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PETROPHYSICAL APPROACH TO ELECTRICAL PROPERTIES OF LOOSE SOILS

Vladimir A. SHEVNIN[1], Dina A. KVON[1], Albert A. RYZHOV[2]
[1] *Moscow State University*, *Moscow*, *Russia*
[2] *VSEGINGEO*, *Moscow region*, *Noginsk district*, *settl. Zeleny*, *Russia*

The paper focuses on the relation between geoelectrical characteristics of the soil: resistivity, polarizability and normalized polarizability (ρ, η, M_n) – and its superficial conductivity (*SC* or σ") using methods of vertical electrical sounding with induced polarization (VES-IP), electric profiling with induced polarization (EP-IP) and frequency characteristic (FC-IP). The authors demonstrate that superficial conductivity can be determined not only from spectral IP data, but also from soil resistivity obtained through petrophysical measurements. In this case normalized polarizability (M_n) is equal to superficial conductivity (*SC*). Superficial conductivity, in its turn, is proportionate to clay content of the soil. Increasing clayiness reduces hydraulic conductivity. It has been demonstrated that interpretation of EP-IP results benefits from combined study of the plots of three abovementioned parameters (ρ, η, M_n). In the aeration zone, incomplete humidity has a significant effect on geoelectrical parameters of the soil. Petrophysical modelling helps to investigate the impact of humidity.

***Key words*:** loose soil, electrical resistivity, polarizability, petrophysical soil properties, clay content, superficial conductivity, filtration coefficient

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Introduction. Current research has been inspired by the ideas of A.A.Ryzhov and A.Weller. A.A.Ryzhov revealed the opportunities of petrophysical approach by showing that soil resistivity could be theoretically described in the forward problem (calculation of resistivity from known petrophysical parameters) and the inverse one (estimation of petrophysical parameters basing on measured geophysical characteristics: resistivity of soil, water etc.). A.Weller demonstrated that a well known parameter of induced polarization (IP), also known as metal factor in mining geophysics and normalized polarizability in hydrogeophysics ($M_n = \eta_k / \rho_k$, where η_k – polarizability, ρ_k – resistivity), is closely related to superficial conductivity. Metal factor was introduced by American geophysicists in late 1950s. In engineering geophysics N.N.Sharapanov proposed an IP parameter: A* [7], similar to the metal factor. V.A.Shevnin studied this parameter in 1970s during his work in Central Kazakhstan [3].

Petrophysical and electrical soil parameters

Parameter	Known 1	Unknown 1	Known 2	Unknown 2	Depends on
1. Temperature	+	–	+	–	
2. ρ_water	+	–	+	–	
3. ρ_soil	+	–	+	–	
4. Sand porosity	+	–	–	*F*	
5. *R*_sand	+	–	–	*F*	
6. Clay porosity	–	*F*	+	–	
7. *R*_clay	–	*F*	+	–	
8. IEC_clay	–	*F*	+	+	
9. Humidity	+	+	+	+	
10. Clay content	–	+	–	+	
11. IEC	–	+	–	+	
12. Soil porosity	–	+	–	+	*f*(4, 6, 10)
13. K_f	–	+	–	+	*f*(10)
14. *RSC*	–	+	–	+	*f*(2, 8, 10)

Note. *R* – capillary radius, IEC – ion-exchange capacity, K_f – filtration coefficient, *RSC* – resistivity (reciprocal of superficial conductivity); number 1 means prevailing sand, number 2 – prevailing clay; plus stands for a known value, minus – for an unknown or insignificant one, *F* – recommended value.

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Methods. Relation between petrophysical soil properties and electrical resistivity was theoretically described by A.A.Ryzhov in [6] and later, in greater detail, in [2]. In these publications soil is regarded as a mix of coarse and fine fractions (e.g. sand and clay) and the pore liquid. Soil resistivity depends on the porosity and capillary radius of each fraction, their share in the overall composition, humidity and salinity (or resistivity) of the pore liquid, ion-exchange capacity and temperature. Knowing characteristics 1-2 and 4-10 (see Table), one can calculate soil resistivity, as well as parameters 11-14. If characteristics 1-9 are defined through experiment, solution of the inverse problem provides the values of parameters 10, 11 and 12-14.

A 2-D resistivity section was prepared, results of its conversion into the sections of clay content and filtration coefficient are presented in Fig.1. It was established that electrical resistivity of the rock can be expressed as a sum of electrolytic σ' and surface σ" conductivities: $\sigma = \sigma' + \sigma''$ [14]. In publication [10] authors proposed a dual-water model, where rock conductivity is a sum of electrolytic conductivity σ' (water in wide pores) and superficial conductivity σ" (water in narrow clay pores). Electrical conductivity is a complex value, its real part corresponds to electrolytic conductivity σ' (water solution), and imaginary part – to superficial conductivity σ" (associated with the double layer in narrow capillaries). F.Borner [9] discovered that σ" is related to Spor (relative pore surface – a ratio between pore surface and its volume) and hydraulic conductivity K_f (filtration coefficient). A possibility to assess hydraulic conductivity using spectral IP data was demonstrated in publications [12, 13].

There are two approaches to superficial conductivity estimation: by means of spectral induced polarization (SIP) [12, 13, 15] or using petrophysical approach to resistivity data, proposed by A.A.Ryzhov [11]. «Petro» software, developed by A.A.Ryzhov, calculates superficial conductivity using the following formula: $\sigma_{SC} = C_{Clay}\sigma_{Clay}/K_{Clay}$ (where C_{Clay} – clay content; σ_{Clay} – clay conductivity, which depends on salinity of the pore liquid and ion-exchange capacity; K_{Clay} – clay porosity). These characteristics are determined using data on soil resistivity and pore liquid salinity and take into account the soil model [5]. Instead of superficial conductivity we often use its reciprocal – resistivity *RSC* [11].

In 2000-2007, investigations of oil contaminations in the soil led us to a discovery that superficial conductivity yielded the best results of separating clean soils from contaminated ones, as compared to resistivity and a number of other petrophysical parameters [11]. Resolution capacity was estimated using histogram separation index $SI = dX / stnd$ (where dX – distance between maximum histogram values of clean and contaminated soils; *stnd* – standard deviation, measure of histogram width).

RSC parameter in Fig.2 was normalized in such a way that its positive values indicated that the soil was clean, whereas negative values meant it was contaminated. It corresponded to $SI = 6$ or, according to the three sigma rule, exhibited total histogram separation. For the case of electrical resistivity, the separation index was lower ($SI = 2.5$, Fig.2). Superficial conductivity of contaminated soils is closely related to oil biodegradation (its emulsification and development of biofilms – bacteria accumulations in the rock pores), which changes the structure of pore space and increases the role of electrical double layer (EDL) by raising the number of fine pores.

The authors of paper [15] established a high correlation ($R^2 = 0.907$) between M_n and superficial conductivity (Fig.3). According to their calculations, M_n/σ'' ratio amounted to 0.2.

We checked the correlation between M_n and *SC* (σ") using data from vertical electrical sounding with induced polarization (VES-IP) and electric profiling with induced polarization (EP-IP), obtained by the students of Moscow State University (MSU) during geophysical internship in the Kaluga Oblast. *SC* value was estimated in A.A. Ryzhov's software «Petrofizika» [2] basing on soil resistivity. We obtained a ratio of $M_n/SC = 1$, i.e. M_n was simply equal to superficial conductivity *SC*. Such difference can be explained by the fact that polarizability changes significantly depending on experiment conditions.

Fig.4 contains two groups of sampling points (two clouds), derived from a quantitative 1-D interpretation of VES-IP data. Greater values of M_n and *SC* correspond to loams, the second cloud – with smaller values – corresponds to sands.

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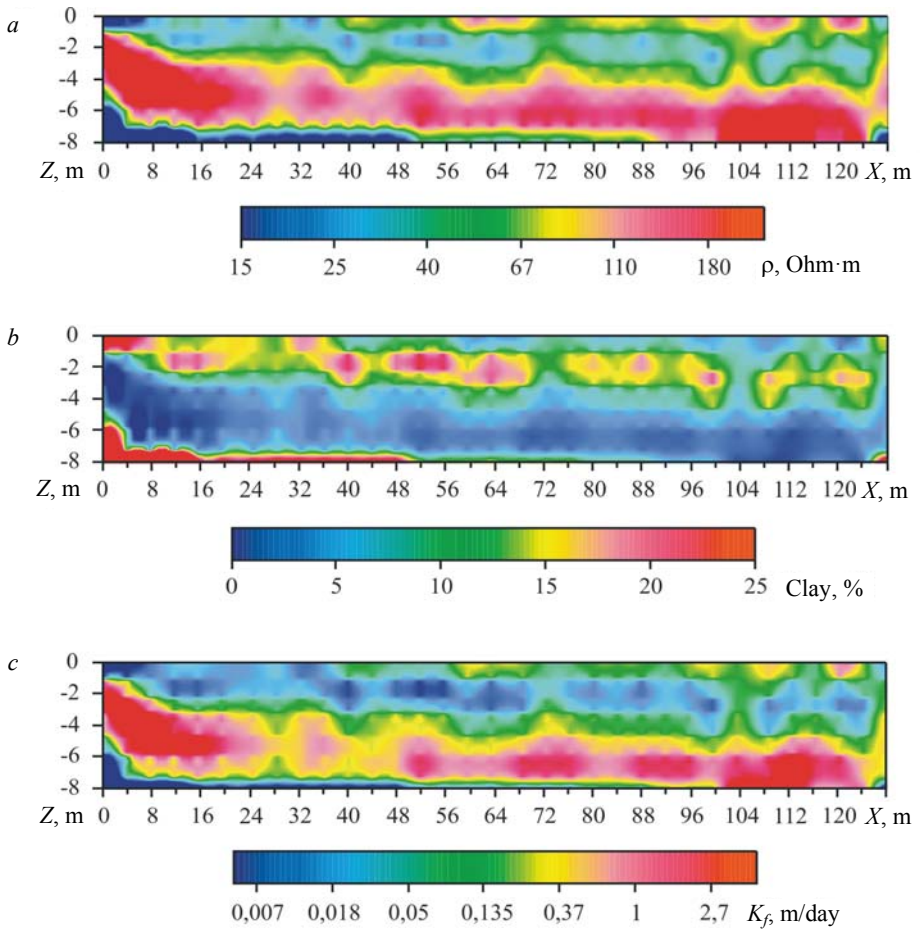


Fig.1. Example of a 2-D resistivity section (*a*), converted into the sections of clay content (*b*) and filtration coefficient (*c*)

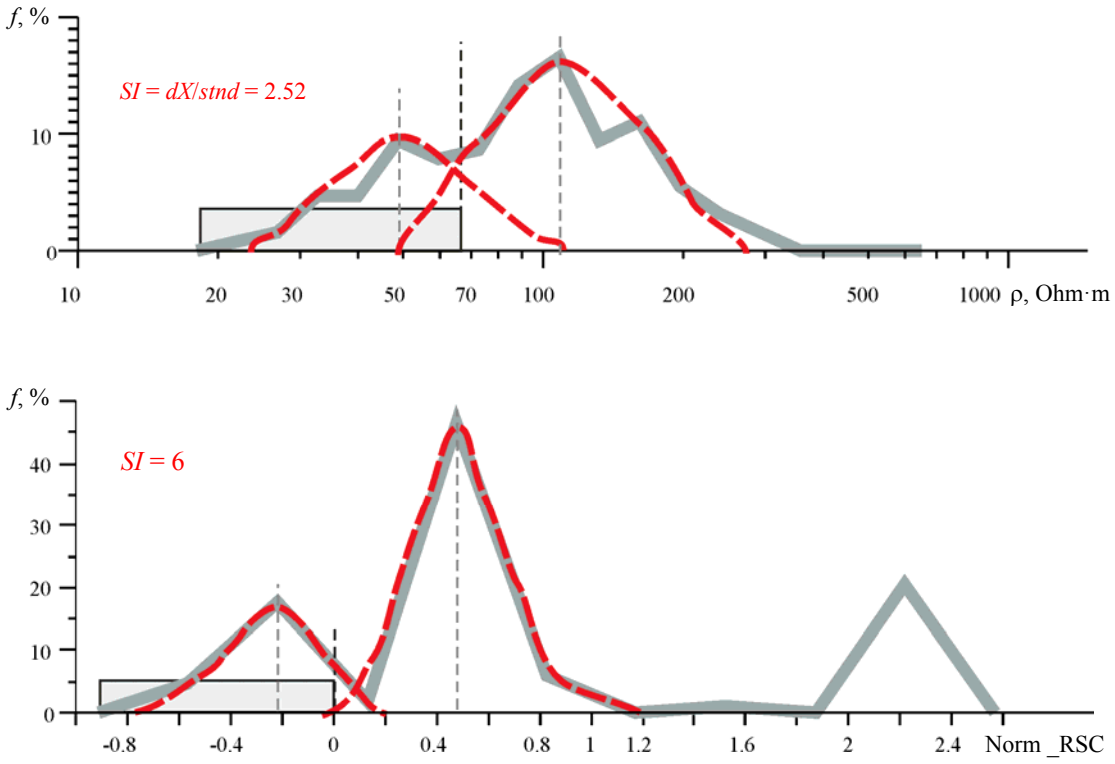


Fig.2. Histograms of electrical resistivity and *RSC* soil resistivity associated with superficial conductivity, and the separation index for clean and contaminated soils

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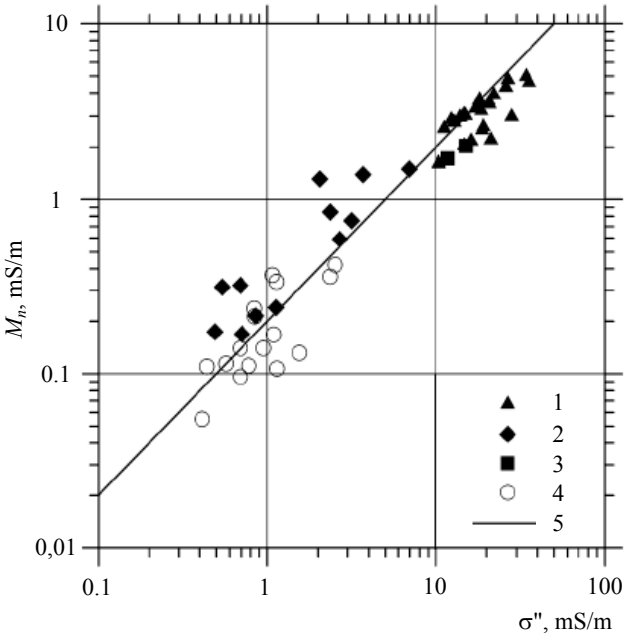


Fig.3. Correlation between M_n and superficial conductivity σ" [15]
1-4 – various soil collections; 5 – correlation line $M_n = 0.2\sigma''$

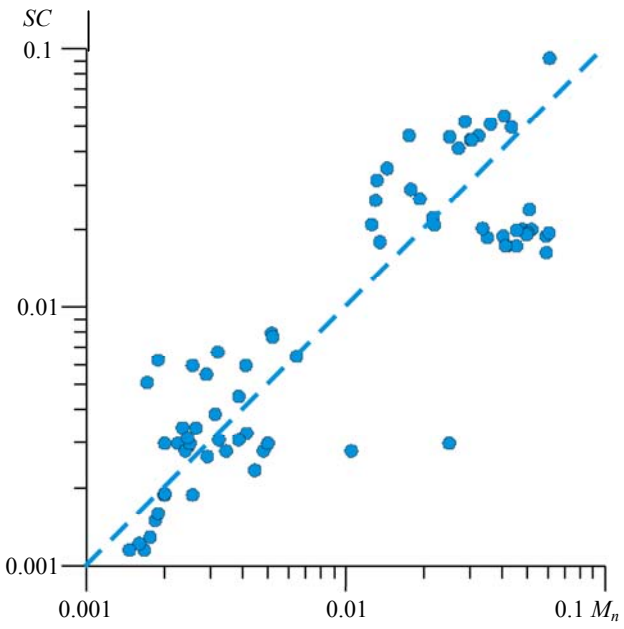


Fig.4. Correlation between the values of $M_n = \eta/\rho$ and superficial conductivity for the actual parameters (1-D interpretation) of VES-IP profile layers (MSU facility «Maloye Ustye», July 2014)

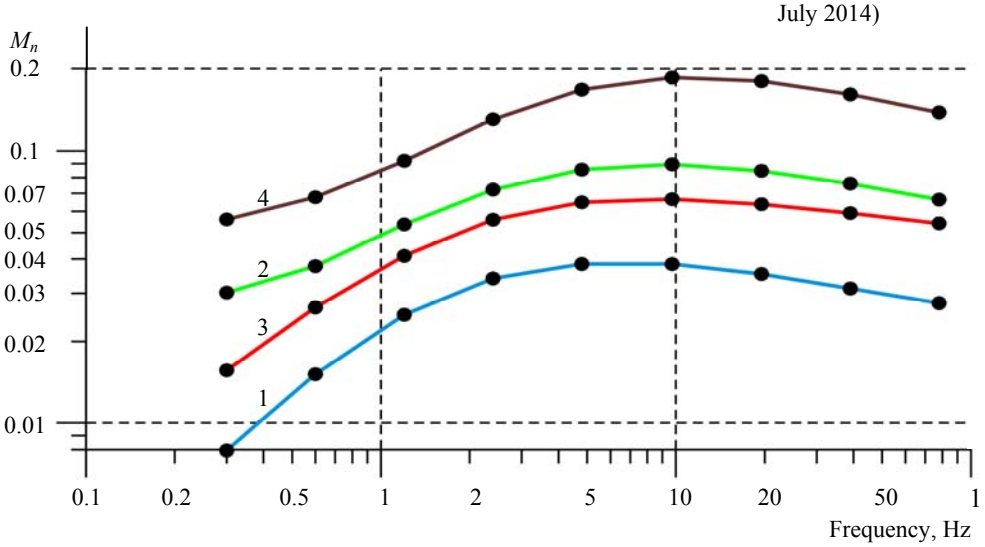


Fig.5. Dependency between $M_n = \eta/\rho$ and frequency for samples 1-4 [8]

Dependencies between M_n and frequency (0.3-78 Hz) were plotted for four soil samples collected from EP-IP profiles (Fig.5) [8]. Advantages of using M_n parameter to separate the curves according to their clay content can clearly be seen (line 4 represents maximum clay content, line 1 – minimum one). Similar frequency characteristics (FC) were measured in the course of EP-IP explorations in 2014-2016. Basing on their M_n value, frequency characteristics could be divided into two clouds: an upper one for loams and a lower one for sands. The upper part of the territory section where EP-IP study has been performed was mostly composed of sands and loams, which resulted in clear separation of the curves. It should be noted that dependencies between frequency and η_k could not be divided as easily as in the case of M_n.

Addition of normalized polarizability M_n to η_k and ρ_k plots in the profiling process (EP-IP) provides better understanding of the section structure (Fig.6). Geological section was obtained by means of electrical tomography on 23 June 2015. From top to bottom the section contains layers of sand, moraine loam, one more interlayer of sand, and bottom loam bed. The actual section differs from the ideal pattern as its slope is covered with a thin layer of scree debris, which conceals the actual outcrop of layer boundaries.

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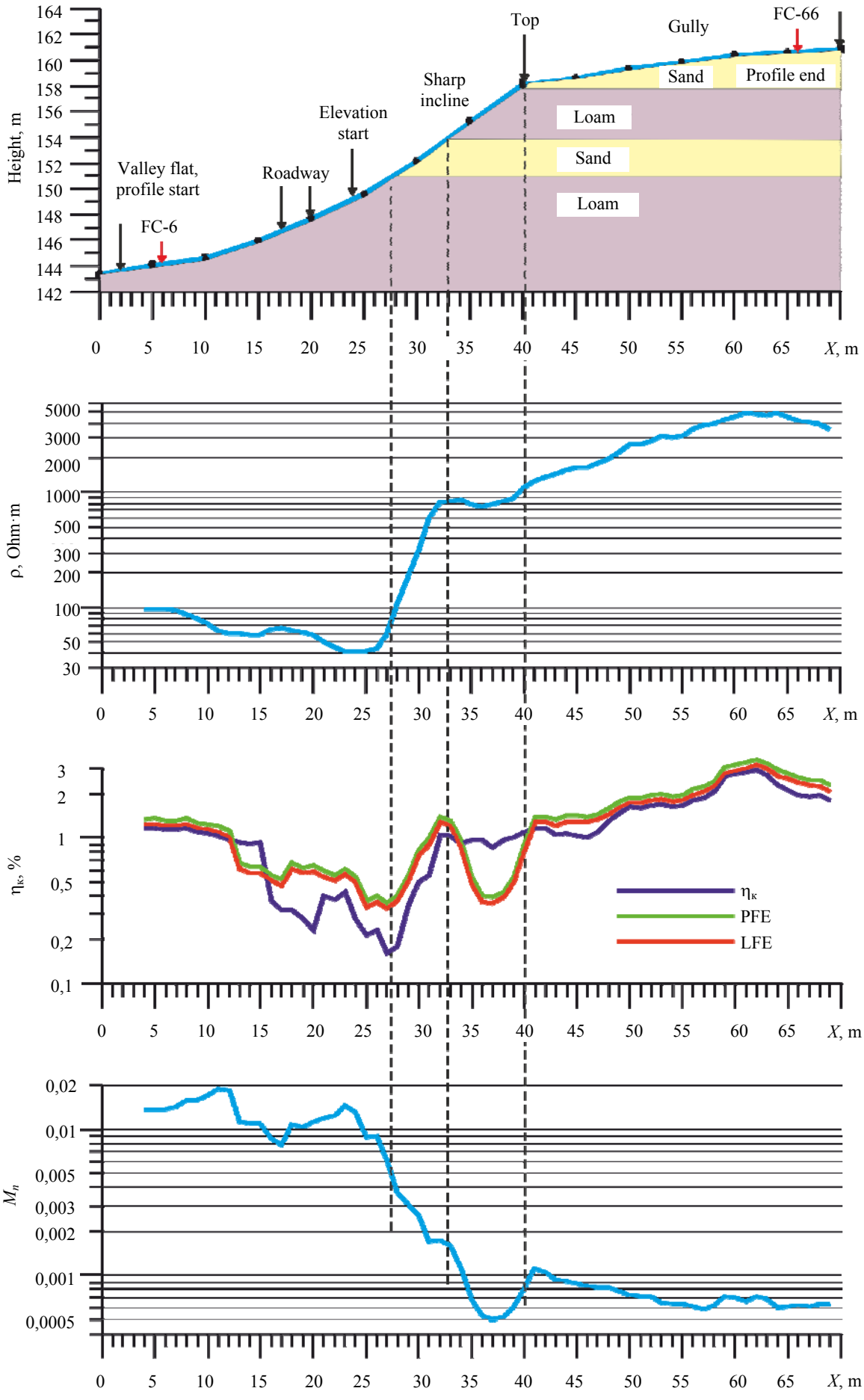


Fig.6. EP-IP plots

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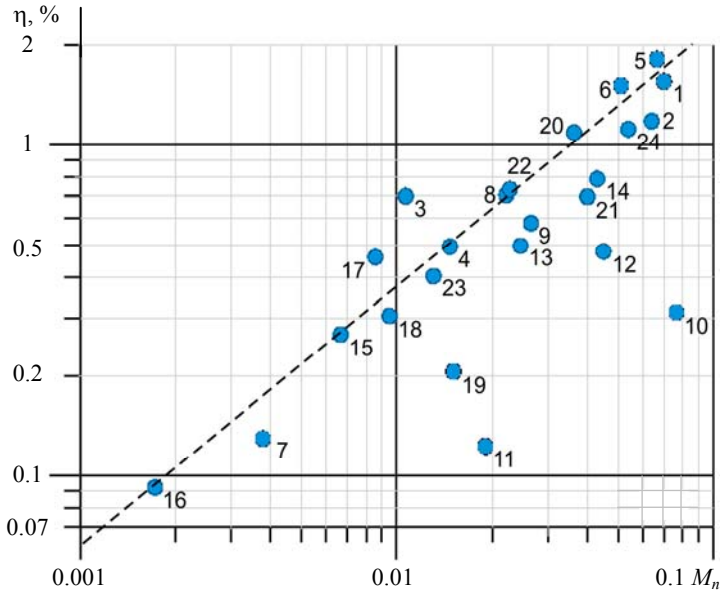


Fig.7. Correlation between IP values of η and M_n for samples 1-24

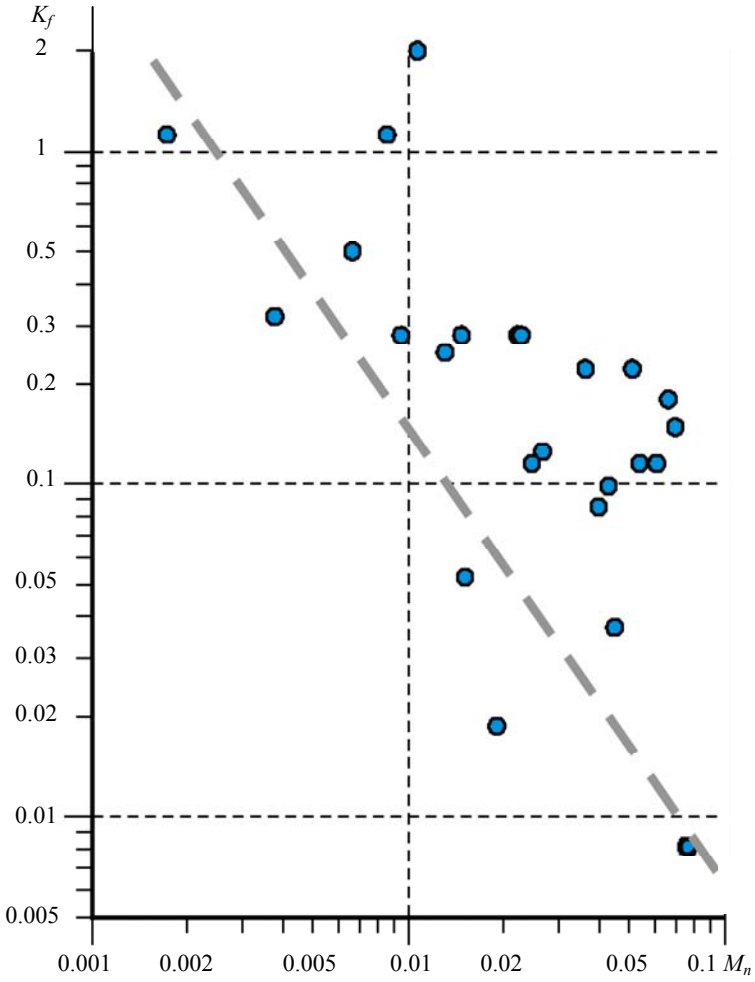


Fig.8. Correlation between K_f and M_n

EP-IP study was carried out with Schlumberger array with $AB = 5$ m, $MN = 1$ m and a step of 1 m, using 2.44 Hz electrical equipment Astra-MARY. MARY measuring unit defined differential phase parameter (DFP) for the 1st and 3rd signal harmonics and registered their amplitudes. DFP value was used to determine polarizability $\eta_k = -2.5$ DFP, whereas amplitudes of the 1st and 3rd harmonics allowed to calculate percent frequency effect (*PFE*) and logarithmic frequency effect (*LFE*). The amplitude of the 1st harmonic together with current intensity served to estimate ρ_k. Five-point moving average smoothing was applied to EP-IP plots.

Comparison of EP-IP plots to the actual terrain and schematic geological section allows to observe the reaction of each parameter to the crossing of geological boundaries. Transition of the bottom sand layer to the slope corresponds to a drastic increase in resistivity, maximum polarizability and a decrease in M_n (at $X = 27$-33 m). An interlayer of loam between two sand layers ($X = 33$-40 m) corresponds to the minimums of polarizability and M_n. The upper layer of sand with its increased thickness is characterized by slowly growing resistivity and polarizability, as well as by a constant value of M_n.

During student internship a variety of soil samples (both from the surface and from the boreholes) were collected in order to measure their resistivity under different salinity, and to estimate polarizability and M_n under different frequencies. Resistivity-salinity plots have been quantitatively interpreted to evaluate clay content of the samples. Correlation between polarizability and M_n of the samples showed (Fig.7) that an increase in M_n coincided with the growth of polarizability. This relationship was slightly different for samples measured in the laboratory at full saturation and specimen measured in the field, where the rocks were partially located in the aeration zone and their saturation varied substantially – more for sands, less so for loams.

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Fig.8 demonstrates a correlation between hydraulic conductivity K_f and M_n for the same sample collection. It has been established that K_f visibly decreases with the growth of M_n.

The impact of soil humidity in the aeration zone can be examined using VES-IP method [4]. The final result for this study is presented in Fig.9 for Alexander plateau dominated by sands. Below the depth of 10 m in the zone of full water saturation bulk humidity equals sand porosity (23 %). The thickness of capillary fringe is 1 m (fine sand). Humidity in the upper part of capillary fringe (CF) amounts to around 20 % of that at the groundwater level (GWL) [1]. Above the capillary fringe humidity decreases and near the surface reaches the value of 1 % (at sand resistivity of (5-10)10^3 Ohm·m). Top soil is dominated by light loams; within its limits an increase in humidity can be observed. In the areas with sand humidity of 2-5 %, VES-IP method detects a substantial growth of polarizability (from 0.5 to 2.8 %) [5].

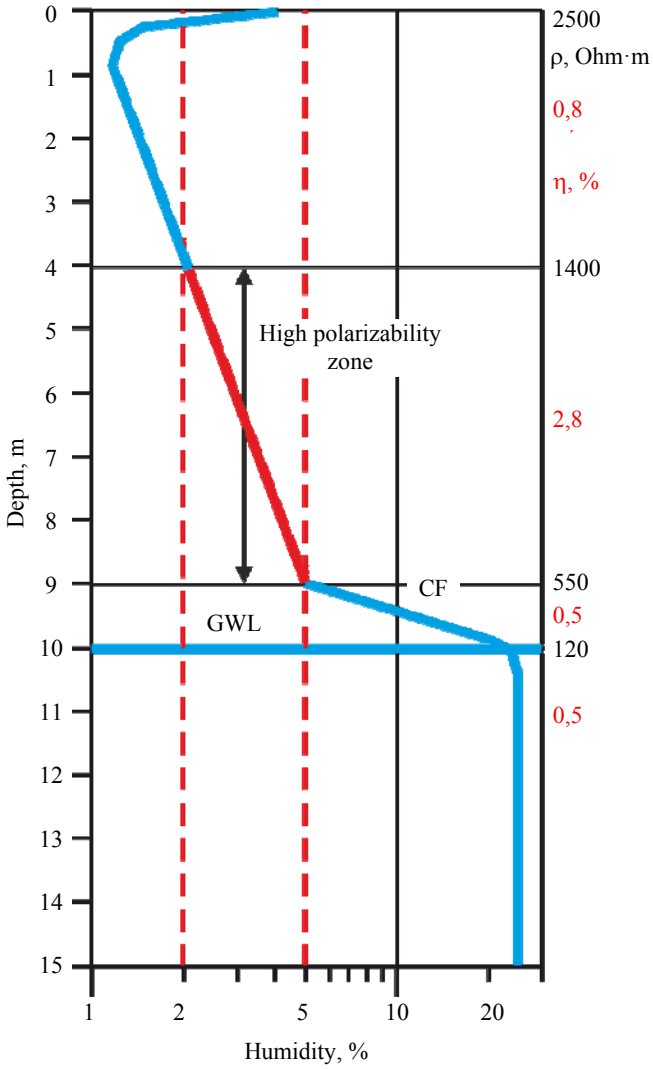


Fig.9. Changes of humidity with depth according to VES-IP data

Conclusions

1. Values of superficial conductivity calculated using IP data equal those obtained with resistivity method.

2. According to our estimations, normalized polarizability M_n equals superficial conductivity.

3. The plots of M_n against frequency display clay content of the soil.

4. Combined study of EP-IP plots of ρ_k, η_k and M_n values offers better understanding of the section structure and lithology.

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***Authors*: Vladimir A. Shevnin,** *Doctor of Physics and Mathematics*, *Professor*, *shevninvlad@yandex.ru* (*Moscow State University*, *Moscow*, *Russia*), **Dina A. Kvon,** *Engineer*, *kvonchikc@rambler.ru* (*Moscow State University*, *Moscow*, *Russia*), **Al'bert A. Ryzhov,** *Candidate of Geological and Mineral Sciences*, *Leading Researcher*, *ryjov@yandex.ru* (*VSEGINGEO*, *Moscow region*, *Noginsk district*, *settl. Zeleny*, *Russia*).

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