T. When contact is broken, the duration of the acoustic response increases and, consequently, the attribute value increases. In accordance with the property of the Fourier transform, the response spectrum becomes narrower and the central frequency of the spectrum becomes lower. Therefore, S_n and f_s decrease with E_n growth (see Fig.1, *b*), and for good (g) and poor (p) contact state the following relationships can be written:

$$E_{ng} < E_{np};\ S_{ng} > S_{np};\ f_{sg} > f_{sp}. \tag{2}$$

General points regarding the relationship of the attributes of the normalized and unnormalized response with the characteristics of excited oscillations are given in Table 1. It should be noted that the S_n/f_s attribute allows to assess the nature of the oscillation energy attenuation, and has a similar physical meaning to the Q-factor. A decrease in this parameter is an indicator of a decrease in the quality factor of the "structure – soil" oscillatory system (energy is redistributed into pronounced low-frequency oscillations). However, unlike other methods of assessing the Q-factor, such an attribute is more resistant to small changes in the response spectrum (since its calculation is not tied to the shape of the main oscillation train) and is suitable for characterizing an oscillatory system with more than one pronounced oscillation frequency (a multi-layer system, which includes the "structure – plugging – soil" system).

Table 1

Connection of dynamic attributes of the normalized and unnormalized response with the properties of the oscillatory system

Attribute	Signal	Normalized signal
Energy E	Oscillation energy	Oscillation duration
Spectrum area S	Oscillation energy	Oscillation frequency bandwidth
Average-weighted frequency f_s	Dominant frequencies of the response spectrum	
S/f_s	Q-factor	

When choosing the impact source parameters, it is important to know the prevailing frequencies induced by the impact. Their range is related to the impact pulse duration τ, which, in turn, is related mostly to the parameters of the signal source (mass, material, radius of the contact surface and impact

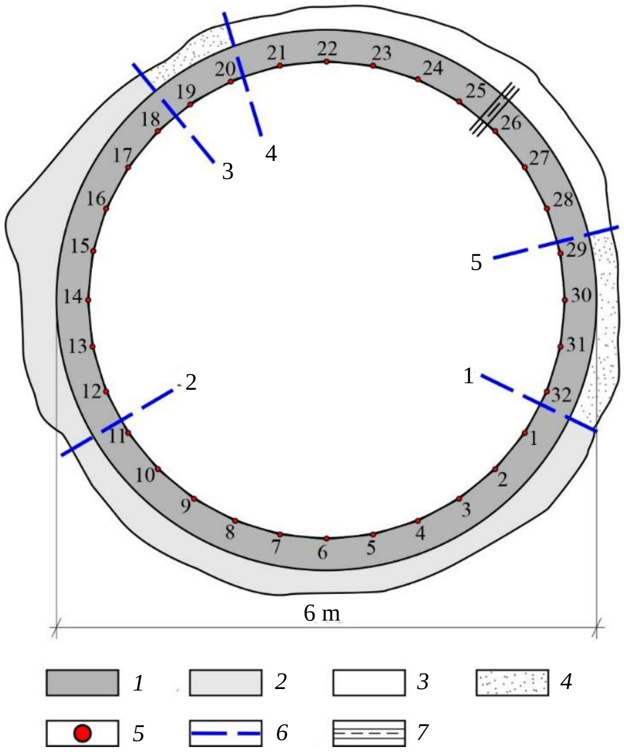

Fig.2. Tunnel liner physical model scheme

1 – reinforced concrete liner; *2* – grouting; *3* – cavity; *4* – loose soils; *5* – IR testing point; *6* – markers of different contact state zones; *7* – tunnel liner break

speed). The first three parameters are modulated by the choice of specific impactors, while the fourth is the most difficult to standardize. Although it varies within relatively small limits. The use of two impactors with "opposite" characteristics (compact metal hammer and a massive rubber mallet as example) has been anchored during the practice of carrying out the physical modeling experiment.

Experimental research was carried out on a model that simulates a tunnel lining. To test the proposed approach, physical modelling on a specially constructed laboratory bench was performed. The stand scheme and the observation points location are shown in Fig.2. A brief description of the experimental results for the energy attribute is given in [26].

Complete tunnel ring was assembled from standard concrete blocks 250 mm thick. The assembled ring was buried into the ground to a depth of the ring width. On the outer side of the ring, a gap between the liner and the soil was equipped with a width of at least 200 mm. For the greater half of the ring circumference (marks 1-2-3), the gap was filled with grouting mortar: the grout width was 20-30 cm for section between marks 1-2, 30-50 cm for section between marks 2-3. Sections 3-4 and 5-1 were filled with loose soil, section 4-5 was initially left unbacked to simulate a cavity/grouting fail behind liner and was backfilled with soil after the first measurement cycle.

The laboratory stand model was chosen to present in practice the main provisions of the technique – the connection between the attributes behavior of the normalized response and the presence of conditioned plugging between the structure and the surrounding soils, acting as a damper for the excited vibrations.

For field measurements, a two-channel seismic station IDS-1 (OOO Logicheskie sistemy) with omnidirectional velocity transducer GTSensor (OOO GEODEVICE) was used for response registration. The signal was induced using a rubber mallet (striker weight – 400 g) and a metal hammer (striker weight – 70 g). Signal processing for all the results presented in the article was carried out in the GeoTechControl software package (OOO GEODEVICE).

On the liner ring inner surface, 32 IR testing points were evenly distributed. Between observation points 25 and 26 (closer to point 26), there was a gap in the lining. For each point, a series of 4 impacts was performed with each of the impact sources. The impacts were applied within 10 cm from the sensor on four opposing sides to suppress the interference caused by the geometric factor when calculating the arithmetic mean and multiplicative spectra for each observation point. After completing a full cycle of observations, the cavity was covered with loose soil and repeated observations were made from point 18 to point 32.

Results and discussion.

Consider the signals behavior for two testing points representing opposite cases – good contact with the enclosing soil through the grouting layer (point 6) and poor contact with the enclosing soil without grouting (cavity, point 24). The calculation results of the attributes are shown in Table 2. The recorded signals, arithmetic mean and multiplicative spectra for both types of impact source are shown in Fig.3.

Visual analysis confirms some of the considerations presented early. For both impact sources, the difference between good and poor contact state is expressed in the appearance of intense oscillations in the time domain ("ringing") and grown "irregularity" of the spectra in the frequency domain. The calculated attributes show a significant increase in the normalized signal energy and a noticeable decrease in the normalized spectrum area. The average-weighted frequency behavior differs from the expected – instead of a noticeable decrease, f_s slightly increases.

Table 2

Dynamic attributes of normalized response obtained for measurement points 6 (good contact) and 24 (poor contact)

Attribute	Point 6		Point 24	
	Metal	Rubber	Metal	Rubber
E_n, conv.un.	243	564	890	1,589
S_n, conv.un.	2,037	602	462	331
f_s, Hz	1,462	632	1,472	895
S_n/f_s, conv.un.	1.393	0.953	0.314	0.370

The observed phenomenon is associated with the limitations of the used single lining ring. When surveying real structures, their linear dimensions (the tunnel length or the slab dimensions in plan) significantly exceed the length of induced oscillations. In the case of the used physical model, the acoustic wave's reflections from the edges of the structure create an interfering signal. Therefore, upon induction of oscillation, not only modes of bending oscillation are recorded, but also various spatial resonance phenomena which associated peaks can be observed in the average and multiplicative spectra. In addition, a break in the tubing located near testing point 26 provides additional acoustic interference.

The calculation results of dynamic attributes for all observation points on the profile are presented in Fig.4. Normalized signal energy value E_n for a rubber mallet showed sensitivity to the grouting change to a cavity (the difference in values is 2.5-3 times, the points of anomalous observations correspond to the cement mortar change to the surrounding loose soil). E_n for a metal hammer showed less sensitivity to the cavity presence behind the liner. After filling the cavity with

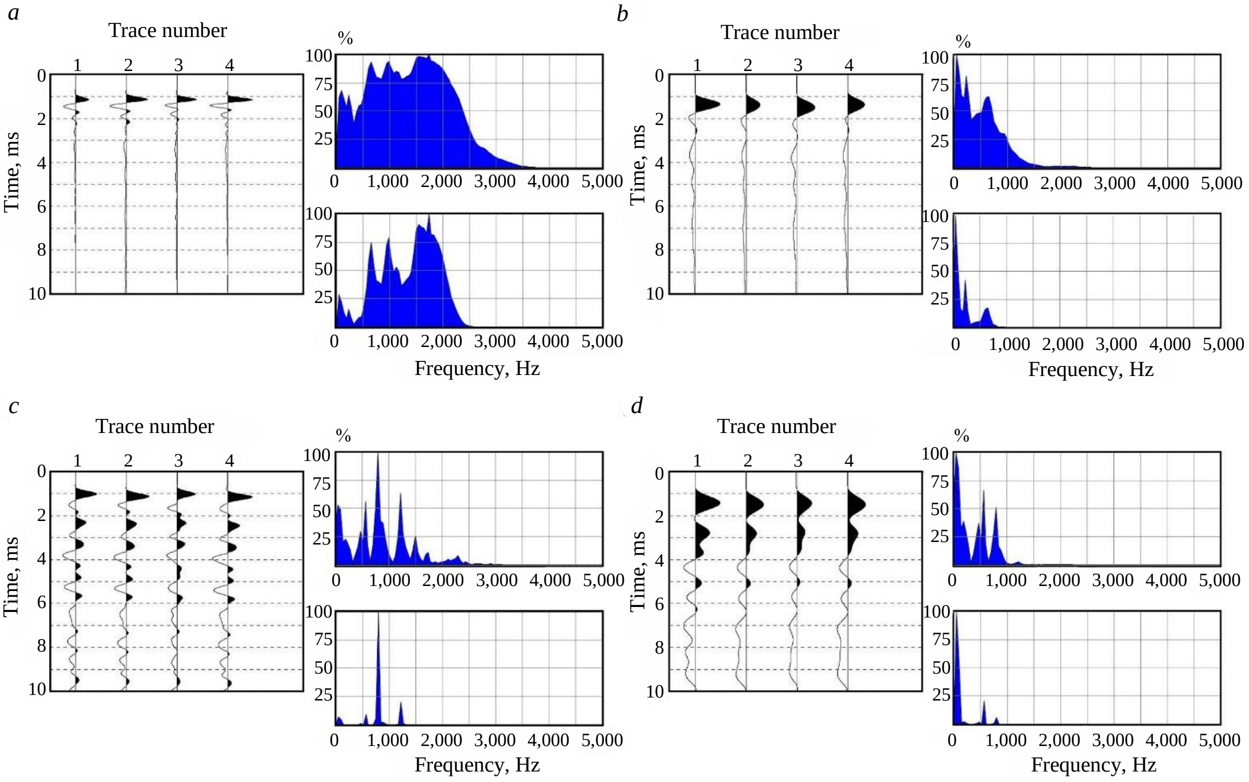

Fig.3. Response in time and frequency (arithmetic mean and multiplicative spectra) domains for points with (*a*, *b*) and without (*c*, *d*) grouting behind liner:
a – point 6, metal hammer; *b* – point 6, rubber mallet;
c – point 24, metal hammer; *d* – point 24, rubber mallet

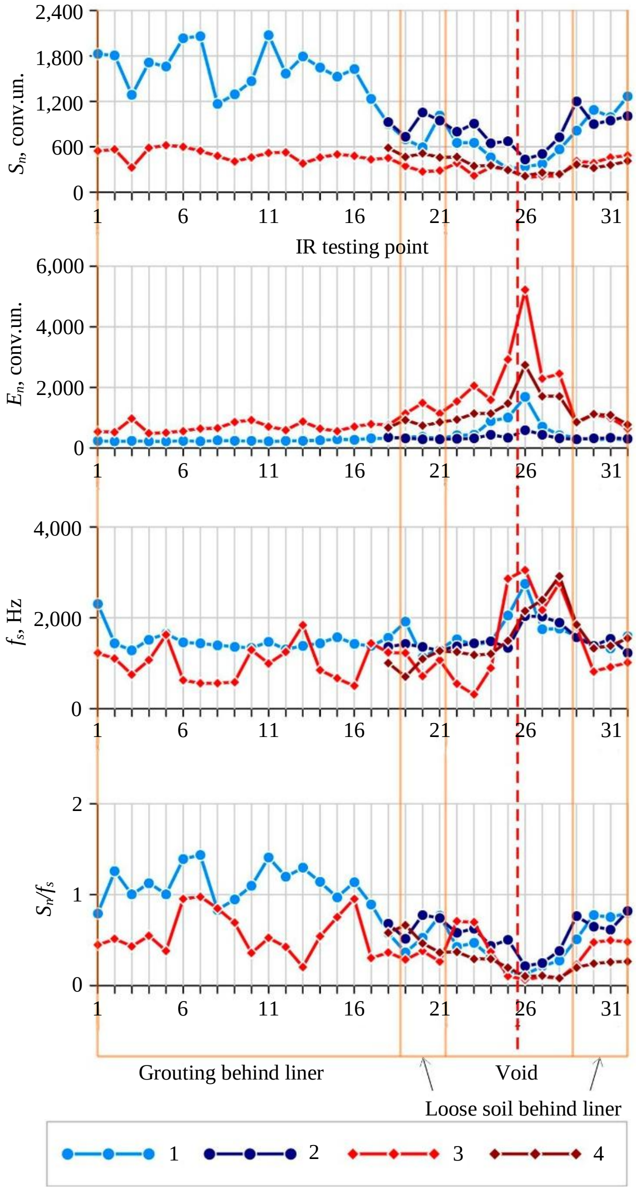

Fig.4. Attributes values obtained due physical modeling

1 – metal hammer, before cavity filling; 2 – after cavity filling; 3 – rubber mallet, before cavity filling; 4 – after cavity filling

loose soils, the anomaly intensity decreases. S_n for a metal hammer demonstrates greater sensitivity in comparison with rubber mallet – a decrease in the attribute values by 2 times coincides with the grout zone boundaries. The ring rupture near point 26 shows in intense anomalous values of the E_n and f_s.

Thus, the relationship between the state of the contact of the concrete-plugging-soil system and the behavior of the normalized response attributes is confirmed in practice. The next step is to clarify the methodology for performing field work, which can be substantiated by the results of a laboratory experiment.

The increased sensitivity of the attributes obtained with a low-frequency impact source (rubber mallet) to changes in the contact state allows selecting them for detailed analysis. Fig.5 shows the results of calculating the response attributes for the mallet, obtained before filling the cavity, with several significant changes made in the calculation.

To reduce the influence of interference of various origins on the attribute values, they were calculated separately for each recorded trace, after which the median value was taken as the attribute value for the research point. This allowed us to partially automate the procedure for rejec-ting broken signals. Manual rejection is difficult when accumulating a large array of data on a real object.

To increase the reliability of identifying points with an abnormal response, the experience of the specialists in mobility curve analysis was used. The mobility curve parameters are calculated for the frequency range (0, 1,000) Hz, since it was established that for this window the behavior of the mobility spectrum is most sensitive to the state of the "plate-like structure – soil" system [9, 21, 36]. In the case of normalized response analysis, the task is to localize the low-frequency "ringing" region for areas of contact failure or poor-quality plugging.

Attributes S_n and f_s were recalculated for (0, 1,000) Hz window. The results of the recalculation, presented in Fig.5, allow us to show the compliance of the behavior of the response attributes with the theoretical criterion (2) for the section with no plugging after making this change. A noticeable decrease of S_n (about 2 times) and f_s (about 25 %) corresponds the more than doubled E_n growth. The results of experiments on numerical modeling of the application of the technique for localizing voids (presented in [40]) also confirmed the correctness of these changes in the calculation method.

Addition of the set of selected attributes with recommendations for their calculation allows us to proceed to the interpretation of the acoustic survey of the structure. The application of the response analysis method allowed us to survey several operating underground structures. Examples of field work results allow us to demonstrate the specifics of analyzing the results using this method.

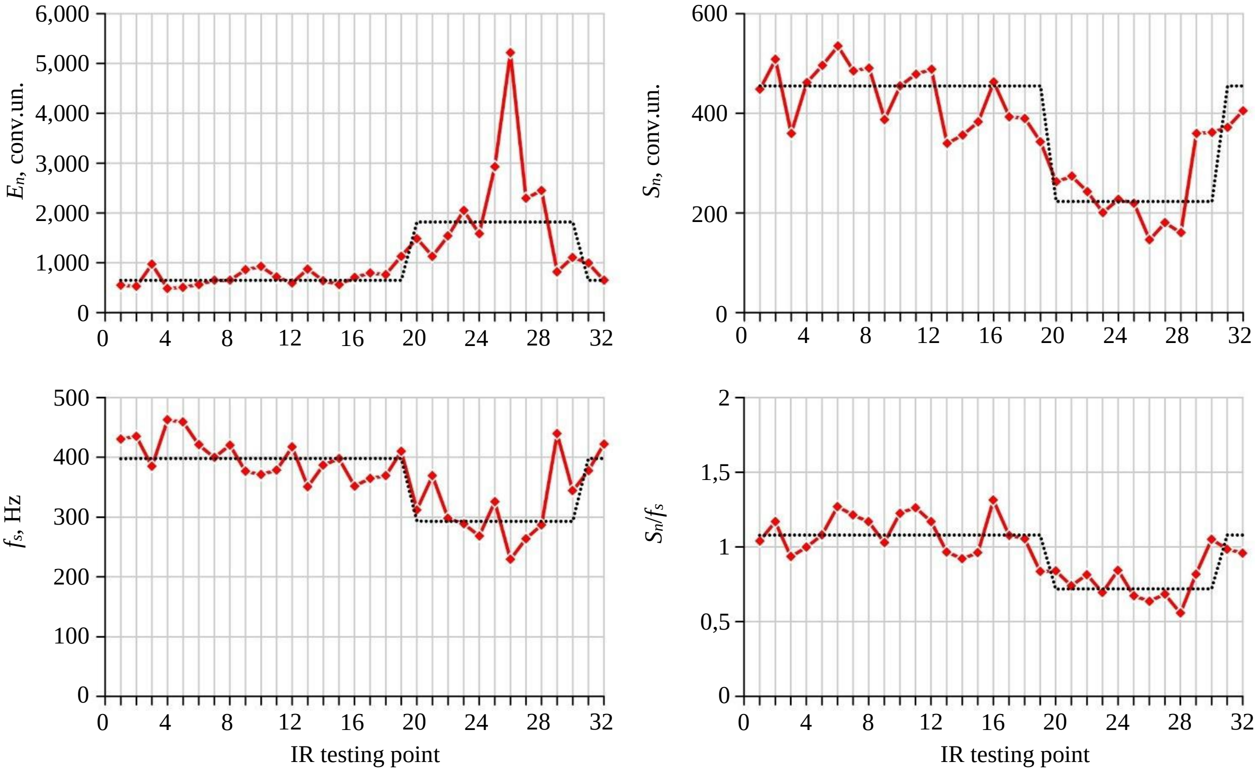

Fig.5. Attributes of the normalized response obtained from the rubber mallet, after rejecting broken signals, calculating median values and recalculating for (0, 1,000) Hz window. The dashed black lines indicate the median values of attributes for areas of normal and abnormal state of the contact "lining – soil"

The first case study is the survey of 0.6 m thick foundation slabs of the object of construction in progress. This thickness value approximately corresponds to the upper limit for adequate survey results because excitation of bending oscillations for a thicker structure with a manual striker may be problematic [36]. An IDS-1 was used for response registration, a rubber mallet (350 g) was used as a source. For each measurement point, 5 signal accumulations were performed. Assigned task was to clarify the areas of contact failures between plates and the base soils with reference to the edges of structures. Previous visual investigations show some consequences of base soil decompaction.

The observation network was planned based on the task as follows – a dense measuring network (about 1 m between adjacent points) evenly covered the outer perimeter. The central parts of the structures were surveyed with less detailed longitudinal profiles (step between neighboring points about 5 m). An additional limitation for the observation network was the need to work outdoors in winter. The preparation of measurement points for the installation of sensors and the limited time for the survey did not allow for more detailed observations for the central parts of the slabs.

The results obtained make it possible to show options for data visualization. Attribute maps (values were interpolated between measuring points by kriging) are presented in Fig.6. Traditional way for the presentation of geophysical survey results is a visualization in the (min; max) color scale. More informative seems to be the use of a data visualization method that allows you to highlight areas of anomalous values in the plan using statistical criteria. The proposed approach to data visualization is in choosing color scale, where the color transitions are determined by the boundaries of the standard deviation σ of the attribute values. The modified 3σ criterion (three-sigma rule, empirical rule) gives a rough statistical estimation for the collected dataset. Its application makes it possible to identify significant deviations from the normal behavior of the studied parameters [26]. Figure 6, *a* shows a good match of the joint behavior of attributes to criterion (2).

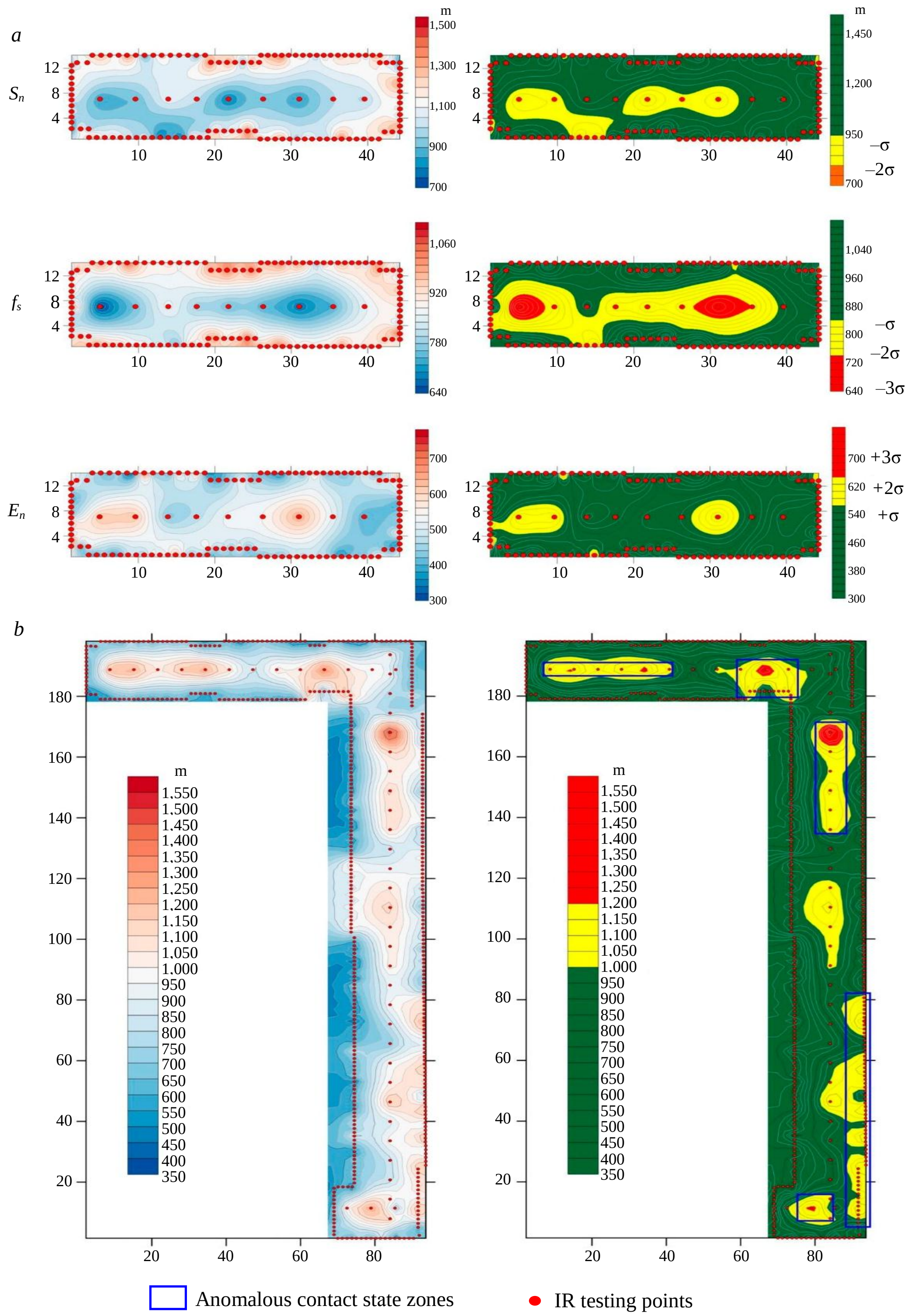

Fig.6. Attributes maps for first tested slab (*a*) and E_n map for second tested slab (*b*).
The color scale on the left changes uniformly from minimum to maximum values;
the color scale on the right is tied to the boundaries of the standard deviation

The second aspect of data analysis is the issue of incorrect use of statistical criteria for the selection of abnormal zones without considering their size and distribution within the tested area [11]. The relative spatial arrangement of the anomalous points allows us to separate random deviations (arising from instrumental or data collection errors) from zones of suspected contact failure traceable for several observation points. Fig.6, *b* shows an example of rejecting anomalous zones at the stage of results interpretation. The sections of the plate with an anomalous response traceable for several neighboring observation points were identified as "suspicious".

This allows us to conclude that the contact of the central part of the slabs with the base soil is relatively weakened. This can be explained by uneven soil settlements due to its incorrect compaction during preparation for the construction of structures. The results obtained from the survey were used in the planning of grout injection grids.

The second case study presents the results of a survey of the foundation slab at the base of the existing underground structure. Slab 32-35 mm thick was examined. In the process of strengthening the soil base of the structure, auxiliary soil-cement columns were manufactured, which led to uneven settlements of the floor slab. The complex of the IR testing and cement injections was used to localize areas of violation of the contact of the floor slab with the subgrade and the development of defects in the slab material.

For acoustic testing, IDS-2 (OOO Logicheskie sistemy, Russia) was used, a rubber mallet 450 g weight was used as an impact source. For each point, 10 signals were accumulated. Data collection was carried out from the surface of the examined structure. The blows with a mallet were applied from different directions from the registration point to increase signal to noise ratio.

The data were processed using the GeoTechControl software. The processing schedule included data sorting and collection, geometry assignment, and spatial filtering (to obtain an average response for each observation point). The attributes of the normalized response were then calculated and, after interpolation of the values (using kriging), maps were constructed (Fig.7). The 3σ criteria and the joint behavior of attributes were used to study the contact of the slab with the soil. Based on the results of the study, two anomalous zones were identified.

The anomalous area identified near observation point 67 was confirmed during hydraulic testing. The cement mortar pumped into the soil base from a depth of 1.5 m began to flow onto the surface of the slab through cracks and cavities in the construction material near the point 67. Decompression of the base soil in the area of points 17, 40, 55 was also eliminated when pumping with a solution.

Summing up the interim results, it is possible to bring up a number of issues for discussion. For the successful application of the proposed technique in underground structures monitoring, the following tasks should be solved:

- studying of the influence of acoustic interference waves and noises caused by the spatial and material characteristics of the structure on registered data;
- clarification of types of contact states due to acoustic response and the development of quantitative criteria for their separation;
- development of an instrumentation and hardware complex that allows quick collecting and processing of data when surveying a structure with non-trivial geometry and hindered access to the examination surface – old mine shafts, metro communications, elements of hydraulic structures.

The question of the influence of acoustic interference waves and noise on the recorded data regularly arises in classical analysis of the mobility curve [8, 9, 21, 22, 36]. The influence of edge effects can be taken into account at the planning stage (grid points are located at a distance from non-standard slab areas) or already during data analysis (zones of non-standard areas response changes are manually marked on the maps).

In Russian practice there are three traditionally distinguished "empirical" types of contact states: firm contact, weakened contact, breached contact [11, 26, 38]. The three-sigma rule can be adapted for this classification as shown above. However, due to the relativity of the criterion, it cannot serve as the only way to reject data and requires additional geophysical and geotechnical interpretation of the results. A number of authors are inclined to the point of view that it is possible to increase the reliability of the application of relative criteria by establishing a sufficient number of observations over the network (at least 200 in the case when quality control of the slab material is required) [36]. Similar guidelines can be developed for the normalized response analysis testing. Additional analysis tools include calculating the coefficient of variation of each attribute sample and constructing scatterplots to simplify the joint analysis of parameters.

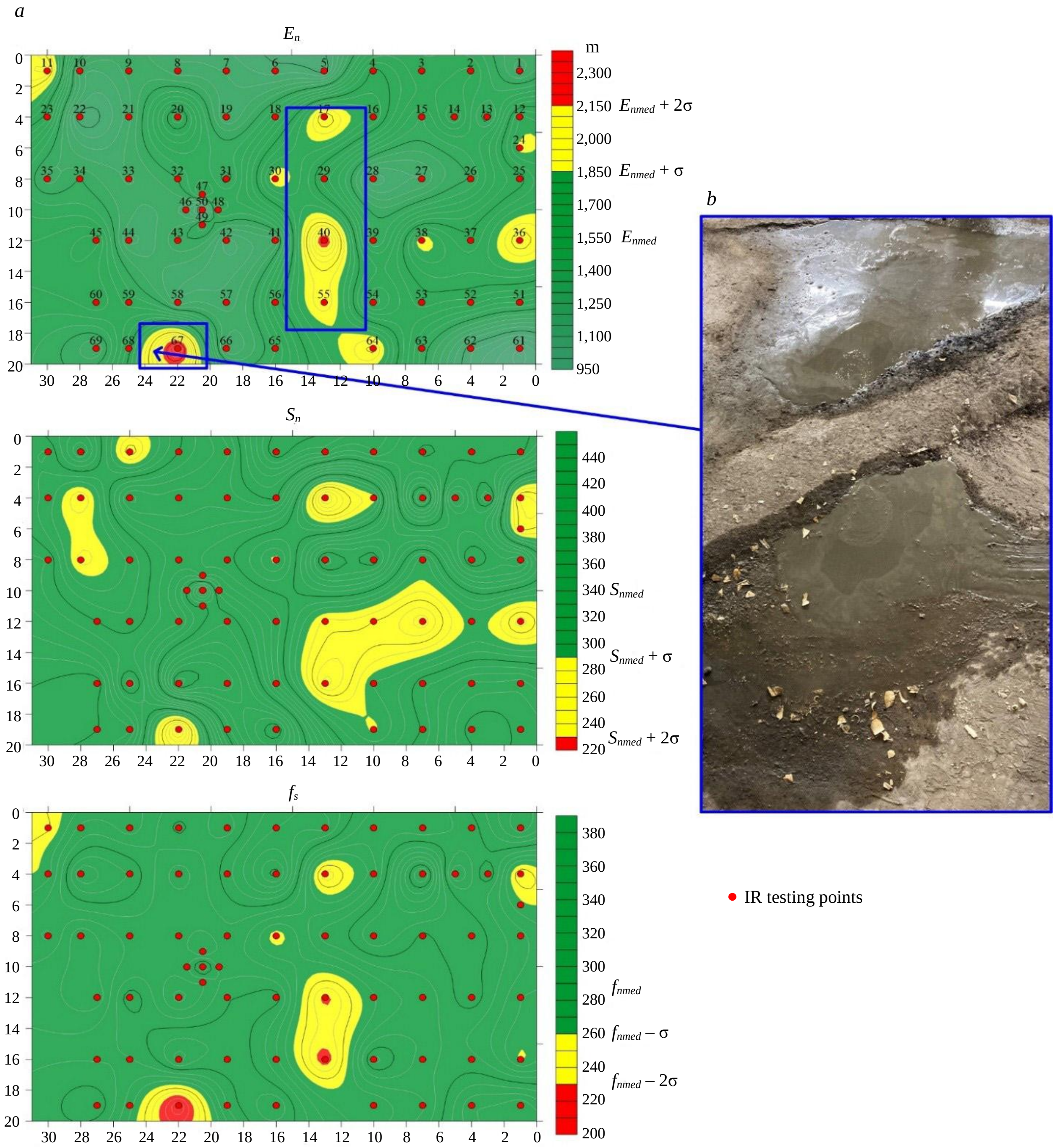

Fig.7. The results of the foundation slab survey at the base of the underground structure (*a*) and confirmation of the defect in the body of the foundation slab near point 67 during the cement mortar injection (*b*). The *nmed* index indicates the median value of the attribute

The development of new synthetic parameters characterizing the multilayer "concrete – grouting – soil" system may provide some perspectives. An interesting way of processing the data is to combine the attributes of the normalized response with the attributes of mobility curve, such as the void index or the slope of the mobility curve [21, 32, 37]. Thus, [40] presents the applicability of the void index from ASTM C1740 for the analysis of normalized response data. The use of spectral characteristics of the impact for response normalization can reduce errors associated with the conditions of signal excitation (despite the initial assumption that the impact force influence on the response is insignificant). An informative parameter can be extracted from a comparative analysis of nonlinear changes in the response. An interesting approach described in [41] still seems problematic for examining real structures, but also needs to be developed.

Undoubtedly, as empirical material accumulates, the number of criteria may change. Of great interest is the emergence of quantitative assessments for the type of filling of cavities behind a structure [33, 38]. A necessary stage for the technique will be the machine learning algorithms (primarily cluster analysis) adaptation to identify anomalous points by analogy with the approach proposed in [42].

For the mobility analysis method, some manufacturers have developed hardware and software packages that completely solve the issue of conducting field tests in accordance with the requirements of ASTM C1740-16 [8-10, 36, 37]. Since normalized response analysis tests can be performed with equipment for pile integrity testing, the main issue is the development of a software package (for example, based on the applied GeoTechControl) and recommendations for equipment manufacturers on recording parameters (sampling frequency, recording length, dynamic range) for collecting good quality data.

Conclusion.

The proposed technique of normalized response attributes application makes it possible to implement a rapid and economical non-destructive technology for different plate-like structures evaluation. The calculation of the attributes is quite simple and does not take much time, which makes it possible to do semi-automatic data processing with a small participation of a data processing specialist. The technique can be used to assess the state of various underground structures during their construction, operation, and to assess the effectiveness of repair work using grout injection. A number of issues of the technique need to be developed and supplemented, which allows us to count on its elaboration in parallel with more widely used techniques for examining plate-like structures, such as the mobility analysis method or the impact echo method.

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