INNOVATIVE APPROACH TO EM RESEARCH AND MONITORING OF ENVIRONMENT

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In 1941 when the German armies invaded Sevastopol (Crimea), the Soviet sappers blew up the arsenals of the Black Sea fleet stored in the limy massif galleries known as the Inkerman galleries. However when undermining only small part of the arsenal has been detonated, the massif was strongly destroyed, and the basic part of the arsenal has remained under blockages galleries. According archive data the area of the galleries at the moment of explosion was more than 1 hectare, there were from 10000 up to 30000 tons of ammunition, mainly, large aerial bombs, sea mines, torpedoes, charges for ship artillery of the big calibers etc. At present, there are some crevices in the destroyed limy massif through which it was possible to penetrate into the blockages of the arsenal and to find kept ammunition on the area about 40 m^2. The find state of the ammunition is quite satisfactory, that allows using the mine clearing and the further recycling technologies.

At the moment of explosion the vaults of the galleries were destroyed and sank on 10-15 m. The rock massif has intensively cracked and turned to a congestion of limestone blocks in the volume up to 1000-5000 m^3. Cracks are filled with the clay formations and water supplied. Intensively progressing karstic processes in cracked limestone create danger of explosive objects of the arsenal corrosion, which is situated within the city boundaries.

On territory of Inkerman galleries SINECO Company carried out measurements of a full vector of magnetic field on a uniform mesh 5m × 5m. Several powerful sign-variable anomalies were revealed there, however their locality and huge gradients (up to 200-400 nT/m) testified to the small size and small depth of bedding (not more than 1-3 m). As the goal of the magnetic survey was the detailed mapping of the ammunition's value, the decision to involve in researches TEM-FAST sounding technology was accepted. This technology is used successfully to solve the engineering, geological, hydro-geological and environmental problems. Primary goals of the research were the following:

1) mapping of the ammunition on the depth of 10-30 m from a surface;

2) three-dimensional mapping of sluggies in the limestone massif.

For the solution of these tasks TEM-FAST 48 HPC (AEMR ltd.) system with 25m × 25m antenna has been used. This system defined transient characteristics of the media in a range of times from 2-4 μs up to 16 ms, both in one-loop configuration, and in configuration loop-in-loop. Preliminary full-scale test has shown, that well conducting layers of limestone screen metal objects even of 5 ton aerial bomb size which practically are not visible at depths more than 10 meters. However the super paramagnetic effect (SPM), caused frequency dependence of a magnetic susceptibility of metals $\chi(\omega)$, is confidently registered even for much big depths. When measurements of transient characteristics of an electromagnetic field the voltage on receiving antenna U(t) in case of SPM-effect [1] is inversely to time $U(t) \sim 1/t^{1+\delta}$ ($|\delta| << 1$). In regulation $E(t) = t*U(t)/I$ the response of the media at $t > 100$ μs weakly depends on time $E(t) \sim t^{-\delta}$. At the same time the induction signal caused by attenuation of the curl currents in rock, attenuates much faster:

$E(t) \sim 1/t^n$, where $n \sim 1$-3. Examples of the transients for two sites: P-38 and P-44 in the above regulation are given in the fig. 1.

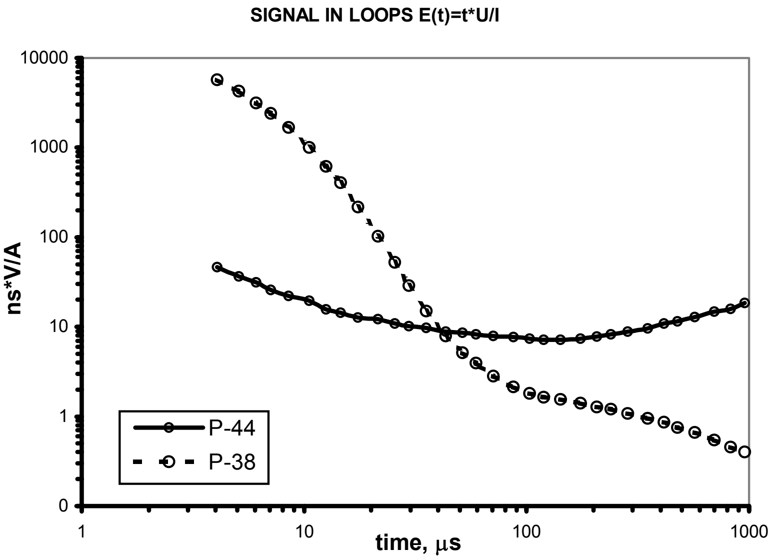

Fig. 1

Curves P-38 and P-44 were received accordingly in sites above karst zones and in zones of accumulation of shells. In both sites early stages of the processes are caused by conductivity of surrounding rock. Since t > 100 μs the form of the curves changes: in site P-38 the amplitude of the signal E (t) continues to fall - process characterizes proceeding attenuation of induction currents. In site P-44 attenuation of the signal slows down and stops at all - the SPM-effect is shown.

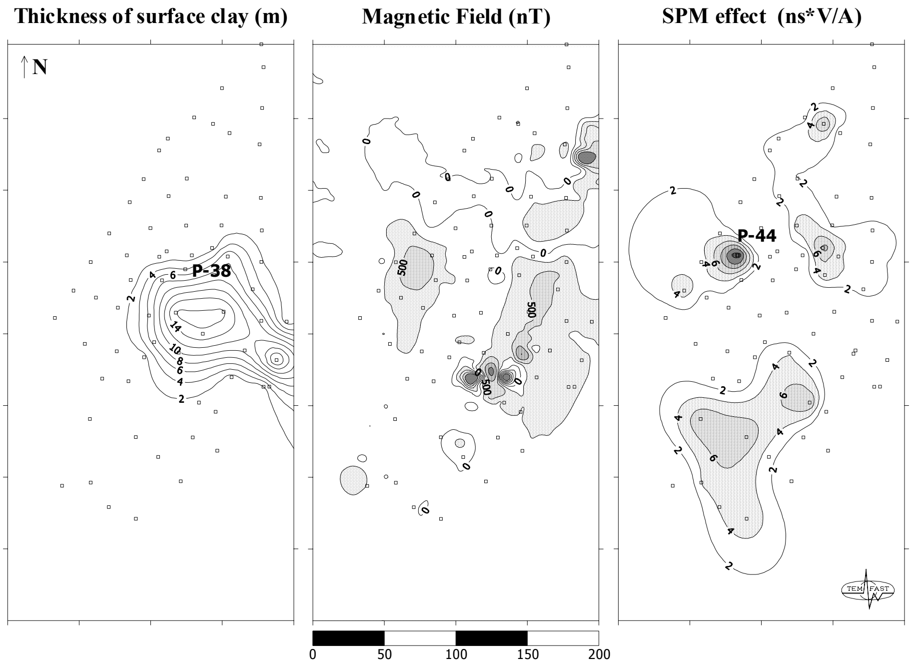

Fig. 2

Three maps are shown in fig. 2: a) thickness of superficial loam filling the sluggy; b) anomalies of a magnetic field ΔT; c) anomalies of SPM-effect. Depth of clay map (a) was constructed on the basis of one-dimensional inversion of TEM data. Resistivity of the clay deposits changes within the limits of 8 up to 30 Ohm·m, and their thickness reaches 16.5 m. The scattering of the resistivity, apparently, is caused by presence of the limy rubble and blocks in the clay. In the map ΔT (b) three anomalies with magnitude |ΔT| > 500 nT are revealed; the anomaly in a northwest part of the area has the magnitude ΔT = -1000 nT. In the other part of the area chaotically distributed anomalies with the magnitude up to 50-100 nT, connected, apparently, with small, superficially deposited metal objects are observed. Such non-uniform man-caused magnetic noise does not allow to locate large, but deeply deposited objects. The right map shows the distribution of SPM-effect E $(t)|_{t=700\ \mu s}$ and characterizes the accumulations of the objects having the anomaly super paramagnetic properties. The contour of the northwest anomaly on a configuration and position in space coincides with a gallery of the arsenal (according to cave explorers). The most intensive anomaly is observed in point P-44. In the same place there is a magnetic anomaly ΔT = 650 nT. Comparison of the levels of signals for the antenna laying on a surface and the antenna, 2 m raised above ground, allows to estimate distance up to SPM - object: h_{spm} = 13-15 m that corresponds to a level location of the galleries base. Similar estimations of depths are received for the appropriate magnetic anomaly. Extensive anomaly in the south wing of a map corresponds to the biggest blown up gallery. Estimations of depth (h) up to SPM-objects here vary in limits from 20 m up to 30 m. Here the greatest heaps of the ammunition apparently are contain. Intensive local magnetic sign-variable anomaly ΔT=1600 nT in this part of the area with a gradient of 300 nT/m corresponds to metal object with depth of bedding no more than 2 m. The area of sluggy represents the greatest danger for arsenal's objects corrosion. At the same time, sluggy is considered by experts as the most effective way of making a pass for mine clearing and recycling of the ammunition. On this site the detailed researches directed on creation of three-dimensional electric model of the karst were carried out.

Fig. 3 shows the apparent resistance time dependence ρ(t) and the modeling curves designed within the class of one-dimensional cross-section model. Measurements have

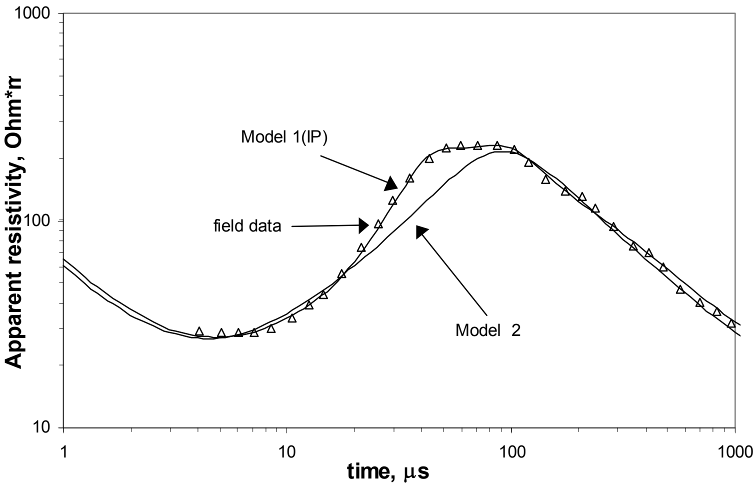

Fig.3.

shown, that all TEM curves in the zone of karstic processes contain polarizing component (IP-effect). This effect is connected with frequency dependence of rock conductivity σ(ω) and caused (in kilohertz range of frequencies) by features of penetration of induction currents through double layers in heterogeneous geological media. IP-effect became apparent in sharp growth of resistivity ρ(t) in a range of times t = 30 - 100 µs. The following table presents the results of one-dimensional inversion of the field data with frequency dependence ρ(ω) and without it.

Model 1							Model 2	
No	ρ	H	A_1	τ_1	A_2	τ_2	ρ	H
1	10	3.5	0.03	10	0.02	27	3	0.75
2	150	115					4000	105
3	3						3	

Here ρ is resistivity and H is thickness of a layer. Frequency dispersion has been calculated by the program TEM-RES (AEMR ltd.) on the basis of generalization of Debye's formula [2], where σ_0 is conductivity at infinitesimal frequency, A_1 and A_2 are dispersive constants, τ_1 and τ_2 are the relaxation constants of IP-effect. Model 2 is result of the modeling and field data fitting within the class of three-layered sections without taking into account the IP-effect. One can see, that the results of inversion without taking into account polarization, first, do not give acceptable closeness modeling and experimental data, and, second, give, obviously, false parameters of section (ρ = 4000 Ohm·m for cracked damp limestones is too big). Besides, almost quadruple error in definition of thickness of clay (layer 1) does not give the possibility of a karstic zone correct mapping. In the real geoelectric conditions *insignificant small* (almost background) dispersion of the clay's conductivity (A_1+A_1~5%) results in essential distortions of the registered transient characteristics of a field and, as consequence, to inadmissible mistakes in interpretation of results.

Let's note also, that everywhere registered low resistivities in a bottom layer at depths from 50 up to 120 m (depend on the altitude of a sounding point), correspond to the sea water-stained limestones (the coastal line is in five hundred meters from the investigated area). Thus, despite of unfavorable geoelectric conditions of researches, IP and SPM effects and a high level of industrial noise, complex application of various technologies allows to carry out TEM sounding of the geological media since 0.5 m up to depths in 100-130 m and to find UXO.

High scensitivity of IP-effect to the electrical properties permits to use it for monitoring of the processes in the Earth inverior. Some examples of such monitoring are discussed.

Conclusions

- high level industrial noise does not permit locating large, deeply deposited metal objects using only magnetic measurements;
- localization of such objects is possible with the help of TEM technology with analysis of SPM effect up to depths of 20-30 m;
- use of coincided antennas small size allows 3D detailed mapping of the karst zones;
- interpretation of TEM sounding data is correct only taking into account IP-effects;
- application of the formula for IP-effects as the multi-component discrete series of elementary Debye's relaxation processes greatly increases efficiency of the inversion procedure of TEM's data.

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