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In-mine Geoelectric Investigations for Detecting Tectonic Disturbances in Coal Seam Structures

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Abstract

The methods of in-mine seam-sounding and transillumination (geoelectric tomography) for the detection of tectonic disturbances of coal seams were developed by the Department of Geophysics of the University of Miskolc in the 1970-80's with the effective support of the former "Borsod" Coal Mines Ltd.

The paper gives an overview about the theory of seam-sounding and a special geoelectric tomographic inversion, and introduces the in-mine geoelectric seam-sounding and transillumination measurement systems using vertical electrode dipoles. In the second part the paper, the results of an in-mine geoelectric measurement are presented, which was carried out in order to detect tectonic disturbances of the Miocene aged coal seams situated in Slovakia. As results of the geophysical investigation, the authors forecasted the tectonic features in the coal seam. The company confirmed the results by independent information about seam disturbances and tectonic features arising from the excavation of the investigated area.

Key words: in-mine geoelectric tomography, seam sounding, drift sounding, tectonic disturbances.

1. INTRODUCTION

Efficiency and safety of coal mining necessitate that the tectonic and lithological features of the coal deposits should be well known. By surface geophysics this information is generally not obtainable with sufficient accuracy. However, there are geophysical methods for which the necessary measurements are carried out within the mine and by which even smaller disturbances of the coal structure can be detected (in-seam seismic reflection and transmission methods). In this paper the in-mine geoelectric tomography method introduced by Csókás *et al.* (1986) is applied for the detection of tectonic disturbances in a Slovakian coal mine.

2. THE PRINCIPLES OF THE IN-MINE GEOELECTRIC METHOD

The physical condition of the usage of the method is that electrically highly conductive (low resistivity) rocks have to embed electrically poorly conductive (high resistivity) rocks. The higher the conductivity difference, the more effectively applicable the methods are. According to a general experience with geological sequences consisting of coal seams this condition is almost always fulfilled: a high resistivity coal seam is usually embedded between a low resistivity floor and roof.

The principle of the methods is shown in Fig. 1. The current electrodes A and B and the potential electrodes M and N are placed at the upper and lower boundaries of the coal seam in an equatorial dipole array. For "seam-sounding" the dipoles are placed in the same drift. The distance r between the dipoles is gradually expanded during sounding. If two drifts are accessible in the investigated area, we can use geoelectric seam-transillumination. In this case, the current dipole is placed in one of the drifts and the potential dipole in the other. The dipole array should cover the bed in a fan-shaped form as far as possible. Thus the current passes the coal seam that has a much higher resistivity compared to its embeddings. If there is no disruption (fault) in the seam, then the current density remains with a very high value to long distances from the current electrodes in the much lower resistivity floor and roof rocks along the high resistivity coal seam close. Therefore, the coal seam acts as an insulator and a high potential difference, ΔU, can be measured between the potential electrodes M and N installed on the upper and lower boundaries of the coal seam (Fig. 1). If the seam is traversed by a fault zone along which the continuity of the seam disrupts and it gets in a direct connection with the floor and roof, then a significant part of the current shorts via this zone. As a result the current density decreases in a long distance from the fault zone, thus the measurable potential difference of the two sides of the seam also decreases depending on the (magnitude of the) measuring current. Consequently, the local decrease of the quotient of

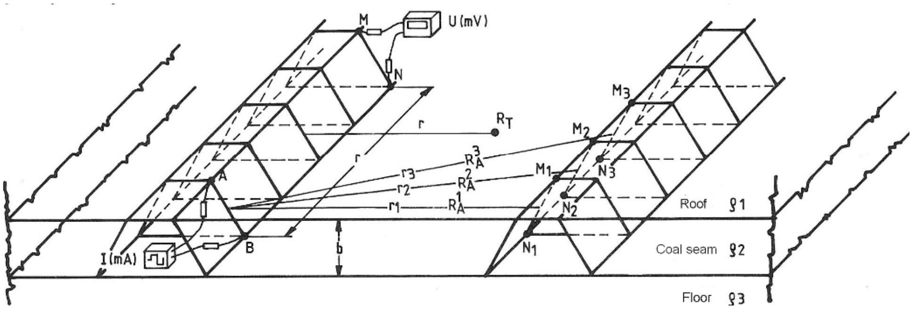

Fig. 1. The principles of geoelectric seam-sounding and (tomographic) trans-illumination. A and B indicate the current and M_i and N_i the potential electrodes; r_i mean the AB–M_iN_i dipole distances; R_A^i is the apparent resistivity measured on the i-th M_iN_i dipole; R_T means the reference point of the seam sounding; b indicates the thickness of the seam; ρ_1, ρ_2, and ρ_3 indicate the resistivities of the roof, coal and floor, respectively.

the potential difference and the measuring current $R_a = \Delta U/I$ [ohm] − *i.e.*, the apparent resistance − indicates the fault zones (Csókás 1979, Gyulai 1993).

During the measurements it is very important to place the electrodes in the highly conductive rocks (near the rock-coal interface). If the coal seam is thicker than the drift diameter, or if the drift was driven partially into the floor or roof rock, the contact with the coal-embedding rocks has to be done using small-diameter, short boreholes.

The basic concept of the measurement evaluation is the normalized deviation, E. In case of in-mine geoelectric explorations, the normalized deviation represents the relative difference between the measured apparent resistance, R_a^{meas}, and the apparent resistance of the undisturbed (tectonic-free) coal bed (*i.e.*, normal value), R_a^{norm}, for a given dipole distance r (the distance between the current and potential dipoles).

$$E(r) = \frac{R_a^{\text{meas}}(r) - R_a^{\text{norm}}(r)}{R_a^{\text{norm}}(r)} \ . \tag{1}$$

If the value of normalized deviation $E(r)$ is zero or close to zero, it indicates that the circuit close via the high resistivity seam; therefore, no tectonic disturbances can be found. In case of a tectonic disturbance the value of the measured apparent resistivity $R_a^{\text{meas}}(r)$ will be lower than the normal value $R_a^{\text{norm}}(r)$ at the same dipole distance. Thus, the normalized deviation $E(r)$ will have a negative value. According to our experiences, these deviations can reach even –10 or –50% values depending on the coal-bedrock resistivity contrast and the size of the fault (Csókás 1979, Gyulai 1993).

For the calculation of the normalized deviations $E(r)$, the normal values $R_a^{\mathrm{norm}}(r)$ are to be determined as a function of the dipole distance r. These values can be also measured directly on the tectonically undisturbed part of the coal mine. If such a seam section is not available, the geophysical model (containing the coal bed) should be estimated using a geoelectric joint inversion method. The normal values $R_a^{\mathrm{norm}}(r)$ can be computed from those model parameters (Csókás *et al.* 1986, Breitzke *et al.* 1987, Dobróka *et al.* 1991, Gyulai 1993).

3. JOINT INVERSION OF IN-MINE GEOELECTRIC MEASUREMENTS

For the determination of undisturbed 1D geoelectric model of the multilayered geological section embedded one or more coal seams joint inversion method was developed (Breitzke *et al.* 1987, Dobróka *et al.* 1991). The input values of this method are the measured data of seam-sounding and the so-called drift soundings.

The drift soundings are special additional in-mine geoelectric methods. Those measurements use an AMNB (*i.e.*, Schlumberger or any other) electrode configuration. The electrodes are positioned at the coal-seam – floor-rock boundary (floor-sounding layout) or at the coal-seam – roof-rock boundary (roof-sounding layout). The in-mine geoelectric sounding methods use different spread geometries, and positioned on different side of the coal seam, and thus have different sensitivities regarding to various layer parameters (*i.e.*, layer thicknesses and resistivities).

The drift soundings are mainly sensitive to resistivity variation in the surrounding rocks: the roof-sounding in the roof, the floor-sounding in the floor. The seam-sounding is the most sensitive to the resistivity variation in the coal seam. This feature is of primary importance in the joint inversion procedure. The sensitivities were defined as a logarithmic derivative of the apparent resistivity (resistance) with respect to the relevant parameter of the geological structure.

The combination of all three methods in one procedure called joint inversion allows optimum resolution in a resistivity-depth distribution of a multilayered geological model including the coal seam. In the 1D joint inversion decreases the effect of equivalence, because of the different sensitivity of the different sounding methods. The inverse problem is solved iteratively using a linearized least squares (LSQ) method. From the resultant undisturbed model one can easily calculate the normal resistance values $R_a^{\mathrm{norm}}(r)$, as shown in Breitzke *et al.* (1987), Dobróka *et al.* (1991), and Gyulai (1993).

4. THE IN-MINE GEOELECTRIC SEAM-SOUNDING AND TOMOGRAPHY

The theory described above is applied in two geoelectric methods, the seam-sounding and the transillumination (geoelectric tomography). The two methods differ in the placement of the current and potential dipoles, and in the methods of data processing and evaluation.

We consider seam-sounding when only one drift is available for the investigation; therefore, the AB current dipoles and the MN measuring dipoles have to be placed in the same drift (Fig. 1).

There is an opportunity for transillumination if the field to be investigated is totally or partially surrounded by air-, transport-, and cross-drifts driven in the seam. In case of transillumination the AB current dipoles and the MN measuring dipoles have to be installed in all the drifts that traverse the field (Fig. 1). The explored field has to be transilluminated in many directions as densely as possible. The less this condition fulfils, the less reliable our map of tomographic results and consequently the tectonic forecast are.

For the evaluation of the seam soundings made with the purpose of tectonic prognosis, the distribution map of the normalized deviation values E has to be constructed. The basis of the map construction is that the normalized deviation value E is illustrated at that point of the seam from where the most significant part of the information comes. If the distance between AB and MN dipoles is measured on a line perpendicular to the axis of the drift in the midpoint of the dipoles, this so-called R_T reference point can be obtained. A contour map can be constructed for these normalized deviation values. These maps only show the anomalous (disturbed) values that are caused by fault zones. According to our former experience, one can decide which contour line follows the tectonic disruption or zone from the normal deviation values between –10 and –30% (Csókás 1979, Gyulai 1993).

The measured transillumination data are evaluated in two important steps with a geoelectric tomography method developed in the Department of Geophysics of the University of Miskolc (Csókás *et al.* 1986). In the first step, the values of normalized deviation $E(r)$ are generated that are the input data of the tomographic reconstruction considered as the second step. The tomographic reconstruction algorithm generates the $R_a^{\text{norm}}(r)$ normal values required for the calculation of $E(r)$ normalized deviations from the transillumination measured data (Eq. (1)).

For the characterization of seam disruptions (inhomogeneities), we introduce

$$e(x,y) = \frac{\rho_a(x,y) - \rho_a^{\text{norm}}(x,y)}{\rho_a^{\text{norm}}(x,y)} , \tag{2}$$

the local resistivity anomaly that denotes how much the resistivity of the undisturbed coal seam changed in the investigated field depending on the x, y horizontal coordinates. The value of $e(x,y)$ is appropriate for the localization of tectonic disturbances. Therefore, the geoelectric tomographic problem implies the calculation of local resistivity anomalies of $e(x,y)$ from the normalized deviation values of $E(r)$ derived from the measured data of $R_a^{\mathrm{meas}}(r)$. Solving the problem $e(x,y)$ is described with a series expansion of a suitably chosen bivariate basis function,

$$e(x,y) = \sum_{n=0}^{N} \sum_{m=0}^{M} B_{nm} \Phi_{nm}(x,y) \ , \tag{3}$$

where B_{nm} denotes the series expansion coefficient, and $\varphi_{nm}(x,y)$ are the bivariate basis functions. The values of M and N indicate the requisite number of the series expansion coefficients in x and y directions, respectively. For the basis functions of $\varphi_{nm}(x,y)$ we applied polynomials.

The connection between the normalized deviation $E_k(r)$ derived from the k-th transillumination and the local resistivity anomaly is defined by the following integral:

$$E_k(r) = \frac{1}{A_k} \int_{S_k} e(x,y) \, dA_k \ , \tag{4}$$

where S_k is the surface of integration lying in the plane of the coal seam, and A_k is its area.

After the substitution of Eq. (3) into Eq. (4) and its rearrangement, we get the connection among the normalized deviation $E_k(r)$ derived from the transillumination and the series expansion coefficients B_{nm} that describe the local resistivity anomaly.

$$E_k(r) = \frac{1}{A_k} \sum_{n=0}^{N} \sum_{m=0}^{M} B_{nm} \int_{S_k} \Phi_{nm}(x,y) \ . \tag{5}$$

The geoelectric tomographic reconstruction – inversion, in other words – is meant by the iterative solution of Eq. (5) using the L_2 norm. As a result of the inversion, the B_{nm} expansion coefficients are generated, and by using the $\varphi_{nm}(x,y)$ basis functions, the local anomaly $e(x,y)$ can be calculated anywhere in the explored field. Mapping the calculated values of $e(x,y)$ the zones with lower values indicate the tectonic disruption (Csókás *et al.* 1986).

5. IN-MINE SEAM-SOUNDING MEASUREMENTS AND THE EVALUATION RESULTS

The method described above was applied in a Slovakian coal mine. Our task was the investigation of two neighbouring fields prepared for excavation (Sasvári *et al.* 2006). In the first field, only one drift was available; therefore we could only give a tectonic forecast based on seam-sounding. In the other field, three drifts were available, thus the suggested tomographic method was applied here. The investigated areas with the reference points of seam-sounding and the ray paths of the transillumination can be seen in Fig. 2.

Prior to the evaluation of the measurements, the normal values $R_a^{\mathrm{norm}}(r)$ [ohm] were calculated. For the calculations, the geoelectric model including the coal seam was estimated by joint inversion from the measured seam- and drift-soundings data (Table 1). The model including the two coal seams consisted of six media according to the resistivity of rocks. The upper, better-quality seam was under exploitation, into which the drifts were cut.

From the model of Table 1 the normal values were calculated that we used for the evaluation according to Eq. (2) (Fig. 3a). The normal values were measured also in a part of the mine which was locally undisturbed (Fig. 3b). Comparing the data sets in the range of 10 to 80 m it can be seen

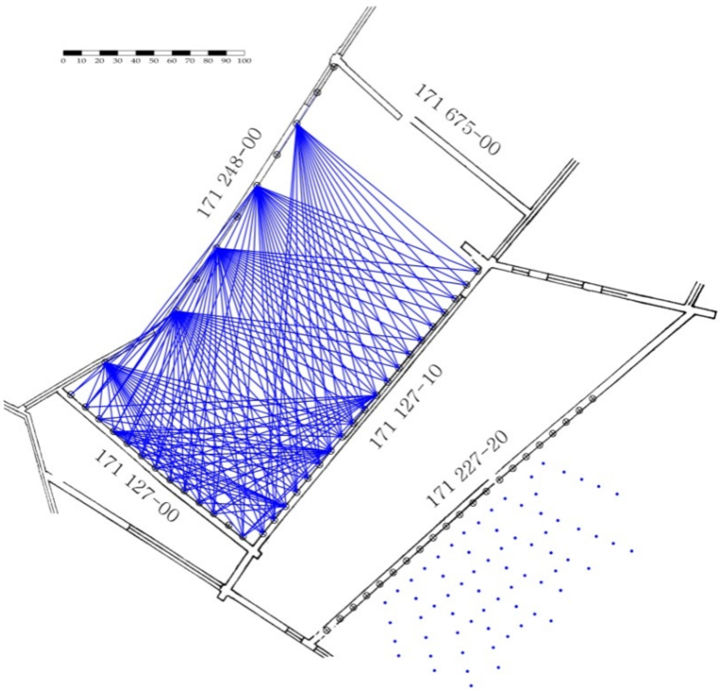

Fig. 2. The sites of the geoelectric explorations in the mine map. Symbol ⊗ indicates the places of AB an MN dipoles, symbol • denotes the reference points of seam-sounding. The transillumination "rays" are highlighted with straight lines.

Table 1

The model of the layered geological structure including coal seams

Layer thickness [m]	Resistivity [ohmm]	Lithology
∞	11	roof
5.5	660	coal seam
5.8	20.3	floor
8.0	8	clay/shale
2.0	200	coal seam
∞	1	clay/shale

Note: The model was calculated by joint inversion from the measured seam-, roof-, and floor-sounding data.

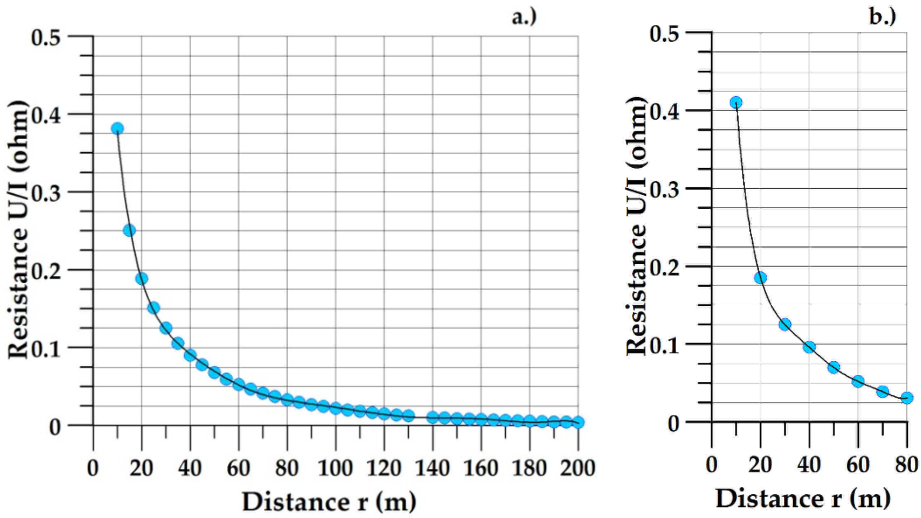

Fig. 3. The normal values of geoelectric seam-sounding and transillumination in the function of the dipole distance: (a) calculated from the data in Table 1, and (b) measured in an undisturbed part of the coal seam.

that the differences between the curves are very small. We did not have a possibility to measure a longer profile, with more than 80 m dipole distance, because of the small locally undisturbed area.

We made experimental measurements for seam-soundings in the drift No. 171 227-20 with a length of 200 m (Fig. 2). The AB current and MN measuring dipoles were installed in the boreholes of 43 mm diameter and maximally 3 m length. These boreholes placed into the floor and roof were

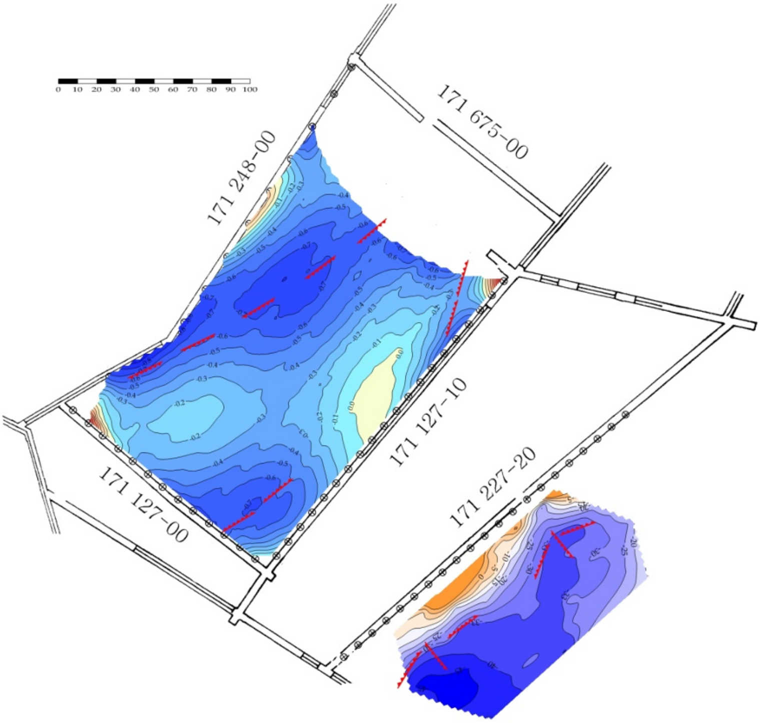

Fig. 4. The results of geoelectric transillumination (tomography) and seam-sounding. The local resistivity anomaly e is presented in the tomography map and the normalized deviation E is described in % in the seam-sounding map. The tectonic features − forecasted according to the measurements − are indicated in red colour. Colour version of this figure is available in electronic edition only.

located every 10 m. The distribution of the normalized deviations $E(r)$ at the reference points was represented in a contour map (Fig. 4). According to our experiences of similar situations we forecasted the fault zone along the contour line of –35%.

Only three (Nos. 171 127-00, 171 127-10, and 171 248-00) of the drifts traversing the field appointed for transillumination (tomography) were accessible. From the side of the fourth drift (No. 177 675-0) (none of which could be used for measurements), the "ray"-coverage of the investigated measurement area is poor (Fig. 3). For the location of the current and measurement dipoles, the company made boreholes every 10 m in this area as well. In the transport drift No. 171 248-00 the measurement construction/ implementation was difficult due to the built-in techniques and the lack of space; therefore, only current dipoles were installed in this drift with a greater distance between each other compared to the opposite ventilations drift.

According to our practical experiences, this rarefaction does not significantly influence the reliability of the tomographic reconstruction, in contrast to the disadvantage that we could not perform a parallel transillumination to the above-mentioned two drifts due to the unusability of the fourth drift.

The results of the tomographic reconstruction – the normalized local resistivity anomalies of the medium – can be seen in Fig. 4 illustrated in a contour map. We marked the fault zones in the map that were indicated by the minimal values of the map.

6. CONCLUSION

The recent application of the in-mine geoelectric methods (seam-sounding and geoelectric tomography) developed by the Department of Geophysics (University of Miskolc) was reported. After giving a theoretical introduction we described the geoelectric measurement systems and presented the results of the interpretation of the in-mine measured data set giving a prognosis for the location of tectonic disturbances and faults in the coal seam structure.

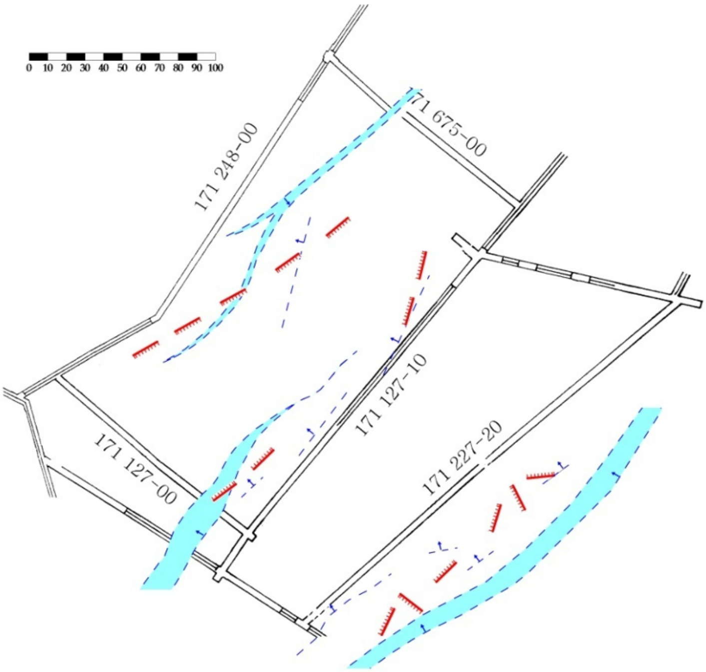

Fig. 5. Comparison of the tectonic prognosis based on the results of geoelectric transillumination (tomography) and seam-sounding and the tectonics discovered during the exploitation. The discovered fault zones are indicated with dashed blue lines and areas, the forecasted tectonic features with red lines. Colour version of this figure is available in electronic edition only.

After our measurements the investigated coal field was excavated and the location of the tectonic zones and faults − found in the excavation − was mapped (Sasvári *et al.* 2006). In Figure 5 we illustrated the faults and tectonic zones forecasted according to our results of seam-sounding and tomography in this excavation map.

The prognosis and the discovered tectonic elements are considered to be fitting very well. Greater difference appears in the area near the drift No. 177 675-00 that was improperly covered by transillumination rays, which was expected due to the above mentioned reasons (Ormos *et al.* 2008a, b, 2009).

The advantages of the method are the low costs, and the relatively short time needs for measurements and interpretation. However, for the reliable result the high resistivity contrast between coal and surrounding formations and the good coverage by "transillumination rays" are very important.

The client company considered the presented exploration as a "test" of the in-mine geoelectric method; therefore, they had not provided the geological-tectonic information that had been already available for the company. Using that *a priori* information a more precise prognosis could have been given.

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