The capability of detailed study of coal- and ore-bearing structures using electrical resistivity tomography (ERT) by means of "well bore-surface" observation system

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Abstract. Coal open-cuts of Khabarovsk and Primorskii krai are characterized by multiple coal beds of small thickness. Important is the task to evaluate structural architecture of landslide blocks distinguishing insecure beds of small thickness. In detailed study of ore deposits it is also needed to distinguish thin beds and rock-fracture zones. Therefore, in order for detailed study of such structures, it is proposed to develop a ERT technology with the use of "well bore-surface" observation system. On this stage, only theoretical justification of proposed technology is given. In order to ascertain the technology capability, the calculation of apparent resistivities for three-layer structures with various correlations of geometrical and electrical parameters was conducted. Calculations were performed with uniform spacing of 20 electrodes in a well bore and 40 of them on the surface with polling of Wenner and Schlumberger four-electrode arrays, axial array and their three-electrode designs. Regularities of electrical field for three fragments of apparent resistivity section were established based upon the analysis of modeling results: electrodes only on the surface (horizontal profile), electrodes in the well bore (vertical profile), electrodes in the well bore and on the surface (mixed profile). Outstanding interest is represented by anomalous areas of mixed profile which are described by new regularities of the field and criteria of distinguishing beds of small thickness. Theoretically it has been demonstrated that new technology is effective with distinguishing beds of small thickness on different depths of geological section **Key words:** coal beds, insecure beds, electrical resistivity tomography, apparent resistivity, anomalous areas.

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1 Introduction

The majority of operating coal open-cuts of the Far Eastern south is characterized by numerous (20–30) coal beds of rather small thickness (meters and seldom tens of meters). Bedding is monoclinal only on separate areas and complicated by a great number of fractures which are required to be distinguished and detected also in order for effective coal mining. During the research, mining and geological conditions of the area of Luchegorsk open-cut (Primorskii krai) using ERT, surface observation systems were distinguishing and detecting coal outbreak under quaternary deposits at the depth from 8 to 50 meters [1, 2]. On the area of the open-cut, the extremely important is the task to evaluate structural and tectonic structure of landslide blocks distinguishing insecure beds of small thickness. In the course of evaluation and forecast of landslide processes, the most dangerous were thin beds (3–6 m) of high plasticity Neogene clays embedding under the complex of soft-firm clays and sand-shale deposits of Quaternary age with the thickness of up to 30 meters. The method of electrical tomography from surface allowed confidently distinguishing and detecting [3] only intercalations and pockets of plastic clays with the thickness of more than 7 meters amidst Quaternary age. The experience in using this method in the study of coal deposits of the Far East Region confirmed the effectiveness of this modification of resistivity method against traditional electric soundings and profiling.

Similar problems appear as well as in case of detailed study of ore deposits structure in Norilskii district [4]. In the Amur Oblast, dense network of well bores with the depth of down to 60 meters were required in order to distinguish thin (2-4 m) bouldery and pebble-bed with pockets of fat clay containing mineable concentrations of gold on Iasno-Polianskoe deposit (Amur Oblast). The use of dense network of vertical electrical soundings (VES) which have the same capabilities as electrical tomography didn't allow detecting this productive bed. Thus, despite the success in the field of geophysical technologies development in order to solve various geological tasks it is necessary to commonly use dense network of well bores.

Therefore, we think that further development of electrical tomography by way of detailed study of coal- and ore-bearing structures extinguishing thin bed and pockets is related to the application of "well bore-surface" or "well bore-surface-well bore" synchronous observation systems. Theoretical justification of proposed electrical tomography method in this article was conducted based upon electrical prospecting basic principle [5, 6] – electric field modeling principle. We consider detailed study of mass rock formations on deposits of minerals in seeking to resolve various tasks as fundamental problem of modern stage of electrical prospecting methods development.

2 Theoretical basis and conditions

The solution of direct problem and the development of software for calculation of apparent resistivities (ρ_r) for horizontally-layered model with unspecified location of sources and receivers on daylight surface and inside structure (along well bore) have been performed and given in the work [7]. In the course of the solution of Laplace's equation, cylindrical coordinate system, interface conditions, conditions in the vicinity of a source and at infinity, Hankel transform and linear filtration were used. The case when the source is located inside the structure comes down to the introduction of dummy boundary inside the bed with the same conductivity and going through the source.

In order to determine the capabilities of new method, mass calculation of electrical field parameters and its analysis for the purpose of establishing the regularities of behaviour of abnormal field areas and criteria of distinguishing and detecting interbedded layer was required. The calculations results were represented as apparent resistivity sections (ρ_r)

where the location of electrodes in a well bore and on surface were plotted against X-axis, and against Y-axis — installation spacing. Sections represent 2D images of electrical parameters of the structure as three fragments: 1 – electrodes only on the surface (horizontal section), 2 – electrodes in the well bore (vertical section), 3 – electrodes in the well bore and on the surface (mixed section).

In the course of analysis, many factors, primarily, the types of resistivity sections and observation systems, various correlations of physical and geoelectric parameters were taken into account. On the first stage, all four types of three-layer structures (H, A, K, Q) with relative parameters were considered: geometrical – to the distance between adjacent electrodes (a), electrical – to specific resistivity of the first or the third bed. The thickness of beds were changing from 1a to 16a and specific resistivity — from 1/16 to 16.

The majority of calculations was conducted with the uniform spacing of up to 20 electrodes in a well bore and 40 — on surface with the polling of four Wenner electrode system (AMNB, AM=MN=NB), Schlumberger array (AMNB, MN<1/3AB), axial array (ABMN, AB=BM=MN) and their three electrode designs. Taking into consideration great information scope, regularities of the field and criteria of distinguishing bends only for Wenner electrode system are considered below. In this case, the section included 19 lines and 570 values of ρ_r with the initial spacing of 1.5a. Fragment 1 includes 57 values, fragment 2 — 247, fragment 3 — 266.

3 Modeling results

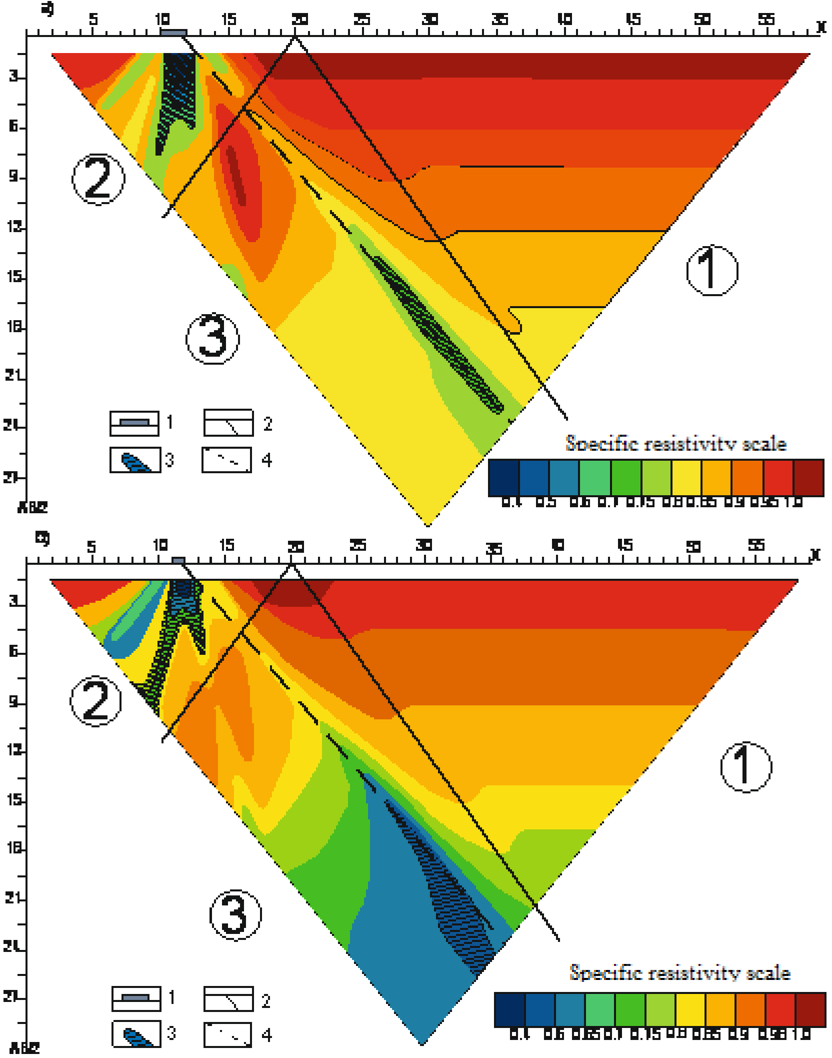
Apparent resistivity section for three-bed model of H type ($h_1/a=8a$, $h_2/a=2a$, $\rho_1= \rho_3=1$, $\rho_2/\rho_1=1/4$) is given in fig. 1a. Special attention during the analysis has been paid to the shape of abnormal areas which were distinguished enveloping isolines with the largest gradients and their connection with the geometry of interbedded layer (superface, subface, extent within a fragment). Note that geometrical sections on the area of development of landslide processes and deposits with interbedding ore bodies may be approximated by such models.

As seen, the least informative for distinguishing interbedded layer with the largest spacing of AB/2=19.5a is the fragment 1. This is quite an expected result since it corresponds to section ρ_r with traditional method of research by surface observation systems. Here isolines ρ_r are located in parallel to x-axis with gradual reduction of values down to 0.8a on spacing of 19.5 and thus specify either horizontal location of boundary at depth or gradient change of structure resistivity.

With electrodes located on vertical profile by the shape of abnormality on small spacings (1.5, 3.0), the thickness of the second bed (2a) is determined steadily, and the value ρ_r=0.34 are close to true bed specific resistivity. On large spacings, the area of low values of ρ_r extends to AB/2=9, where ρ_r=0.72. Zones of increased values of ρ_r related to screening effects are specified around the zone. In fig. 1a, such zone is well detected from fragment 2 section on fragment 3 section where ρ_r reach the value of 1.01 on spacing AB/2=9.

In case when electrodes located synchronously on vertical and horizontal profiles of fragment 3 section, except for the zone of increased values of ρ_r, abnormal area of low values (0.72-0.79) which has wedge-like shape and reflects horizontal horizontal location of the second bed on trial profile is well distinguished. Extreme values of the zone on various spacings are located along the line nearly in parallel to boundary between fragments 1 and 3 and the continuation of this line to the vertical profile defines the situation of the second bed mid.

With the reduction of bed thickness (h_2=1a) and specific resistivity ρ_2/ρ_1 =1/16) for this type of model, noted regularities of the field on fragments 1 and 3 sections change slightly (fig. 1б). In the first fragment of section, ρ_r isolines are also located in parallel to x-axis specifying horizontal horizontal bedding of possible boundary at the depth where value ρ_r on the largest spacing equals 0.72. In the field of section ρ_r of fragment 3, wedge-like abnormal area with narrow range of extreme values which reflects horizontal bedding of the second thin bed on the profile under study is distinguished. The continuation of lines of these values to the vertical profile defines the depth of bedding.



Legend: 1 – the projection of the second bed onto vertical profile, 2 – fragment parting line and their numbers, 3 – zones of the lowest resistance, 4 – the line of extreme values.

Fig. 1. Apparent resistivity sections for three-bed models of type H with the parameters as follows: a) $h_1/a=8$, $h_2/a=2$, $\rho_1= \rho_3=1$, $\rho_2/ \rho_1=1/4$; б) $h_1/a=8$, $h_2/a=1$, $\rho_1= \rho_3=1$, $\rho_2/ \rho_1=1/16$, Wenner electrode system.

More complex pattern of abnormal area location is observed in the fragment 2 section (fig. 1б). Since none of electrodes was located within the second bed, the bed thickness is to be defined roughly by dimensions of local region of lowest values (0.55) by vertical profile. As seen, these values are essentially differ from true values of specific resistivity of the bed. On different sides from area abnormality, zones of anomalous values related to screening effects are distinguished.

"Well bore–surface" observation system may confidently distinguish and detect beds of increased resistivity and small thickness. Such conditions are met in resistivity sections with beds of brown coal, effusive rocks and sandstones among clays, argillites and aleurolites. Anomalous areas of horizontal profile on apparent resistivity sections for type K model are characterized by known regularities of a field for bedded structures. The field analysis on the fragment of vertical profile demonstrates that anomalous area with increased values defines the depth of bedding and approximate thickness of the second bed. The location of thin bed of increased resistivity and its extent are well defined on mixed profile. Wedge-like area is distinguished on small spacings (up to AB/2=9.5) by values of ρ_r being less than 1.0, and on large spacings by values being more than 1.0, by isolines of which it is possible to establish the depth of bedding and the extent of bed on trial profile. Extreme values (ρ_r=1.19) differ from true bed resistivities. The continuation of these values lines allows establishing approximate bed location. At large for this model, field regularities are nearly analogues to type H model but with the opposite sign.

Capabilities of distinguishing interbedded layer for types A and Q models slightly drop, but as well as in case with types H and K, main field regularities are fulfilled. The most informative are also sections of fragments 2 and 3. Their anomalous zones allow distinguishing bed at the depth and its extent by a profile, and apparent section — closer to true specific resistivities.

Sections for type A with parameters as $h_1/a=8$, $h_2/a=2$, $\rho_2/\rho_1=4$, $\rho_3/\rho_1=16$ (fig. 2a) and $h_1/a=4$, $h_2/a=1$, $\rho_2/\rho_1=4$, $\rho_3/\rho_1=16$ (fig. 2Б) are given in fig. 2. The depth of bedding and the thickness of the second bed are distinguished by abrupt concentration of isolines of ρ_r with the values of 2, 4, 6, 8 on fragment 2 sections. At that, the thickness may be defined in the first case in more reliable manner (fig. 2a). This implies that main factor for bed discovery is a ratio between thicknesses and distance between electrodes (h_2/a). Values of ρ_r in the central part of concentration of isolines with the range of 3.9 – 4.2 almost define true specific resistivities of the second bed. Long wedge-like areas which reflect horizontal orientation of a bed are distinguished on fragment 3 sections (fig. 2), and continuation of extreme values isolines to vertical profile defines an approximate depth of bedding. Value of ρ_r on spacing AB/2=28.5 in case when $h_2/a=2$ equals 2.66, and with $h_2/a=1$ — 4.20. But conditions for distinguishing the second bed in the first case (fig. 2a), are absolutely better.

On fragment 1 sections, gradual increase of ρ_r means, as well as for type K, presence at the depth of a bed of increased resistivity or gradient change of structure resistivity.

Regularities of the field for type Q models is analogous to fields of type A, but with the opposite sign. At that, interbedded layer with the reduction of resistivities is distinguished in more reliable manner with depth increase. Thicknesses and the extent of a bed nearby a well bore are defined by concentrations of isolines on fragment 2 section, in the center of anomalous area ρ_r values are close to true specific resistivities. In fragment 3 section, anomalous wedge-like areas allow defining the conditions of bedding, and the continuation of extreme values lines to vertical profile shoes its location. On large spacings ρ_r are close to true specific resistivities. Field regularities demonstrate that the increase of bedding depth without sacrificing other parameters of the structure do not influence distinguishing it in the sections of fragments 2 and 3. The least informative in distinguishing bed is also fragment 1 section.

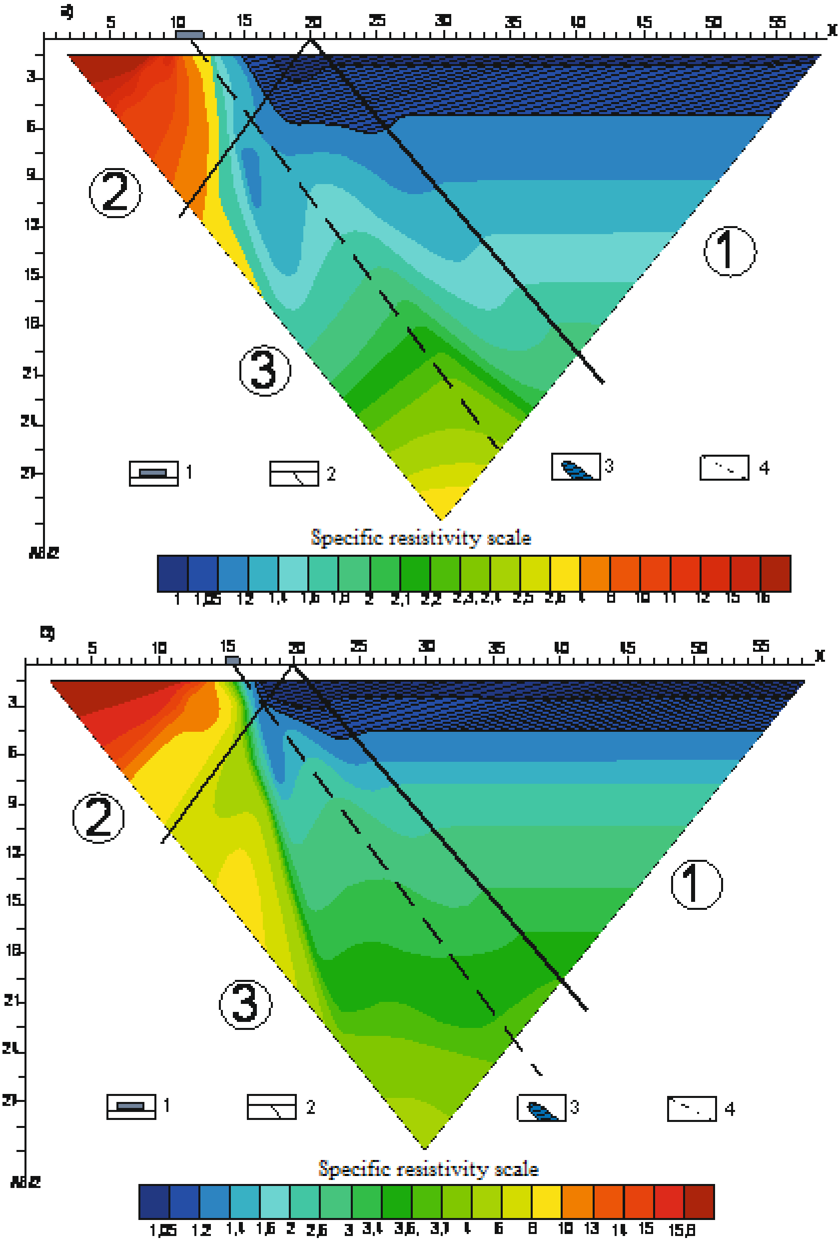


Fig. 2. Apparent resistivity sections for three-bed models of type A with the parameters as follows: a) $h_1/a=8$, $h_2/a=2$, $\rho_2/\rho_1=4$, $\rho_3/\rho_1=16$; б) $h_1/a=4$, $h_2/a=1$, $\rho_2/\rho_1=4$, $\rho_3/\rho_1=1$. Legend in fig. 1.

4 Conclusions

Thus, based upon modeling of electrical field for selected three-layer structures and "well bore-surface" observation system, the regularities of anomalous areas of apparent resistivity sections have been established and criteria for discovery and detection of thin beds at different depths. Regularities sufficiently depend on section fragments which are defined by the location of electrodes: on the surface (horizontal profile), in a well bore (vertical profile), in a well bore and on the surface (mixed profile). As follows from the analysis of sections, the effectiveness of the proposed electrical tomography method for distinguishing bedding thickness, extent of interbedded layers and its electrical properties.

"Well bore-surface" observation system reliably distinguishes thin beds in types H and K resistivity sections and slightly worse for types A and Q. The most informative are the areas of sections of vertical and mixed profiles. Field regularities demonstrate that the increase in depth of bedding of interbedded layer with the retention of other parameters of a model do not influence the conditions of distinguishing it. The least informative in the discovery of a bed is the section of horizontal profile.

The following field peculiarities should be used in analysis and interpretation of practical apparent resistivity sections obtained by new methods:

- anomalous areas of vertical profile section are characterized as known field regularities in geophysical well logging (apparent resistivity method, lateral sounding), electrical tomography observation system in case of dense location of electrodes by vertical profile (in a well bore) allows confidently defining thickness, extent and specific resistivities of thin beds at various depths close by a well bore;
- anomalous area of mixed profile section are characterized by new field regularities and criteria for distinguishing interbedded layers, wedge-like areas on section allow specifying the location of a bed by depth, detect its low-angle or tilted bedding away from a well bore on trial profile as well as defining regularities of change of electrical properties of a bed and host medium;
- anomalous areas of horizontal profile are characterized by known field regularities for bedded structures and surface observation systems, they are the least informative compared to reviewed profiles.

In sum, in order to put the proposed method into practice of geophysical activity, bore hole cables with electrodes are required. The technology of such cables manufacture is known in the procedures of geophysical well logging.

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