Complex electromagnetic monitoring of salt mines

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Abstract

The Earth's surface collapses are a serious hazard on salt mine areas. Electromagnetic methods are characterized by a number of substantial informative capabilities within salt deposits. Electromagnetic monitoring technology has been developed on the base of electrical and electromagnetic sounding. Analysis of the experimental monitoring surveys results allowed to determine a number of predictive criteria and indications of the salt karst processes in electromagnetic fields, including the expressed dynamics of water mineralization change, gas-dynamic and subsurface subsidence-collapse cyclicities. The obtained information has been used as a basis for a dynamic geoelectrical model of collapse formation.

Keywords: monitoring, salt mines, prediction, electromagnetic sounding, electrical methods, dynamic geoelectrical model

Introduction

Development of monitoring technologies to determine and predict possible negative processes is an important problem these days. One of such negative processes is the formation of collapses and subsidence of the Earth's surface as a result of intensive karst processes caused by natural and anthropogenic reasons. The salt karst process is extremely intensive. The examples of this are the collapses and subsidence occurred during potash deposits mining in Canada, USA, Russia, Germany and other countries. Geological, geophysical, hydrogeological, geodetic and other methods are applied to provide the safety of salt deposits exploration (Contrucci *et al*. 2011; Land and Veni 2012; Pain *et al*. 2012; Siemon *et al*. 2012). The difficulty of their implementation is connected with the necessity to analyse many factors including physical-geological conditions of the investigated territory and various phenomena associated with the karst processes as well as with peculiarities and contrast of their manifestation in physical fields.

This paper deals with the results of a research aimed at developing an electromagnetic monitoring system adapted to the Upper Kama salt deposit conditions (Russia, Perm region). The acute need for these investigations was connected with the flooding of one of the mines accompanied by a series of subsequent collapses (fig. 1). The geological section of the investigated depth interval includes the potash salt strata, rock salt beds, clay-marl complex, limestone-sandstone complex, and quaternary sediments (Andreichuk *et al*. 2000). There are up to four aquifers within the oversalt strata with quite high water content. The lower part of the clay-marl complex and the evaporate strata, isolating the aquifers from the mines, are referred to as a waterproof complex (Andreichuk *et al*. 2000). The top of the evaporate beds within the investigated territory can be found at a depth of 140-180 m, however, the potash salt layers and mine system are located at a depth of approximately 200-230 m. An important peculiarity of the investigated area is the position of a large part of mines within the city. Their location increases both hazardous level of possible negative phenomena and relative difficulty of the implementation of geophysical monitoring methods.

Methods

Electromagnetic methods have unique informative capabilities within salt deposits. Electrical resistivity depends on such physical properties as porosity and water

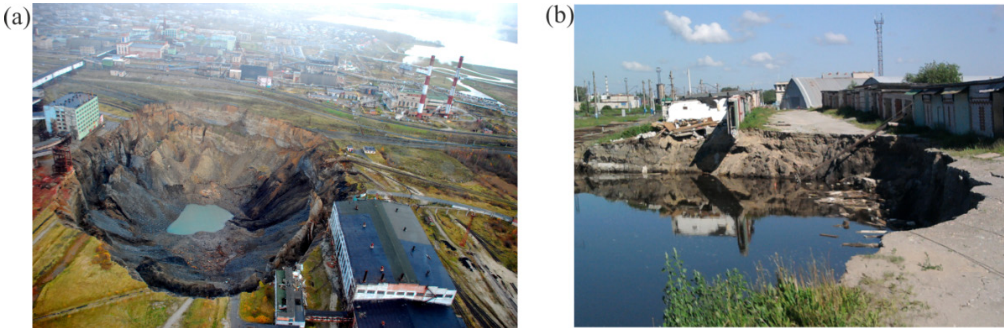

Figure 1 *The first collapse (a) and example of the following collapses (after 4 years) (b).*

content of rocks, it is sensitive to changes of water mineralization and gas content, which are associated with the salt karst process development.

Under the conditions of the Upper Kama salt deposit the water mineralization changes from 0.5-1 g/L (oversalt aquifers of the limestone-sandstone strata) to 400-450 g/L (saturated brines in the salt rocks dissolution zone) (Andreichuk *et al*. 2000). So electrical resistivity of water can decrease by a factor of hundreds (to 300-400) as a result of the mineralization rising in the salt dissolution zone.

The same contrast of electrical resistivity change is connected with the gas content of rocks. Due to the dielectric properties of gas the increase of the gas content of rocks upon filling the voids can lead to the electrical resistivity rise of hundreds of per cent. Salt rocks contain (in adsorbed, molecularly connected, nonassociated condition) a substantial volume of gas of different types (hydrogen sulfide, carbon dioxide, methane, and others). The distortion of salt crystal structure generally occurring as a result of its dissolution leads to gas accumulation and gas dynamic processes.

To monitor the physical condition of rocks in the depth interval from the Earth's surface to the productive part of the salt strata a complex of complementary methods has been developed. It contains: 1) electromagnetic sounding based on the use of controlled source (CSEM) and industrial electromagnetic fields (industrial magnetic field method, IMF) (Kolesnikov and Laskina 2015) which provide an opportunity to investigate the salt rocks layers; 2) direct current method (DC) which allows to control the oversalt part of geological section; 3) stationary electrical monitoring system, aimed at the predictive assessment of the negative processes development stage in anomalous areas determined by the complex of the EM and DC methods. The stationary monitoring systems are based on the DC method with the use of multielectrode array, commutator and specific software (Kolesnikov *et al*. 2017). It provides an opportunity for real time spatial-temporal control of the physical condition of oversalt geological section with the required measurement period, safety of work and data transmission via the Internet.

For the analysis of the survey results in addition to electrical resistivity the following dynamic interpretation parameters are used: a) relative difference $\Delta_{i,1}$ between obtained values $\rho_i(r)$ for i-th and initial $\rho_0(r)$ stages of survey; b) velocity of the electrical resistivity change v_i for the time period $\Delta t_{i,i+1}$ between i-th and (i+1)th surveys; c) dynamic activity which is the sum of amplitudes of variations $\delta_i(r,t)$ exceeding the noise level (δ_0) determined in the process of test measurements.

Experimental surveys

Developed monitoring complex was applied to investigate several areas (approximately 2 km^2 each) within the flooded mine territory. The surveys were conducted on 1080 investigation points annually. A complex analysis of the results obtained for all investigated areas allowed us to form a general scheme of the salt karst processes development and collapse formation on the salt deposit territory.

Figure 2 shows the results of the monitoring of the salt strata with the help of the IMF method. It demonstrates the typical formation of the decreased resistivity anomaly with an extension of the zone and increase in its intensity. One of the most likely reasons of the formation of this zone is the increased intensity of salt rocks dissolution in this depth interval, causing the extension of the cavity and the rise in mineralization of water, filling the mines. It is typical for the initial stage of possible collapse formation.

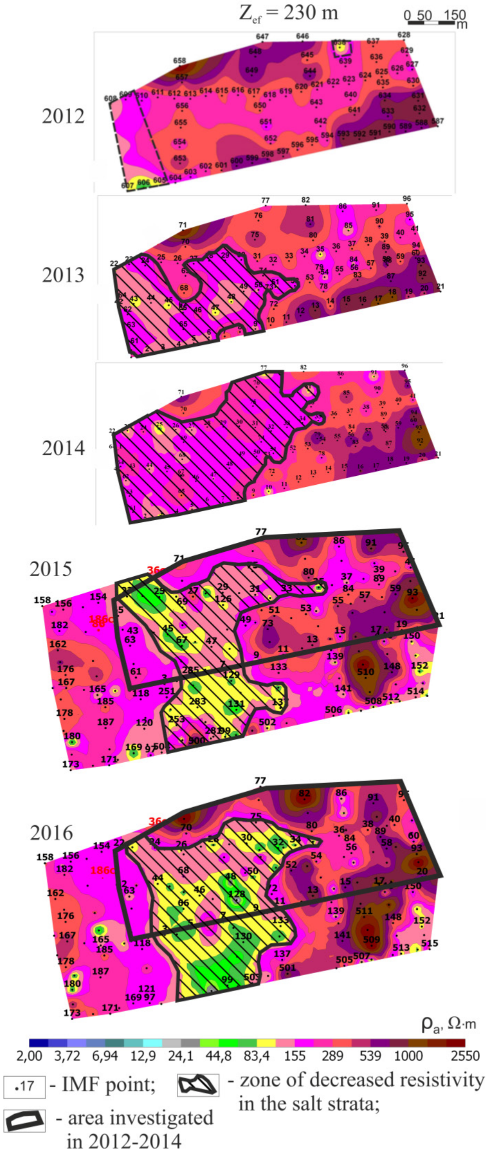

Figure 2 An example of an electrical resistivity monitoring survey on one of the IMF investigated areas at a depth of approximately 230 m with the extension of the investigated zone in south-west direction (area 1).

The following dynamic of resistivity variations can be accompanied by a number of other processes. We suppose that the most substantial of them are the so-called cyclic processes, which are evident in a periodic dramatic resistivity increase in a certain part of the geological section followed by a decrease in the anomalous effect as well as by some specific phenomena in the overlying sediments. Such processes were observed as a result of regional DC and EM surveys and stationary monitoring systems application.

Regional surveys were conducted once a year on the most of the investigated territory. It allows to recorde only general behaviour of the dynamic process accompanied by a set of indications in salt and oversalt parts of the section and determine probable nature of the most intensive spatio-temporal changes in the electrical resistivity of the medium (with the intensity to 300-900 %). At the same time, stationary monitoring systems implemented at anomalous sites (identified by the results of regional monitoring surveys) detected the repetition of these processes with a relatively reduced intensity (on average 15-20%, in some cases up to 100-150 %) with an interval from 15-20 days to 1.5-2 years showing the periodical changes in electrical properties. The cyclicity is explained by the increased sensitivity of electrical resistivity to changes in water mineralization, density and gas content of rocks within the zones of increased rocks fracturing. Each process has its own pecularities in the electromagnetic field. Analysis of the anomalous effect and the dynamics of the electrical properties variation, observed within the determined subvertical fractured zones, showed that there exist two types of cyclicity: 1) gas-dynamic; and 2) subsurface subsidence-collapse.

The most probable reason of the first type of cyclicity is the substantial increase of the gas content of rocks in the oversalt strata, caused by the the distortion of the gas-shield properties of the covering salt rocks and the subsequent outburst of gas accumulations, formed as a result of the salt rocks dissolution. This process leads to a substantial increase in the electrical resistivity of the near salt strata. The existence of the subvertical fractured zones in the overlying sediments contributes to gas migration, in a number of cases up to the Earth's surface, causing the gradual decrease in the anomalous effect with time as a result of the gas emission from substrata.

Some examples of the gas-dynamic cyclicity are shown in Figure 3. It reflects the observed dramatic resistivity increase (to 300-400 %) in 2013-2014 in the near salt strata with the traceability of the anomalous zone in the overlying sediments and the following relative decrease of resistivity in 2014-2015.

The second type of cyclicity is connected with the processes of subsurface collapse. It manifests itself as a formation of a dramatic resistivity increase zone within the salt karst area without well-defined anomalous features in the overlying sediments in the initial time period. This process is the evidence of the possible rocks density rise and is typical for the subsurface rocks collapse in the interval of the karst cavity.

Verification example of this is the precollapse process, detected by a stationary monitoring system in a potentially dangerous area, considered in the results of the analysis of the gas-dynamic cyclicity, which appeared two years before a small collapse (fig. 3). In contrast to the gas-dynamic cyclicity the stationary monitoring system indicated a dramatic resistivity increase in the near salt strata (to 800 %) without the well-defined anomalous effect in the overlying sediments (fig. 4). This manifestation, which is typical for the subsurface subsidence-collapse cyclicity, was observed 14 days before a small collapse in this place. The reason for it is the distortion

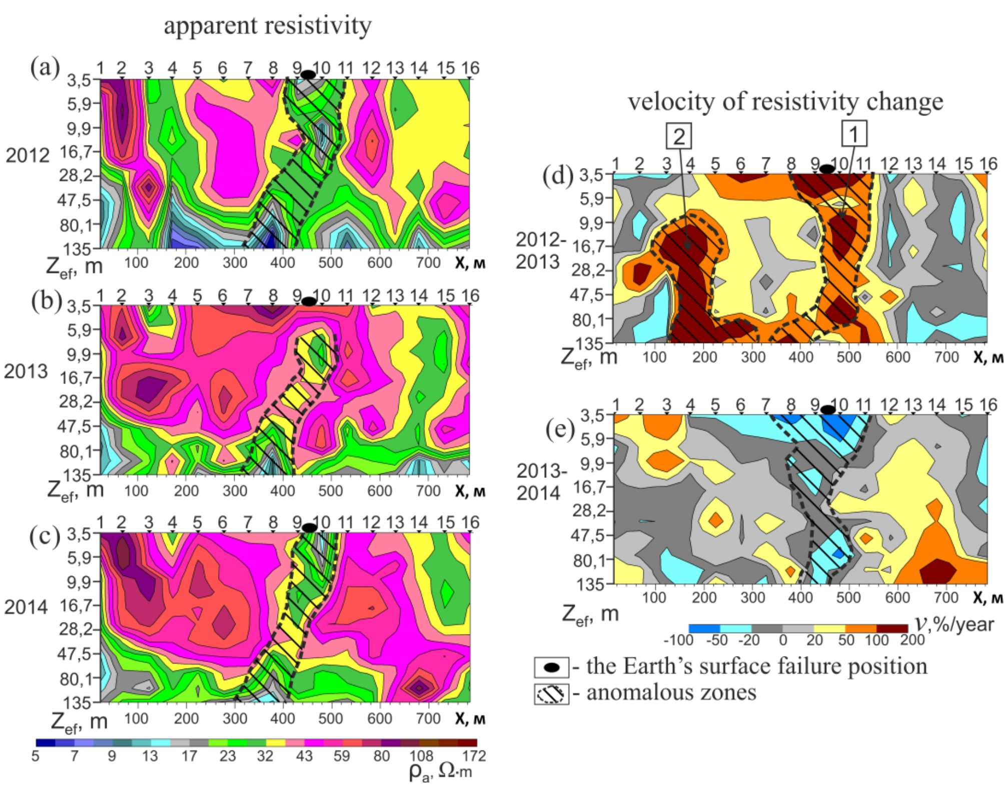

Figure 3 *Sections of the apparent resistivity (a, b, c) and velocity of the resistivity change (d, e) 2012-2014 on the territory of the collapse occurrence (area 2).*

of the physical-mechanical properties and a breakdown of the overlying rocks in the karst cavity under the influence of gravity.

Analysed examples show that the defined types of cyclicity, detected within the subvertical zones of the fractured rocks, are important diagnostic features for the predictive estimation of the position and time of possible collapse formation. The time interval between the beginning of the subsurface subsidence-collapse phenomena and the Earth's surface collapse occurrence depends on the depth of cavity formation and physical condition of the overlying sediments. Geodetic survey has been applied as one of the methods for the verification of the karst development zones, determined by the electromagnetic methods. Comparative analysis of the defined electrical diagnostic features of karst processes has shown the further spatial correlation with the zones of the intensive subsidence of the Earth's surface.

As a result of the analysis of experimental monitoring investigations conducted in 2012-2016 a predictive dynamic geoelectrical model of the development of the collapse formation process under the conditions of the flooded mine territory has been created. The model shows four basic stages.

1. The first (initial) stage corresponds to the beginning of the formation of an intensive salt rocks dissolution zone in the productive interval. It is reflected by a decreased resistivity area with a tendency towards a rise in the anomalous effect.

2. The second (progressive) stage is characterized by the increased intensity of the distortion of the covering salt rocks and overlying strata. It is indicated in the resistivity survey results as: a) increased dynamics of the waterproof strata resistivity change; b) decrease in relative electrical resistivity in the waterproof strata with the cyclical processes of resistivity variations in the oversalt sediments, caused by the likely disturbance of the gas-shield properties of salt rocks and gas migration; c) traceability of the previously determined zones of decreased resistivity in the productive interval, indicating the absence of substantial rock collapse in this depth interval.

3. The third (precollapse) stage corresponds to the beginning of the subsurface subsidence-collapse processes. The typical features of this stage: a) decrease in the anomalous effect in the salt strata,

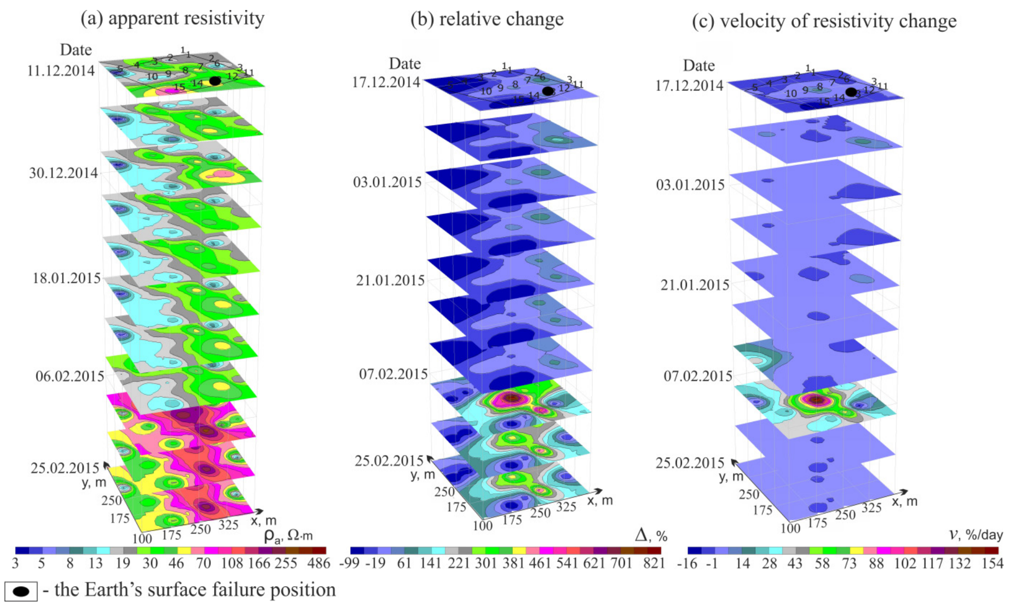

Figure 4 The subsidence-collapse cyclicity fragment observed with the help of the stationary monitoring system in the oversalt strata at a depth of 130 m in the precollapse period (central part of area 2).

associated with a density properties increase as a result of the likely filling of the brine-filled cavity by the breakdown material; b) cyclicity of resistivity variations, which is typical for the subsurface subsidence-collapse processes; c) subvertical zones of decreased resistivity in the overlying sediments, showing intensive fracturing of rocks; d) tendency to the resistivity decrease in the waterproof strata and overlying rocks, connected with a possible increase in the water content of these rocks.

4. The forth (collapse) stage is characterized by intensive dynamics of the subsurface subsidence-collapse cyclicity in the oversalt strata with the tendency towards the approach to the Earth's surface.

Conclusions

Developed electromagnetic monitoring technology allowed us to determine important criteria to predict salt karst processes including two types of cyclic resistivity variations: gas-dynamic and subsurface subsidence-collapse. Formed dynamic geoelectrical model of these processes can substantially increase the accuracy of salt karst prediction.

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