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COLLABORATIVE INTERPRETATION OF THE DATA OBTAINED BY RESISTIVITY AND GROUND PENETRATING RADAR METHODS FOR ASSESSING THE PERMEABILITY OF SANDY CLAY SOILS

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A method for estimating the filtration factor of sandy clay soils is considered on the basis of a joint interpretation of the data of a set of methods of engineering electrical exploration, including electrical resistivity tomography and ground penetrating radar studies. The solution of this problem is based on the use of known empirical connections between the imaginary and real parts of the complex dielectric permittivity, specific electrical resistance, and *Q* factor. An example of the effective joint use of the ground penetrating radar and non-contact electrical resistivity tomography shows how to obtain qualitative and quantitative estimates of a changing filtration factor in a draining road layer. It is necessary to use precise engineering geological information in order to provide the required estimates. The proposed approach makes it possible to describe continuous profiles of a pavement and underlying layers by ground penetrating radar and electrical resistivity tomography, as well as to assess soil properties when conducting an electrical survey from the surface of asphalt concrete pavement. Recommendations for the implementation of the developed methods of complex engineering and geophysical research are given for solving issues of repair work design, supervision, and quality control of road construction.

Key words: ground penetrating radar; non-contact electrical resistivity tomography; complex dielectric permittivity; specific electrical resistance; *Q* factor; clay content; filtration factor; pavement monitoring

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Introduction. Assessing of petrophysical features of soils is an actual task in carrying out an engineering-geophysical research. Quantitative Petrophysics basing on the Slichter and Kozeny – Carman equations is mainly widely used in oil and gas geology [1]. The possibility of obtaining qualitative and quantitative estimates of filtration, as well as physical and mechanical properties of soils using techniques of engineering geophysics is justified theoretically and experimentally (A.A.Ogilvy, A.A.Ryzhov, V.A.Shevnin, K.V.Titov, M.L.Vladov, V.A.Yavna, V.V.Kapustin and others). The major factor limiting applied defining of the parameters is the need for a large volume of laboratory measurements to obtain correlation dependencies connecting geophysical and petrophysical parameters for a particular study area.

Advantages of engineering geophysics methods are in the possibility for rapidly assessing scale and nature of changes in petrophysical parameters of soils in undisturbed conditions. The determination of sand filtration coefficient in artificial embankments and draining layers of pavement foundations is of special importance in design, construction, and operation of various engineering structures, especially highways.

In road construction, special requirements are imposed on the coefficient of filtration of building materials that characterises water permeability, since this parameter determines directly the sand quality and application possibilities for embankment filling [3, 7, 8, 10, 11]. The low value of sand permeability indicates a heightened content of clay impurities that significantly limits the possibility of effectively using such materials for road construction.

The existing methods for permeability determination use well-established laboratory methods of sample testing, which are regulated by directing documents. Disadvantages of using these methods are firstly connected with the laboriousness of their conduct and the need to test soils with the help of wells. The sampling procedure, including a local destruction of road pavements, does not allow continuous studying the spatial distribution of the filtration coefficient values in soil and collecting undisturbed sand samples.

The use of engineering geophysics methods is an opportunity to significantly broaden the information, obtained by laboratory analyses and, thereby, to minimise an impact of the aforementioned shortcomings on the results of engineering and geological investigations. Application of a set of methods of engineering electrical exploration, including ground penetrating radar and electrical resistivity tomography, allows continuous studying a geological section and obtaining qualitative and quantitative evaluations of sand permeability. Quantitative estimates require the use of highly-precise geological or engineering data on the structure and properties of a geological section or a geotechnical construction.

Materials and methods. Water permeability of soils depends on many factors that does not allow describing a dependence of the filtration coefficient (K_f) on parameters of a particular soil profile in a precise analytical form [4].

Numerous experimental data showed that the fundamental Dakhnov – Archie's law describes these dependencies for rocks not containing an appreciable amount of finely dispersed (clay) fraction. This significantly limits the possibility of its applied use, since the content of clay particles is one of the main factors influencing soil permeability [4, 9, 15].

Adding 10 % of clay particles to the sand reduces permeability by more than 50 % [4]. Quarry sand, widely used in producing concretes and construction mixtures, as well as pouring of roads and foundations, is characterized by values of the filtration coefficient varying from 0.5 to 7 m/day.

A series of dependencies describe relations of the filtration factor K_f and the content of clay particles C [9, 18].

A generalising approximation of V.A.Shevnin is used for applied purposes [17]:

$$K_f = C^{-2} \cdot 7.2 \cdot 10^{-4}. \tag{1}$$

A formal analogy between the geofiltration field in a porous medium and a constant electric current field is a prerequisite for the existence of stable relationships between the parameters determining the permeability of dispersed rocks, and their electrical conductivity [9]. However, this relationship is very complicated, since it depends on the set of factors, among which are, in the first place, size and shape of grains composing the soil, total porosity, pore space configuration, water mineralisation, temperature, composition of rock cement and many other conditions.

Experimental data indicate the relatively stable correlation between specific electrical resistance (SER) and permeability in conditions of low-mineralised waters. SER of sandy clay rocks increases usually monotonically with growing K_f in limited areas. Moreover, changing mineralisation of groundwater can fundamentally alter this relationship, therefore, it is more reasonable to use such an auxiliary parameter as relative resistance, with regards to SER of pore moisture [5, 9, 13].

Despite a number of limitations in practical use, an approach based on measurements of soil SER and groundwater salinity is nowadays a generalising technique for determining permeability [12, 15].

We consider an approach based on calculating the Q factor of sandy-clay soils according to ground penetrating radar data as an alternative to the current methodology for permeability determining. Q is the ratio of the energy stored in the oscillating resonator to the energy dissipated per cycle by damping processes [16]. Q is used in ground penetrating radar to characterise dielectric losses or attenuation and scattering of electromagnetic waves [14] and can be considered as an additional independent electrophysical parameter to distinguish the soil properties. It is known that the increasing content of the clay fraction is the main cause of decaying electromagnetic wave in the soil [6].

Correlation between clay content and the ratio of the real ε' and imaginary ε'' parts of the dielectric permittivity [20]

$$C = \sqrt[0.15]{\frac{\varepsilon'' + 0.23}{0.19\varepsilon'}}\,, \tag{2}$$

as well as between clay content, the Q factor and humidity θ

$$C = \sqrt[0.16]{\frac{28.2}{Q\theta^{0.1}}} \tag{3}$$

allow with considering (1) finding a dependence between the ratio of the real and imaginary parts of the dielectric permittivity and permeability:

$$K_f = \frac{1}{\sqrt[0.15]{\left(\frac{\varepsilon'' + 0.23}{0.19\varepsilon'}\right)^2}}\,7.2\cdot 10^{-4}. \tag{4}$$

Calculation of permeability value through the Q factor and humidity with considering (1) and (3) can be formulated as follows:

$$K_f = \frac{1}{\sqrt[0.16]{\left(\frac{28.2}{Q\theta^{0.1}}\right)^2}}\,7.2\cdot 10^{-4}. \tag{5}$$

Dependencies (2) and (3), obtained by [20] and altered taking into account (1) for samples with different permeability values are shown in Fig. 1.

Fig.1, *a* shows that the ratio of the imaginary and the real parts of the complex permittivity depend on changing humidity and permeability; the latter, in turn, is controlled by the content of clay particles. Moreover, the change in humidity is reflected to a greater extent on the real part of the complex dielectric permittivity, and permeability dynamics affects the imaginary part. Fig.1, *b* wit-

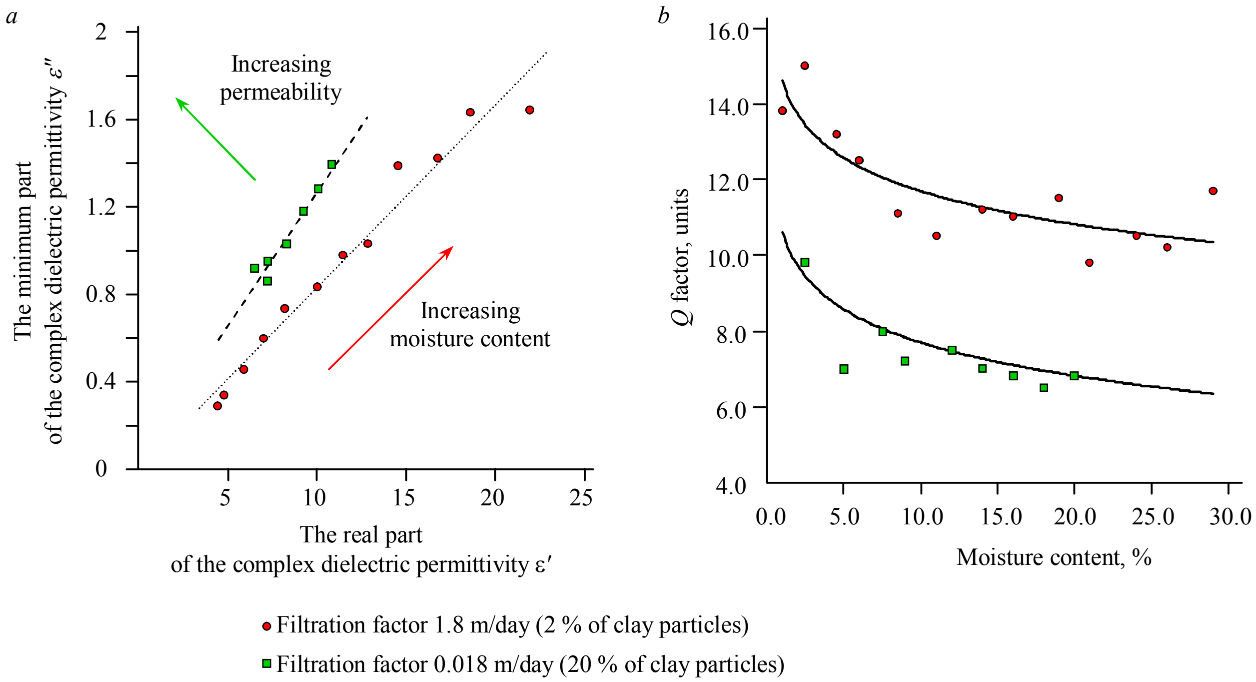

Fig.1. The ratio of the imaginary and real permittivity parts (*a*)
and Q factor depending on moisture content (*b*) for samples with different filtration factors

nesses that at the same moisture content in samples, the higher sand permeability is, the higher the Q factor becomes.

The relationship between the Q factor, electrical conductivity, and the real and imaginary parts of dielectric permittivity is described by the following equations:

$$\sigma_{ef}(\omega) \approx \sigma_{DC} + \omega\varepsilon''(\omega) \tag{6}$$

and

$$\varepsilon_{ef}(\omega) \approx \varepsilon'(\omega), \tag{7}$$

from which follows [17]

$$Q = \frac{\omega\varepsilon_{ef}(\omega)}{\sigma_{ef}(\omega)} \approx \frac{\omega\varepsilon'(\omega)}{\sigma_{DC} + \omega\varepsilon''(\omega)}, \tag{8}$$

where $\sigma_{ef}(\omega)$ is effective conductivity; σ_{DC} is electric conductivity of continuous current; $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ are the imaginary and real permittivity parts respectively; $\varepsilon_{ef}(\omega)$ is effective dielectric permittivity.

Taking into account that the angular frequency $\omega = 2\pi f$, specific electrical resistance $\rho = 1/\sigma_{DC}$ and electrical permittivity of vacuum $\varepsilon_0 \approx 8.85\cdot10^{-12}$ F/m, the formula can be derived from (8):

$$\varepsilon'' \approx \frac{\varepsilon'}{Q} - \frac{1}{\rho f\cdot 2\pi\varepsilon_0}, \tag{9}$$

where f is frequency.

Then, substituting (9) into (4), we get the formula suitable for applied calculations:

$$K_f \cong \frac{1}{\sqrt[0.15]{\left(\dfrac{\rho f\cdot 2\pi\varepsilon_0\varepsilon' - Q + 0.23Q\rho f\cdot 2\pi\varepsilon_0}{Q\rho f\cdot 2\pi\varepsilon_0\cdot 0.19\varepsilon'}\right)^2}}\,7.2\cdot10^{-4}. \tag{10}$$

Complexity is the advantage of equation (10) because of considering a number of measured electrophysical parameters that affect permeability. Values of ε', f are determined by ground penetrating radar, ρ values are found by the resistance method. The dependence of the Q factor on the filtration factor and its relative change $\partial Q/\partial K_f$ are shown for sand with given properties on Fig.2.

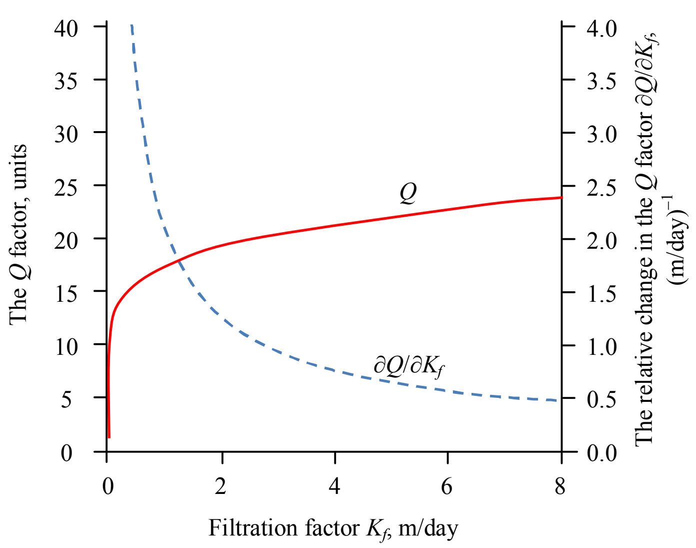

Fig.2. Dependence of the Q factor on the filtration at a frequency $f = 1$ hHz for sand with $\varepsilon' = 4$ values; $\rho = 900$ Ω·m and the relative change in the Q factor $\partial Q/\partial Kf$

The boundary of the transition through the 3 m/day value of the filtration factor between water-permeable and highly water-permeable soil [2], is followed by a steady increase in the Q factor from 15 to 25 units and its high sensitivity to changing filtration factor in the range from 1 to 10 m/day.

To perform calculations using formula (10), it is necessary to determine the Q factor. The method of amplitude decay, realized in the time domain is one of the simplest and most widely used methods for determining the Q factor [19]. The

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Q factor is calculated from the signal amplitude ratio recorded before and after the passage of a wave through an absorbing medium:

$$Q = \frac{\omega \Delta x}{2V} \left\{ \ln \left[\frac{A(x_0)}{A(x_1)} \right] \right\}^{-1}, \tag{11}$$

where $\omega = 2\pi f$ is a centre frequency of a signal; Δx is a layer thickness; V is wave speed; $A(x_0)$ and $A(x_1)$ are amplitudes of the original and reflected signal, respectively.

In the case of the ground penetrating radar method, the amplitude of a direct wave spreading in the air is usually used as the initial amplitude $A(x_0)$. The velocity of the wave is determined by the well-known relation

$$V \approx \frac{c}{\sqrt{\varepsilon'}}, \tag{12}$$

where c is the light speed in a vacuum; ε' is the real part of the complex dielectric permittivity, which is determined on the basis of veritable geological information or ground penetrating radar sounding data.

In the case of a two-layer model of a medium, the overall Q factor of the model and of the first layer are calculated by the formula (11). The Q factor of the second layer is determined using the expression:

$$\overline{Q} \cdot \overline{h} = Q_1 h_1 + Q_2 h_2, \tag{13}$$

where $\overline{Q}$ is the effective (general) Q factor of a two-layer model with a thickness $\overline{h} = h_1 + h_2$; Q_1, Q_2 are the Q factors of the first and second layers; h_1 and h_2 are thicknesses of the layers.

A similar approach is used for multi-layer models if we know the reflected signals of the amplitudes that limit a sole and roof of the layer, for which Q factor is to be determined.

Thus, the determination of the Q factor by the well-known technique based on the method of resistance and ground penetrating radar using empirical dependence (10), obtained on the basis of (1), (2), and (8), allows determining the filtration factor of sandy clay soils using veritable information on the depth of the boundaries h_i.

Object of research. Testing of the proposed methods of studying the filtration properties of sands according to the complex application of ground penetrating radar and electrical resistivity tomography was performed on a section of a highway right after completion of its construction.

Texture and geometric parameters of structural layers of the pavement at the surveyed site, in accordance with the design and performance documentation, are presented in the following form: asphaltic concrete $h_1 = 0.21$ m; crushed-stone layer $h_2 = 0.40$ m; draining layer of fine-grained sand $h_3 = 0.45$ m; crushed-stone layer $h_4 = 0.15$ m; geotextiles and geogrids $h_5 = 0.05$ m.

The lower part of the roadbed is located under the geotextile and covered with fine sand, which underlays natural clay soils. A lens of peat was found under the soil of the surveyed road section. According to the executing documentation, the peat layer was removed only partially that led to subsidence of the soil of the roadbed during construction. Geophysical surveys using ground penetrating radar and electrical resistivity tomography were executed through the transect crossing the asphalt-concrete pavement. The central transect part went through the subsidence area of the roadbed.

Ground penetrating radar profiling operations were performed using Zond-12e equipment (Radar Systems, Inc., Riga). The two-frequency survey at the central frequencies of the probing pulses 500 and 1000 MHz was performed to investigate the pavement section. The use of two frequencies provided the sounding at different depths with diverse spatial resolution. The survey was carried out using the standard methodology of ground penetrating radar tracking profiling.

The electrical resistivity tomography was performed using Alfa-1 Resistivity System (Special Design Bureau for Seismic Instrumentation, JSC, Saratov) in the mode of multi-bearing profiling with a non-contact dipole axial installation at a frequency of 16.5 kHz. The sizes of the measuring and feeding capacitive dipoles are 1.25 m. The distances between the centres of the dipoles were: 1.25; 2.5; 3.75; 5; 10; and 15 m.

Research results. The georadargram obtained with a 1000 MHz antenna shows bright and elongated coherence axes, controlling the boundaries between layers of pavement and consisting of asphalt concrete, gravel, sand, and polymeric geogrid and geotextile (Fig.3). According to the executing documentation, the surface of both geogrid and geotextile is located horizontally and at a constant depth. Nevertheless, the in-phase axis corresponding to the wave reflected from this surface is stepwise immersed at the georadargram in the region of PK1+60. Dynamic attributes of a wave field allow relating this distortion of the in-phase axis to the change in the propagation speed of electromagnetic pulses in the drainage layer. Speed in the first interval (0-50 m) is greater than in the second (50-100 m), which may be due to sand moistening within the second interval. Changes in wavelength, structure and intensity of the electromagnetic wave field indicate this (Fig.3).

Thus, the layer of the drainage sand cushion is compressed on the time section at the first interval PK1+00 – PK1+50. This layer, on the contrary, expands on the interval PK1+50 – PK2+00 and it seems that in the area of PK1+70 – PK1+80, the base of the pavement is subsiding.

Meanwhile, all the stages of construction of this section of the highway were detailed in the executive documentation, stating that the geometry of the pavement layers strictly corresponds to the initial design. In addition, ground penetrating radar research was carried out immediately after the construction was completed, and in such a short period the subsidence of the pavement base could have occurred with a low probability.

Based on this information the layer-by-interval interpretation was accomplished and consisted in the assignation of the dielectric permittivity value to each interval of the selected layer so that the transition from a temporary vertical scale to a deep one kept the geometry of the pavement without deformations of its base. The results of layer-by-interval interpretation are shown in Fig.4.

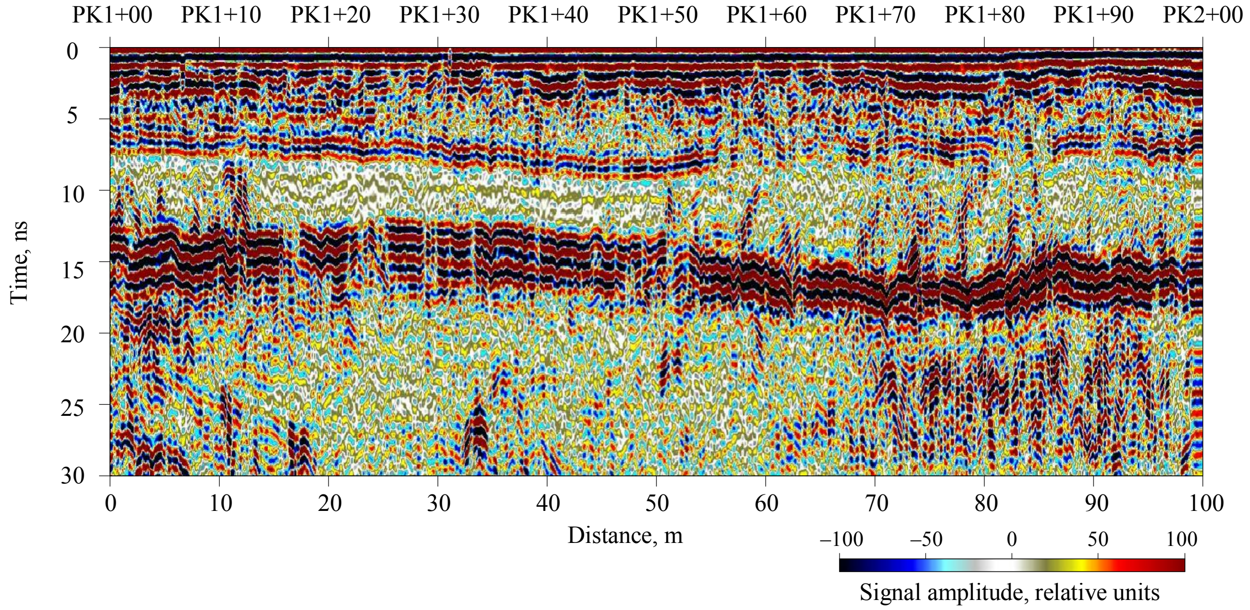

Fig. 3. Temporal ground penetrating radar section at 1000 MHz

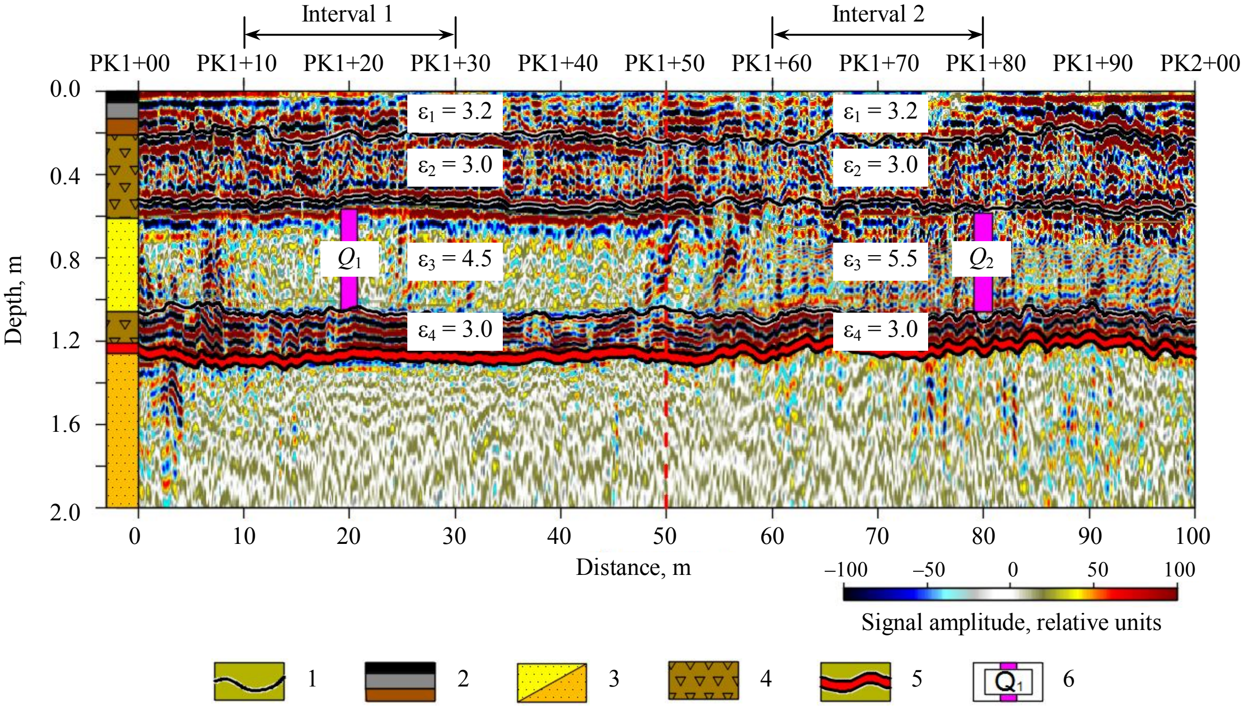

Fig.4. The structure of the upper pavement part according to the ground penetrating radar data

1 – established boundaries according to ground penetrating radar reconnaissance data; 2 – asphaltic concrete; 3 – fine sand; 4 – crushed granite; 5 – polymeric geogrid and geotextile; 6 – Q-switching intervals

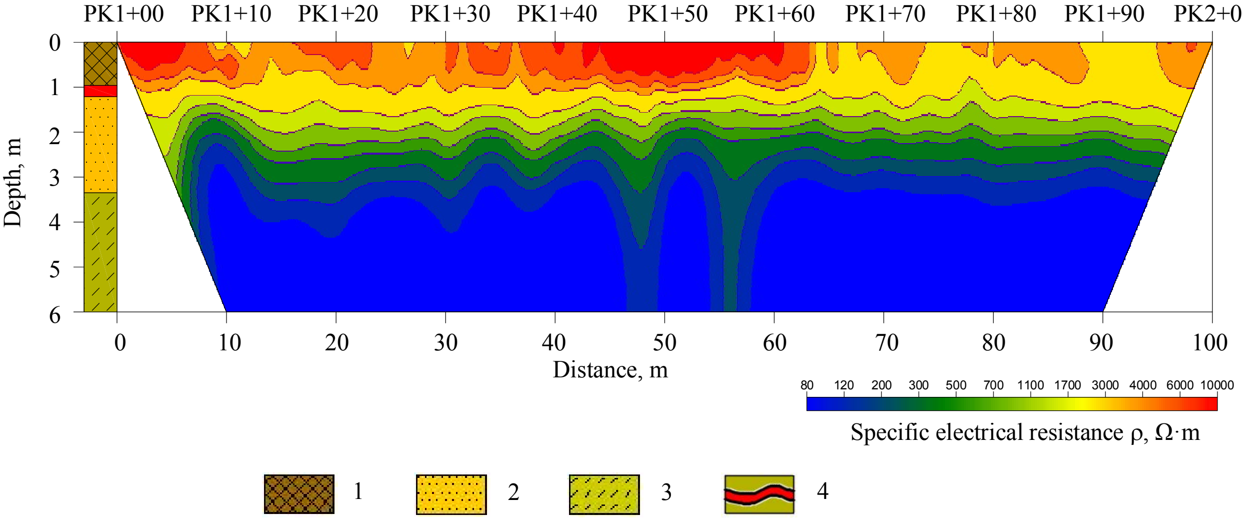

Fig.5. SER distribution model by results of 2D inversion

1 – pavement; 2 – roadbed; 3 – underlying layer of natural soils; 4 – polymeric geogrid and geotextile

An electro-tomography model (Fig.5) is calculated based on multi-purpose non-contact electrical profiling. The model reflects well the structure of the main layers of pavement and its foundation. The SER values are high in pavements, average in the roadbed, and low in natural underlying soils. The even distribution of SER is a disadvantage of the model allowing to assume the spatial location of interpretational boundaries, but not to draw them unambiguously.

SER integral values were obtained in 1D inversion mode for selected layers of a road with fixed boundaries chosen on the basis of ground penetrating radar data (Fig.6).

SER values were obtained for each interval by averaging three neighbouring observed curves of electric dipole zoning (EDZ). Averaged three-layer EDZ curves of the *Q*-type and the corresponding SER models are shown in Fig.7.

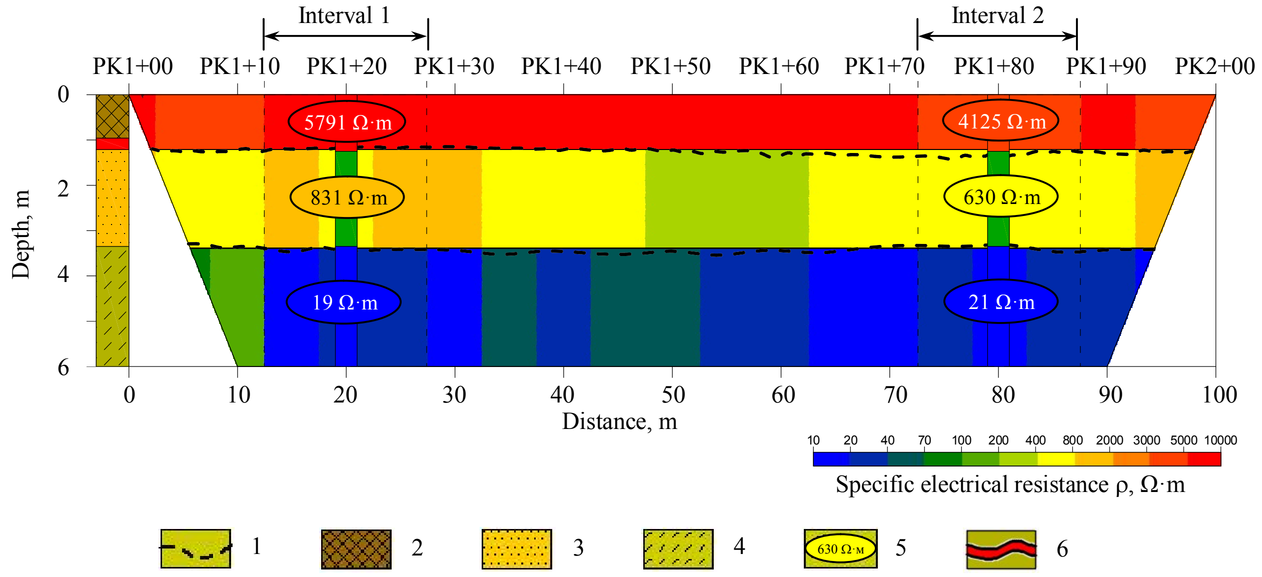

Fig. 6. SER distribution model by results of 1D inversion with fixed ground penetrating radar area and interval interpretation of the SER

1 – borders determine by geolocation; 2 – pavement; 3 – roadbed; 4 – underlying layer of natural soils; 5 – SER levels; 6 – polymeric geogrid and geotextile

Two intervals of the sand layer in the area of PK1+20 and PK1+80 were selected to determine the *Q* factor. The intervals, as can be seen on the radarogram, differ significantly from each other in the wave pattern. An averaged trace (Fig.8, *a* and *b*), was obtained for both intervals in order to conduct further calculations of electrophysical and petrophysical parameters. The results of calculations are presented in the table.

Calculation of electrophysical parameters and derived petrophysical characteristics for paving sand showed that the first interval of PK1+20 is characterized by high values of the SER and *Q* factor, which is reflected in the resulting insignificant amount of clay particles, and, as a consequence, relatively high 4.4 m/day filtration coefficient. The second interval of PK1+80 is characterized by lower values of SER and the *Q* factor relative to the first interval, which is reflected in increased in clay content and much smaller 1.4 m/day filtration factor.

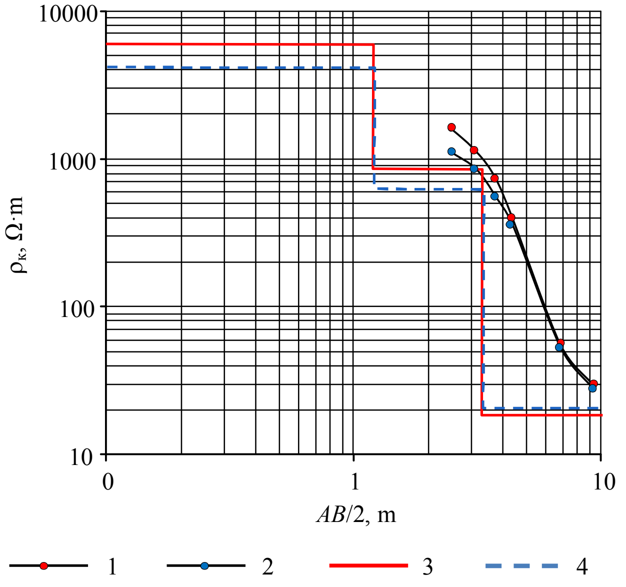

Fig. 7. Averaged EDZ curves and the SER models derived from them for intervals 1 and 2

$\rho_{\text{к}}$ – apparent resistivity;
AB – current line spacing

1, 2 – averaged EDZ curves on intervals 1 and 2, respectively;
3 – SER model on the interval 1 (8 % discrepancy);
4 – SER model on the interval 2 (7 % discrepancy)

Laboratory analysis of the filtration factor of draining sand cushion taken from the roadside showed the values of K_f = 3.5 m/day. This level differs significantly from the K_f values calculated from the data of ground penetrating radar and electrical resistivity tomography. The difference between laboratory data and geophysical data indicates that the sands could be contaminated during construction. It should be noted that the intervals studied differ substantially in their electrophysical and petrophysical properties. Data obtained on the basis of geophysical studies allow characterizing the layer of the drainage sand cushion in the second interval of PK1+80 as more humid (lower SER, higher ε') and less permeable (increased clay content *C*, lower filtration coefficient K_f) relative to the first interval.

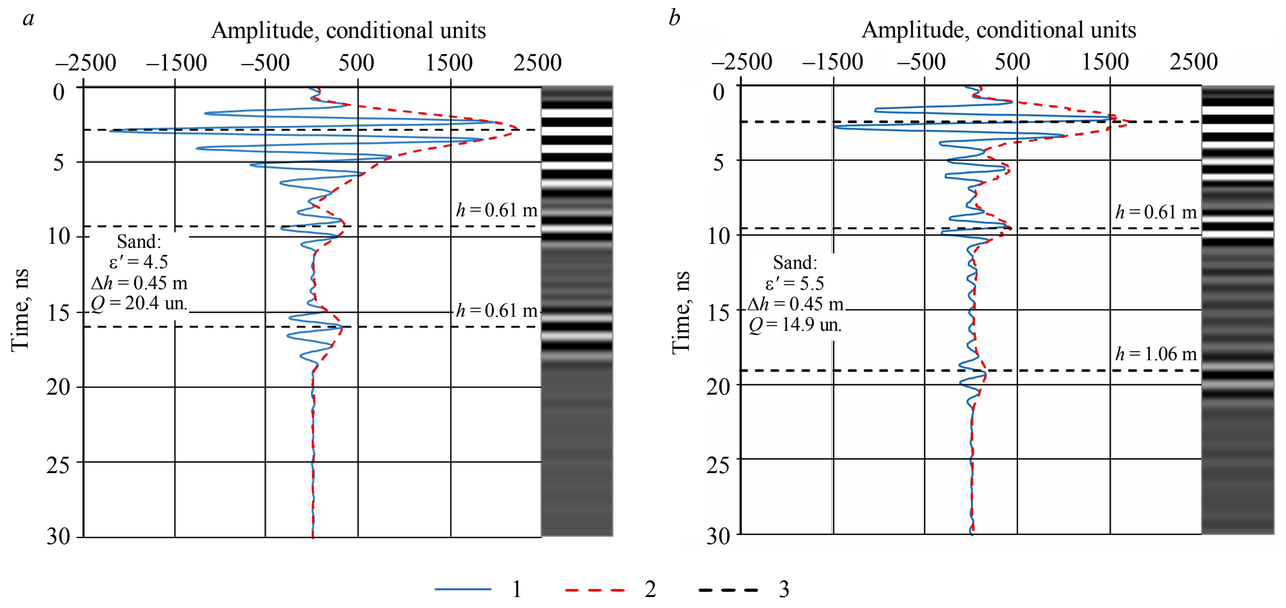

Рис.8. Averaged traces with calculating parameters for intervals 1 (*a*) and 2 (*b*)

1 – averaged trace; 2 – signal envelope; 3 – position of reflecting boundaries

Measured electrophysical and calculated on their basis petrophysical parameters for two intervals of drainage sand cushion layer

Characteristics	Interval 1	Interval 2
ε'	4.5	5.5
ρ, $\Omega\cdot$m	5791	4125
Q, units	20.4	14.9
K_f, m/day	4.4	1.4

Despite the fact that the numerical values of the filtration factor and clay content were obtained for a sand layer, it is necessary to take into account the empirical nature of the dependencies on the basis of which they were calculated, and treat them not as a quantitative definition of these parameters, but as their relative qualitative assessment.

Conclusion. An alternative approach to assessing the filtration factor of sandy clay soils is considered based on a set of resistance and ground penetrating radar methods. Determination of clay content, which is controlled by a petrophysical relationship between imaginary and real parts of the dielectric permittivity and specific electrical resistance connected through the Q factor and obtained on the basis of resistance and ground penetrating radar methods, allows estimating the filtration factor of sandy clay soils. High data resolution of ground penetrating radar methods is an indisputable advantage of this approach in relation to the already existing. This gives an ability to evaluate petrophysical parameters of thin soil layers. The disadvantage is the limited area of use that consists in the need to have radarograms of bright reflecting ground penetrating radar borders and well-maintained direct wave that is possible only at an ideal contact between an antenna and a surface investigated.

An applied example of the use of ground penetrating radar methods and non-contact electrical resistivity tomography showed the effectiveness of this complex in working conditions on asphalt pavement. Ground penetrating radar tracking studies carried out according to a standard procedure, allowed to characterize the structure of both pavement and soil base with a high degree of detail. The electrical resistivity tomography studies made with a non-contact induction electric survey equipment, which use on asphalt road surfaces is innovative, also showed their effectiveness. The electrical resistivity tomography high-resolution model reflected all the major elements of the pavement and roadbed. Data obtained by independent geophysical methods characterise the number of pavement layers and their geometric relationships and correlate with each other and with the data presented in the project documentation. Basing on rapid assessment it was also possible to find changes in the filtration factor of the sand pavement layer and to describe its relative quantitative characteristics for different road sections.

Thus, the considered set of ground penetrating radar and contactless electrical resistivity tomography methods can be recommended for solving the problems of author supervision and quality control of road construction.

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