MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES

Theses of doctoral dissertation

COMPLEX ELECTROMAGNETIC RESEARCH INTO MAGNETOTELLURIC AND GPR METHODS

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I. Scientific background and aims

The electromagnetic (EM) geophysical methods play an important role in the shallow and deep exploration projects as well. They are powerful tools when explorational, environmental, geotechnical or archeological problems need to be solved. Comparing to the other geophysical techniques, they have the most variants, considering the source, the arrays, the frequency domain etc. The aim of my research was to test, develop and compare modern evaluation methods that are related to current research directions in the case of magnetotelluric (MT) and ground penetrating radar (GPR) methods.

Over the last decades, significant progress has been made in developing effective methods of inversion of magnetotelluric data (Constable et al. 1987, Parker 1994). Multiple 3D inversion methods and algorithms have been introduced (e.g. Newman and Alumbaugh 2000, Sasaki 2001, Siripunvaraporn et al. 2005, Zhdanov et al. 2011ab, Kelbert et al. 2014, Avdeeva et al. 2015, Čuma et al. 2017, Varılsüha 2020), based on finite-difference (FD), finite-element (FE), and integral equation (IE) numerical modeling techniques. In case of my MT research, I applied some of these modern inversion techniques in order to get new geological-geophysical information from the two target area (Cserehát, NE Hungary and Western Superior Region, North America).

Ground Penetrating Radar (GPR) related research is also in the focus of the Department of Geophysics, University of Miskolc – among other EM methods. It is an active source electromagnetic geophysical method. Its great advantage is the fast imaging and being non-destructive. Today, it has been applied in many fields, from cavity exploration (Lyu et al. 2020) to the study of engineering facilities (Pajewski et al. 2013) to archaeological surveys (Trinks et al. 2012).

The reflected wave response from the investigated medium depends on the EM parameters: permittivity (ε), magnetic permeability (μ), conductivity (σ) and the frequency (f). All of the EM parameters are frequency dependent quantities. The magnetic permeability does not influence the radar wave propagation significantly, unless the investigated medium is ferromagnetic. Its effect is negligible in the case of materials with relative magnetic permeability value around one ($\mu_r \approx 1$). The permittivity is the key parameter in GPR measurements. The conductivity or its reciprocal, the resistivity, plays an important role in GPR practice as well (Jol 2008). Basically, GPR cannot be applied in a low resistivity environment successfully because of fast wave attenuation and absorption, but sometimes it can be applied under relatively low resistivity (10–100 Ωm) conditions, very low penetration in particularly, using highly sensitive instruments. My aim was to model the changes of the EM parameters and associate them with practical GPR parameters (wave propagation velocity, reflection depth, resolution etc.).

In many cases, the knowledge of the exact response of the examined medium is not necessary. The use of the equations for dielectric can be enough when measuring in very high resistivity ($\rho > 100$ Ωm) environment. But sometimes a complex interpretation of three-dimensional EM parameter distribution is needed, such as in the case of soils, where the resistivity can be lower, or in utility mapping, where accurate depth estimation is indispensable. This way, the precise interpretation of GPR data can have financial significance as well.

The dielectric approximation is reasonable in many cases, but the application of the equations for lossy media can facilitate the prediction of the frequency dependent EM parameters of a soil and can be useful in accurate velocity and depth estimation.

II. ACCOMPLISHED INVESTIGATION

In NE Hungary, in the Cserehát region, between Irota and Gadna villages an indication of sulfide mineralization is well-known. In order to delineate the ore mineralization, I performed magnetotelluric (MT) measurements along three nearly parallel profiles, at 24 stations altogether. The MT measurements were carried out with Metronix GMS-06 24-Bit MT-System. The recordings were registered in three (LF1, free, LF2) frequency bands, with 4096, 512 and 64 Hz sampling frequencies. The registration time at one station was about one hour, so relatively high frequency (0.01 – 1 Hz) MT data were collected.

I processed the raw data and the elements of the impedance tensor were determined. I performed statistical analyzes in connection with a Hungarian MT dataset before the inversion runs. I applied classical and modern statistical tools as well (Nádasi et al. 2017). I edited correlation maps and among the multivariate statistical methods, I applied clustering based on the probing curves.

2D inversion evaluation was performed according to the method of nonlinear conjugated gradient by Rodi and Mackie (2001). The 3D inversion run was implemented based on the regularized Gaussian-Newton algorithm in the data space (Gribenko and Zhdanov 2017).

During my pre-doctoral scholarship at the Consortium for Electromagnetic Modeling and Inversion (CEMI) at the University of Utah, I dealt with more aspects of MT forward modeling and inversion. I worked on a dataset which covered a part of the Ontario and Manitoba provinces of Canada, as well as US states Minnesota and North Dakota. This is called the Western Superior Region and two projects contributed to the data set, the Lithoprobe and the EarthScope.

Because the applied inversion code (Gribenko and Zhdanov 2017) is not capable of producing models with anisotropic conductivities, I performed anisotropic forward modeling (Cai et al. 2014) to understand the recovered 3D resistivity model better. For this reason, I also compared the XY and YX observed phase differences at four different frequencies and produced maps from that. The 3D inversion processing of the Western Superior dataset revealed three extended conductivity anomalies in a north-south direction (Gribenko et al. 2021).

The concept of my GPR related theses have been worked out from the EM wave theory. The basic idea was to compare the calculated GPR parameters using equations for dielectrics and lossy media. The calculated parameters were plotted in the function of conductivity and were edited in MATLAB. In the dissertation, six GPR parameters (wave propagation velocity, wavelength, vertical and horizontal resolution, skin depth, reflection depth) were investigated (Nádasi and Turai 2017, 2018).

I introduced parameter sensitivity quantities in case of GPR measurements based on DC geoelectric analogies. The wave propagation velocity – conductivity and the wave propagation velocity – relative permittivity sensitivities were defined and evaluated (Nádasi and Turai 2020).

In order to model the effect of resistivity change, MATGPR (Tzanis, 2010) modeling software was used. Synthetic GPR B-scans were generated and analyzed with the Split-step methods of Bitri and Grandjean (1998).

III. NEW SCIENTIFIC RESULTS

Thesis 1.

Field MT measurements were processed by correlation analysis and cluster analysis.

a) Using correlation analysis, I showed that the layer sequence is 1D below the eastern part of the Cserehát research area, while it is multidimensional (2D or 3D) below the central and western part.

b) With the non-hierarchical cluster analysis of the MT measurements, I proved the existence of WSW-ENE directional structural lineaments (faults).

Thesis 2.

I performed magnetotelluric (MT) measurements in the Cserehát, in the exploration area near Irota and Gadna settlements.

a) I have shown that under the MT-1 section, the Paleozoic basement gradually deepens to a depth of 200 m from the surface in the southern direction.

b) I have shown that below the Cserehát research area, between the depths of 200 m and -500 m, there is a conductive body with a resistivity of 4 Ωm, the horizontal extent of which is more than 200 m.

Thesis 3.

I calculated the phase differences between XY and YX components of the observed MT impedance. I pointed out consistently higher XY phase in the central and South-West regions of the survey area for frequencies 0.001 and 0.01 Hz. This indicates higher conductivity in the North-South direction which proves the presence of conductivity anisotropy.

Thesis 4.

In the Western Superior region, between a depth of 100 km and 300 km, I detected three conduction anomalies extended in a north-south direction, confirming the existence of the presumed deep electrical anomaly.

Thesis 5

The relative differences between different GPR parameters (wave propagation velocity, wavelength, resolution, reflection depth) calculated from lossy medium or dielectrics were systematically investigated and characterized. The relative error between the two calculations was given and visualized in the function of conductivity.

a) Wave propagation velocity: I found that in case of the wave propagation velocities that our medium has an average dielectric constant of at least $\varepsilon_r = 5$ and a resistivity above 100 Ωm, the relative error is below 2%. But examining the high conductivities ($\sigma > 0.05$ S/m), it can be stated that the relative error can be several hundred percent.

b) Vertical resolution: I showed that while in a medium with a measuring frequency of 100 MHz with a relative dielectric constant $\varepsilon_r = 5$ and a resistivity of 1000 Ωm, only reflecting surfaces larger than a vertical distance of 34 cm can be separated, at a frequency of 1.2 GHz objects with a depth difference of more than 3 cm can be separated. For media with a resistivity of 10 Ωm and a relative dielectric constant of $\varepsilon_r = 5$, the limits for vertical resolution are 21 cm at 100 MHz, 6 cm at 500 MHz and 2.7 cm at 1.2 GHz.

c) Wavelength: I showed that if the relative dielectric constant is at least five ($\varepsilon_r \geq 5$), the maximum wavelength at 100 MHz is 1.3 m, at 500 MHz it is 27 cm, and at 1.2 GHz it is 12 cm. These values start to decrease with decreasing resistivity, at 100 MHz from 100 Ωm, at 500 MHz from 30 Ωm, at 1.2 GHz from 10 Ωm.

d) Horizontal resolution: I found that with increasing depth, the horizontal resolution is lower (expressed by number, it is higher). In a medium with a dielectric constant of 10 ($\varepsilon_r=10$) and a resistivity of 100 Ωm, for a 100 MHz antenna, at a depth of 3 m, the horizontal resolution is 1.75 m.

e) Skin depth: I showed that if relative dielectric constant is not higher than twenty ($\varepsilon_r \leq 20$) and the resistivity is under 100 Ωm, the skin depth cannot be higher than 2.4 m. As the specific conductivity increases, the skin depth decreases significantly. With a constant increase in relative dielectric, with constant specific conductivity, the skin depth increases.

f) Reflection depth: I showed that while $\varepsilon_r=10$ and $\rho=20$ Ωm the depth difference is bigger than 15 cm even in 2 m depth. This is almost 10% error. It could increase up to 20% if the ε_r would decrease to 5 beside the same resistivity.

Thesis 6

I have shown by parameter sensitivity calculations that the conductivity sensitivity of the propagation velocity is the highest for the medium with 1 relative dielectric constant and 0.08

S/m conductivity, and this sensitivity decreases with increasing relative dielectric constant and conductivity.

Thesis 7

I have shown that the rebar structure at a depth of 0.1 m can be well detected using a GPR antenna with a frequency of 1 GHz, however, using the 500 MHz antenna, the resolution is significantly worse.

PRACTICAL APPLICATION OF THE RESULTS

The theses in the dissertation - related to either MT or GPR methods - are related to important research directions, mainly in the field of forward modeling and inversion.

The results related to MT contributed to the refinement of the geophysical-geological model of the two presented target areas in terms of practice. In Hungary, the geometry of the well-conducting zones related to the ore indication has been clarified. The results presented from the North American area are mainly of geodynamic relevance and serve to understand the deep structure. Both target areas have a special geophysical-petrophysical feature. In case of the Hungarian MT dataset from the Cserehát, the special physical condition is the induced polarizability, the presence of the IP effect. In case of the North American dataset, the special physical feature is the conductivity anisotropy.

Theses related to GPR are important for measurement design as well as for deciding applicability, and the examination of parameter sensitivities can be useful in the field of forward modeling. The dielectric model cannot be used for georadar survey on relatively low resistivity and complex structures (e.g., certain soils). The comparative analyzes and models presented in the dissertation should be considered in GPR practice. In relatively low resistivity (< 100 Ωm) environment, the accuracy of depth estimation can be increased applying the lossy media approach. Modeling the detectability of reinforcement bar structures with different geometries is also a promising research direction which can be used in the field of civil engineering.

BIBLIOGRAPHY CITED IN THE THESIS

Avdeeva, A., Moorkamp, M., Avdeev, D., Jegen, M., & Miensopust, M. (2015): Three dimensional inversion of magnetotelluric impedance tensor data and full distortion matrix. Geophysical Journal International, 202 (1), 461—481.

Bitri, A., Grandjean, G. (1998): Frequency - wavenumber modelling and migration of 2D GPR data in moderately heterogeneous dispersive media. Geophysical Prospecting, 46, pp. 287–301.

Cai H., B. Xiong, M. Han, and M. S. Zhdanov (2014): 3D controlled-source electromagnetic modeling in anisotropic medium using edge-based finite element method: Computers & Geosciences, 73, 164-176.

Constable, S. C., R. L. Parker, and C. G. Constable (1987): Occam’s inversion: A practical algorithm for generating smooth models from electromagnetic sounding data: Geophysics, 52, 289-300.

Čuma, M, A Gribenko, and M. S. Zhdanov (2017): Inversion of magnetotelluric data using integral equation approach with variable sensitivity domain: application to EarthScope MT data: Physics of the Earth and Planetary Interiors, 270, 113-127

Gribenko, A. V., and M. S. Zhdanov (2017): Regularized Gauss-Newton method of nonlinear geophysical inversion in the data space: Applications to 3D magnetotelluric inversion: In Expanded Abstracts, Proceedings of the 87th SEG International Exposition and Annual Meeting; Society of Exploration Geophysicists: Tulsa, OK, USA, 1052-3812.

Gribenko, A. V., Nádasi, E., Zhdanov, M. S. (2021): Regularized Gauss-Newton method in the data space: applications to 3D inversion of the Lithoprobe and EarthScope magnetotelluric data. Proceedings of Annual Meeting of Consortium for Electromagnetic Modeling and Inversion, University of Utah, Salt Lake City, UT, U.S.A., June, 2021, pp. 35-66.

Jol, H. M. (2008): Ground Penetrating Radar Theory and Applications. Elsevier.

Kelbert, A., N. Meqbel, G. D. Egbert, and K. Tandon (2014): ModEM: A modular system for inversion of electromagnetic geophysical data: Computers and Geosciences, 66, 40—53, doi: 10.1016/j.cageo.2014.01.010

Lyu, Y., Wang, H., Gong, J. (2020): GPR Detection of Tunnel Lining Cavities and Reverse-time Migration Imaging. Applied Geophysics, Vol. 17, No. 1. pp. 1-7.

Nádasi, E., Turai E., Szabó N. P. (2017): Statistical investigation of magnetotelluric data. In: Bodzás, Sándor (szerk.) Műszaki Tudomány az Észak-Kelet Magyarországi Régióban 2017 : konferencia előadásai. Debrecen, Magyarország: Debreceni Akadémiai Bizottság Műszaki Szakbizottság (2017) 630 p. pp. 318-324. , 7 p.

Nádasi, E., Turai, E. (2017): Analysis of electromagnetic petrophysical parameters in GPR survey (in Hungarian). Magyar Geofizika, 58/4, pp. 253–258.

Nádasi, E., Turai, E. (2018): Increasing the accuracy of GPR measurements. Geosciences and Engineering: A Publication of the University of Miskolc, 6 (9), pp. 142–150.

Nádasi, E., Turai, E. (2020): The accuracy of depth estimation in GPR surveys. Geosciences and Engineering: A Publication of the University of Miskolc, 8 (13), pp. 108-115.

Newman, G. A., and D. L. Alumbaugh (2000): Three-dimensional magnetotelluric inversion using non-linear conjugate gradients: Geophysical Journal International, 140, 410—424, doi: 10.1046/j.1365-246x.2000.00007.x.

Pajewski, L., Dérobert, X., Benedetto, A., Giannopoulos, A. (2013): Applications of Ground Penetrating Radar in civil engineering – COST action TU1208. 7th International Workshop on Advanced Ground Penetrating Radar (IWAGPR 2013).

Parker, R. L. (1994): Geophysical Inverse Theory: Princeton University Press.

Rodi, W.-Mackie, R.L. (2001): Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion. Geophysics, 66, 174-187.

Sasaki, Y. (2001): Full 3-D inversion of electromagnetic data on PC: Journal of Applied Geophysics, 46, 45—54,doi: 10.1016/S0926-9851(00)00038-0.

Siripunvaraporn,W., G. Egbert, Y. Lenbury, and M. Uyeshima (2005): Three-dimensional magnetotelluric inversion: data-space method: Physics of the Earth and Planetary Interiors, 150, 3-14, doi: 10.1016/j.pepi.2004.08.023.

Trinks, I., Kucera, M., Hinterleitner, A., Löcker, K., Nau, E., Neubauer, W., Zitz, T. (2012): Large-Scale, High-Definition Ground Penetrating Radar Prospection in Archaeology. Geophysical Research Abstracts, vol. 14, p. 13447, EGU General Assembly, April 2012.

Tzanis, A. (2010): matGPR Release 2: A freeware MATLAB® package for the analysis & interpretation of common and single offset GPR data. FastTimes, 15 (1), pp. 17–43.

Varılsüha, D. (2020): 3D inversion of magnetotelluric data by using a hybrid forward-modeling approach and mesh decoupling: Geophysics, 85 (5), E191, doi:10.1190/geo2019-0202.1.

Zhdanov, M.S., L. Wan, A. Gribenko, M. Čuma, K. Key, and S. Constable (2011b): Large-scale 3D inversion of marine magnetotelluric data: Case study from the Gemini prospect, Gulf of Mexico: Geophysics, 76 (1), F77-F87.

Zhdanov, M.S., R. B. Smith, A. Gribenko, M. Čuma, and M. Green (2011a): Three-dimensional inversion of large-scale EarthScope magnetotelluric data based on the integral equation method: geoelectrical imaging of the Yellowstone conductive mantle plume: Geophysical Research Letters, 38 (8), L08307.

IV. LIST OF RELATED PUBLICATIONS AND PRESENTATIONS

JOURNAL ARTICLES

1. Nádasi E., Madarasi, A., Turai E. (2015): Magnetotelluric exploration in the vicinity of Irota and Gadna, Geosciences and Engineering. A Publication of the University of Miskolc 4:6, pp. 105-115. 2015.
2. Nádasi, E. (2021): The complex geophysical interpretation of the conductivity anomaly near Irota (in Hungarian). Multidisciplinary Sciences A Publication of the University of Miskolc. 11 (1) pp. 98-103, 6 p.
3. Nádasi, E., Dobos, E., Pecsmány, P., Turai, E (2020).: Ground Penetrating Radar (GPR) soil suitability map of Hungary based on physical and pedological parameters (in Hungarian). Magyar Geofizika 61: 4 pp. 191-198., 8 p.
4. Nádasi, E., Turai, E. (2017). Analysis of electromagnetic petrophysical parameters in GPR survey (in Hungarian). Magyar Geofizika, 58/4, pp. 253–258.
5. Nádasi, E., Turai, E. (2018). Increasing the accuracy of GPR measurements. Geosciences and Engineering: A Publication of the University of Miskolc, 6 (9), pp. 142–150.
6. Nádasi, E., Turai, E. (2020): The accuracy of depth estimation in GPR surveys. Geosciences and Engineering: A Publication of the University of Miskolc 8: 13 pp. 108-115. , 8 p.
7. Nádasi, E. (2020): GPR forward modeling for reinforcement bar structures in civil engineering. Műszaki Földtudományi Közlemények 89 : 1 pp. 383-388. , 6 p.
8. Nádasi, E., Turai E., Kiss A. (2020): Electromagnetic (EM) parameter cross-plots for low frequency GPR measurements (in Hungarian). Műszaki Földtudományi Közlemények 89 : 1 pp. 377-382. , 6 p.

PROCEEDINGS OF INTERNATIONAL CONFERENCES (EXTENDED ABSTRACTS)

1. Gribenko, A. V., Nádasi, E., Zhdanov, M. S. (2021): Regularized Gauss-Newton method in the data space: applications to 3D inversion of the Lithoprobe and EarthScope magnetotelluric data. Proceedings of Annual Meeting of Consortium for Electromagnetic Modeling and Inversion, University of Utah, Salt Lake City, UT, U.S.A., June, 2021, pp. 35-66.
2. Szalai, Novák, Szokoli, Nadasi (2016): New ERT arrays to increase the depth of detectability. In: EAGE 22nd European Meeting of Environmental and Engineering Geophysics, Near Surface Geoscience 2016. Barcelona, Spain, 2016.09.04-2016.09.08. Houten: European Association of Geoscientists and Engineers (EAGE), Paper Tu 22P2 11. 4 p.
3. Turai, Nádasi (2014): In Field Classification of Waste Site Material Using Tau-Transformation of IP Data. In: Gombkötő Imre (edit.) 18th International Conference of Waste Recycling. Miskolc, Hungary, 2014.10.09-2014.10.10. 9 p. (ISBN:978-615-5216-61-9).

PROCEEDINGS OF DOMESTIC CONFERENCES

1. Nádasi, E., Turai E., Szabó N. P. (2017): Statistical investigation of magnetotelluric data. In: Bodzás, Sándor (szerk.) Műszaki Tudomány az Észak-Kelet Magyarországi Régióban 2017: konferencia előadásai. Debrecen, Magyarország: Debreceni Akadémiai Bizottság Műszaki Szakbizottság (2017) 630 p. pp. 318-324., 7 p.
2. Turai, E., Nádasi, E., Szilvási, M. (2016): A geoelektromos geofizikai módszerek terepi alkalmazásának új eredményei a környezetvizsgálatok területén, Műszaki tudomány az Észak-Kelet Magyarországi régióban 2016, ISBN: 978-963-7064-33-3, Miskolc, Debrecen, pp. 680-689, 10 p.

INTERNATIONAL CONFERENCE PRESENTATIONS

1. Nádasi E., Madarasi A., Turai E., Szilvási M. (2016): Magnetotelluric Ore Exploration near Irota, NE Hungary. In: 78th EAGE Conference and Exhibition Student Conference 2016. Vienna, Austria, 2016.05.30-2016.06.02. Houten: European Association of Geoscientists and Engineers (EAGE).
2. Szilvási M., Turai E., Nádasi E. (2017): Resistivity and IP monitoring near a tailings storage – a case study from Hungary. In: 79th EAGE Conference and Exhibition Student Conference 2017. Paris, France, 2017.06.12-2017.06.15. Houten: European Association of Geoscientists and Engineers (EAGE).

DOMESTIC CONFERENCE PRESENTATIONS

1. Nádasi E., Turai E. (2016): 3D inversion of magnetotelluric data measured near Irota. Inversion Conference 2016. Hungarian Academy of Sciences, Miskolc, 2016 14th of November.
2. Nádasi E. (2019): Large-scale 3D inversion of magnetotelluric data from the western Superior Province, Ontario, Canada. The New Generation of PhD Students in Geophysics. Hungarian Academy of Sciences, Budapest, 2019 4th of December.
3. Nádasi E. (2018): The role of conductivity in GPR wave propagation velocity estimation. Meeting of Young Geoscientists 06-07 April 2018, Hajdúszoboszló, Hotel Silver.
4. Nádasi E. (2017): 3D magnetotellurikus inverzió a gyakorlatban. XX. Tavaszi Szél Konferencia 2017. március 31-április 2. Miskolc.
5. Nádasi E. (2017): Különböző közegek eltérő elektromágneses paramétereinek hatásvizsgálata a földradar (GPR) kutatásoknál használt hullámok frekvenciatartományában. Doktoranduszok Fóruma, 2017. november 16. Miskolci Egyetem.
6. Nádasi E. (2018): A georadar (GPR) mérések kiértékelésének gyakorlati problémái. Inverziós Ankét. MTA Miskolci Akadémiai Bizottság Székháza, 2018. április 20-21, Miskolc.
7. Nádasi E., Turai E. (2018): A földradar (GPR) mérések pontosságának növelése. Műszaki Tudomány az Észak-Kelet Magyarországi Régióban, 2018. május 31., Szolnok.