Near surface exploration for horizontal welling using CSRMT method: case study.

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Summary

Horizontal welling is a common method for the laying of the pipelines. This technology requires detailed exploration of first 20-30 m of subsurface for searching the optimal path for the welling tools and minimization of the damaging risks. Situations when the pipeline trace crosses the river are very common. In such a case, it becomes necessary to explore geological cross-section just under the river and in the surrounding area. Usually this task is being solved using the following methods: seismic, vertical electrical soundings, electrical resistivity tomography and ground penetration radar. In this paper we discuss the case study of application of the controlled-source radiomagnetotelluric (CSRMT) method for near surface exploration in winter period along the pipeline path which cross frozen rivers.

Introduction

In the second half of the 20th century electromagnetic methods based on measuring the signals received from powerful industrial radio transmitters, such as very low frequency (VLF) were developed. These methods use narrowband magnetic and electric fields of remote radio transmitters (10-30 kHz) for fast and cheap mapping of ore bodies mainly in both land and airborne variants. However, narrowband EM field provides relative information about background resistivity in one plane only (profiling mode) without significant quantitative analysis.

In the end of 1990s electromagnetic methods, based on measuring the radio signals, attended a new turn of development. Corresponding broadband receivers (10 -1000 kHz) were created in Russia (Parfentev, Pertel, 1991; Teskan, Saraev, 2008), France (Turberg et al, 1994) and Sweden (Bastani, 2001).

Radio transmitters are usually vertical electric dipoles (VED). Primary field of VED has three components: vertical electric component E_z, horizontal electric component oriented to the source E_x and horizontal magnetic field component H_y normal to E_x. Starting from distances of about first kilometers (in the far-field) the surface impedance $Z_{xy} = E_x / H_y$ becomes equal to the impedance of plane vertically incident wave – basic model of magnetotelluric method (MT). That means that the impedance of EM field from radio transmitter depends only on frequency and conductivity distribution in the subsurface. Therefore, we can use well developed MT approach and algorithms for RMT data processing and inversion.

Nowadays RMT method refers to broadband measurements of surface impedance of remote radio transmitters (Tezkan, 2008). Usually the process of RMT realization contains the following stages:

1. Measurements of horizontal and orthogonal electric and magnetic components of radio transmitter EM filed in the frequency band of 10-1000 kHz. Two-channel (E_x, H_y), four-channel (+ E_y, H_x) or five-channel (+ H_z) measurements are possible.

2. Automatic or manual detecting of radio signals in frequency domain with sufficient signal-to-noise ratio, coherence and bearing to the radio transmitter relative to receiver antennas (bearing has to be collinear with electric antenna ±20-30°).

3. Calculation of the surface impedance Z_{xy} on selected frequencies (usually in Europe there are 20-30 appropriate radio transmitters in the frequency band 10-1000 kHz). In the four-channel variant we are also able to obtain Z_{yx} component or full impedance tensor. If we are measuring vertical magnetic field we have tipper $T_{yz} = H_y/H_z$ and $T_{xz} = H_x/H_z$ which is non-zero in 2D and 3D media only.

4. Transforming the frequency spectrum of the surface impedance to apparent resistivity and impedance phase curves: $\rho_a = |Z|^2/(\omega\mu_0)$, $\varphi_Z = \mathrm{atan}(\mathrm{Im}(Z)/\mathrm{Re}(Z))$, where ω – angular frequency, $\mu_0 = 4\pi 10^{-7}$ H/m – magnetic constant. From this point, we become able to perform inversion using any MT code.

RMT method is a powerful tool when studying inhomogeneous near-surface media. Receivers are very portable and could be operated by 1-2 people. Electrical antennas are 5-20 m long. Magnetic sensors are made as little coils. It means that measurements are local but they still contain information about surrounding 2D and 3D inhomogeneous media. The software for 1D, 2D and 3D problems are well developed making RMT method as easy to use.

CSRMT method

Now the application of the RMT method is the most effective in urban regions where it is possible to measure signals of radio transmitters of VLF (10-30 kHz), low frequency (LF, 30-300 kHz) and medium frequency (MF, 300-1000 kHz) ranges.

In remote regions the number of available radio transmitters could be very limited. Usually we can measure only the most powerful VLF signals in 10-30 kHz frequency band which significantly reduce information content of soundings. Therefore, the use of controlled source becomes necessary. This modification of RMT method is called the controlled-source radiomagnetotellurics (CSRMT). The first works on the development of the CSRMT equipment Enviro MT were carried out in the University of Uppsala (Sweden) [Bastani, 2001].

Our experience [Simakov et al., 2010] shows that the most appropriate type of source in CSRMT method is a grounded electrical line. The electrical source has several advantages compared to magnetic (loop) sources: 1) larger magnitude of signal; 2) broader survey area with fixed source position; 3) possibility to use higher subharmonics of main (squared wave) signal frequency; 4) reduced time of measuring. Complicated structure of primary field of the horizontal electric source (superposition of galvanic and inductive modes) in transition zone opens new opportunities on the study of the rocks macroanisotropy – a parameter which allows solving new tasks [Shlykov and Saraev, 2015].

Used equipment

For conducting CSRMT soundings we used digital electromagnetic receiver RMT-5 and portable powerful AC transmitter GTS-1 [Saraev et al., 2014]. The receiver (developed in Saint Petersburg State University) has five input channels (two electric and three magnetic), total frequency band 1-1000 kHz and the 16-bit ADC. The RMT-5 receiver allows to use ungrounded (capacitive) electric antennas which significantly increase the usability of method. The GTS-1 transmitter has 1 kW output power, up to 300 V output voltage, 0.1-7.5 A output current and frequency band 0.1 The transmitter is powered by portable gasoline engine generator. The squared wave output signal allows to use main harmonic of the signal and its higher odd subharmonics which increase the performance of the soundings.

Case study

The case study was carried out in the Arkhangelsk region near the Kotlas city, Russia. In this place the project pipeline path crosses the Viled river. The width of the river is 230 m. For solving the task of estimation the optimal depth of laying of the pipeline we conducted the CSRMT measurements along three profiles 1540 m long across the Viled river and six vertical electrical soundings (VES or DC) for comparing results (Figure 1). Distance between profiles was 25 m. Distance between the sounding points along the profile was approximately 25 m: about 66 soundings for each profile.

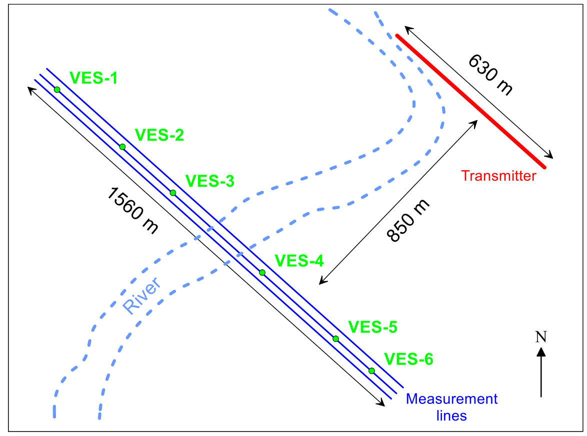

Figure 1. Configuration of the CSRMT survey area. Green dots indicate points of VES.

Geophysical measurements on the relatively wide river is a complicated time-consuming task. Cold winter weather and the usage of RMT-5 receiver provides fast and easy way for measurements on the ice with ungrounded (capacitive) electrical receiving antennas.

In case study area signals of powerful VLF radio transmitters in frequency band 11.9 – 25 kHz were only available. For covering total frequency band 1-1000 kHz of the receiver we used the 630 m long grounded wire with GTS-1 transmitter as a controlled source. The following frequencies of transmitter were used: 1 kHz (with odd harmonics 3, 5, 7, 9 kHz), 70 kHz and 105 kHz (with odd harmonics 315, 525, 735, 945 kHz). This array of frequencies including VLF radio signals completely fills the receiver's frequency band.

Measurements were conducted in the equatorial area of the source (Figure 1). One horizontal electrical component along the source wire and one horizontal magnetic component orthogonal to the source wire were measured - scalar CSRMT measurements with estimation of one component of the impedance tensor. In Figure 2 the example of apparent resistivity and impedance phase sounding curves is presented. Sounding curves clearly indicate two-layer structure of the geoelectrical cross-section with resistive top part and conductive basement. We can see that basement resistivity is lower than 10 Ω·m. For the lowest frequency (1 kHz) the skin depth $d \approx 500 \cdot \mathrm{sqrt}(f/\rho)$ is less than 50 m, where f is frequency in Hz and ρ is resistivity in Ω·m. In the equatorial area of the horizontal grounded wire the far-field boundary starts from 4d = 200 m in this case [Zonge, Hughes, 1991]. The used source-receiver distance is 850 m and more. That means that we can apply far-field approximation and use magnetotelluric software for inversion.

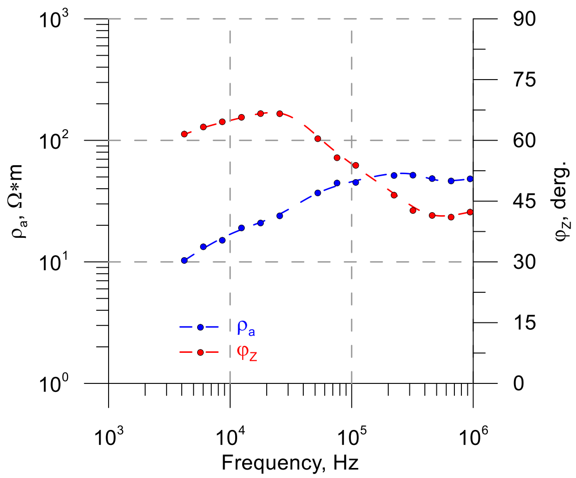

Figure 2. Example of the CSRMT sounding curves – apparent resistivity and impedance phase.

For 2D inversion we used the ZondMT2D software. After 15 iterations of smoothness constrained inversion algorithm it had converged and we had obtained 6% misfit for apparent resistivity and 8% misfit for impedance phase. The results of 2D inversion of CSRMT data along the middle profile compared with results of 1D inversion of VES data are presented in Figure 3.

The result of 2D inversion of the CSRMT data is in good agreement with the VES data. The top layer of sandy soils with gravel has resistivity about hundreds Ω·m and variable thickness 4-8 m. Resistivity of the clayey basement estimated by the CSRMT data is 1-8 Ω·m and has no significant lateral variations. VES data give higher value – 20-60 Ω·m. This difference can be explained by distortion effect of high resistive grounding conditions for galvanic VES soundings. Other possible reason is a macroanisotropy of the basement. Clayey soils can contain relatively thin sandy resistive layers. Thin resistive layers have no affects to results of inductive soundings (as CSRMT) because of horizontal orientation of primary electrical field and induced currents, but they are significantly increase the transverse resistance of the sequence of the layers and DC apparent resistivity [Maillet, 1947].

Conclusions

We discussed the case study of controlled-source radiomagnetotelluric method application for solving near-surface tasks. CSRMT method has several advantages over the traditional DC (VES) soundings. Single and fixed position of the transmitter allows to cover the large survey area. The receiving equipment is very portable and allows to use ungrounded electrical antennas. The impedance phase is unbiased by near-surface distortions and provides information about deeper horizons. Our experience shows that CSRMT soundings are up to 10 times faster than DC soundings with the same depth of investigation.

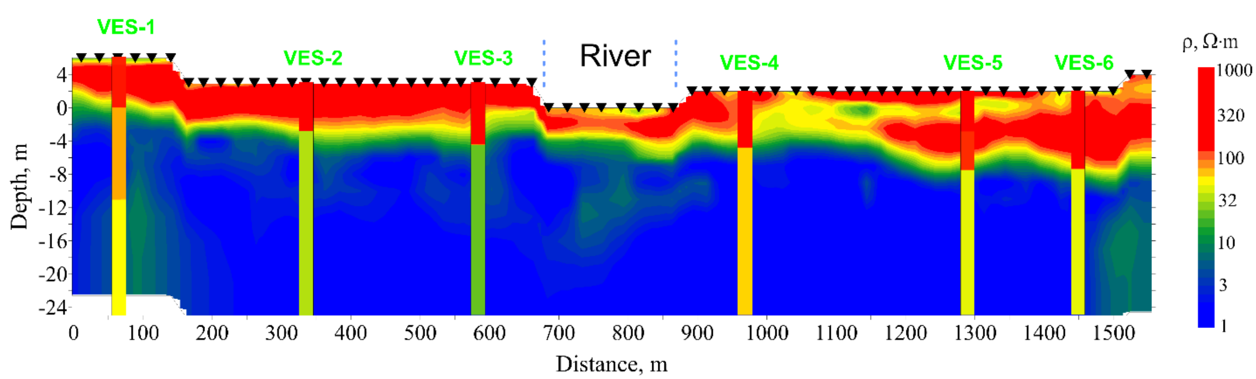

Figure 3. Results of 2D inversion of CSRMT data. Color columns represent results of 1D inversion of VES data. Black triangles indicate CSRMT measurement points.

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