Method of evaluation of earth surface subsidence on mining fields of Kalush mining industrial region according to high-precision gravimetry data

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SUMMARY

The aim of this paper is to demonstrate the efficiency of using geophysics to predict the emergencies that were caused by the subsidences and failures of the surface. It is about mine fields of potash and rock salt deposits, which are the most dangerous. The research facility is Kalush-Holyn potassium salt deposit, which is located in the Ukrainian Carpathians.

The research was conducted using high-precision gravimetry. The novelty of the results is in the proof of the reliability of predicting the possible areas of subsidences and failures based on model calculations and concepts that demonstrate sufficient resolution of gravitmetry.

The method of calculating the quantitative characteristics of surface subsidence based on analysis of decompacted rocks recorded by gravimetry in monitoring mode is offered in the article. Options for calculating for both discrete and gradient environments are presented. The results are necessary with regard to their informativity for further substantiation of managerial decisions on further exploitation of research areas.

Introduction

An effective approach to solving problems associated with the dangerous ecological and geological situation at the Kalush-Golynsky deposit of potassium salt is a study of the depleted mining space by geophysical methods. One of these methods is high-precision gravitational exploration which is used for detailing the geological structure in dangerous areas and it provides monitoring of karst development and forecast of the sinkholes on this surface, as well as the evaluation of the degreee of land surface subsidence. The effectiveness of geophysical methods of ecological control has been demonstrated at various deposits in Ciscarpathian and Transcarpathian regions [Anikeyev et al., 2019, Tiapkin et al., 2017].

Input data and methods

According to the administrative division, the study area is located in Ivano-Frankivsk region in western Ukraine, geologically - in Sambir subzone of the Ciscarpathian Expanse. The Novo-Golyn mine of the Kalush-Golinsky deposit is located to the east of the city of Kalush and includes two ore fields: East-Golyn and Sivka-Kaluska, which were depleted in 1966-1995. In total, there were 12 158,5 m^3 of voids at the Novo-Golyn mine, which were partially filled with unsaturated brines of the Dombrovsky quarry in the volume of about 11 900 m^3.
The subsidence of the earth's surface at the Novo-Golyn mine has been recorded since 1979. The subsidence processes over the depleted minefields lead to the formation of pits, in which wetlands develop and lakes are formed.
In order to determine the possibilities of high-precision gravimetry for predicting karst formations, sinkholes and subsidence of the earth's surface as well as studying the dynamics of their development at different depths, modeling of gravitational anomalies of them on the example of real geological section of the potassium mine "Novo-Golyn" was carried out [Kuzmenko et al., 2017].
The authors of the article propose a method for determining the maximum possible degree of subsidence of the earth's surface due to the processes of destruction of mountain ranges over the minefields according to the data of regular gravimetric observations. The maximum subsidence of the earth's surface, caused by destruction (dissolution) within a certain layer (vertically homogeneous), can be determined as follows:

$$\Delta h(x_i) \leq \left(\frac{h_{init}(x_i) \cdot [\sigma_{init}(x_i) - \sigma_a(x_i)]}{\sigma_{init}(x_i)} \right); \qquad (1)$$

where h_{init} – layer thickness; σ_{init} – initial layer density; σ_a – layer density after destruction; x_i – arbitrary point along the profile.

For the medium with n boundaries and depth-averaged values of rock density within the layers before and after destruction, the formula will be as follows:

$$\Delta h(x_i) \leq \left(\sum_{j=1}^{n} \frac{h_{init,j}(x_i) \cdot [\sigma_{init,j}(x_i) - \sigma_{a,j}(x_i)]}{\sigma_{init,j}(x_i)} \right); \qquad (2)$$

where n – quantity of layers; j – ordinal number of a layer.

In order to take into account the complex distribution of isodense within the zones of destruction (Fig. 1), the formulas are the following:

$$\Delta h(x_i) \leq \sum_k H^k(x_i) \cdot \Delta\sigma_k(x_i); \qquad (3)$$

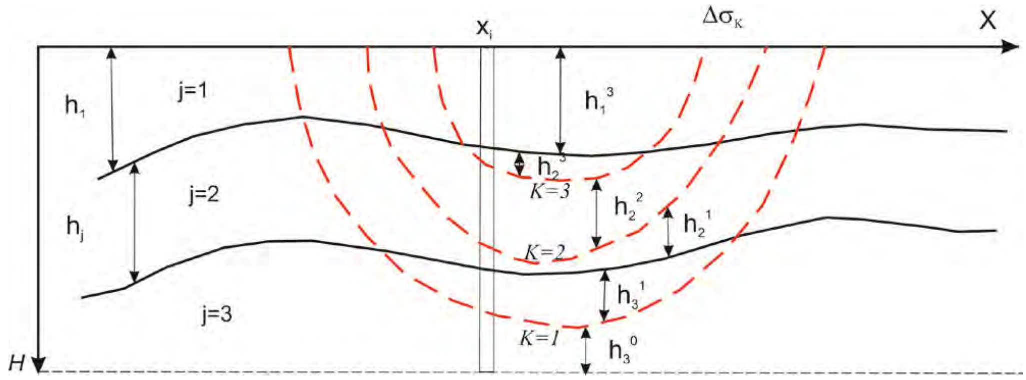

Figure 1 *Schematic geological model of the environment and destruction isodense*

$$H^k(x_i) = \sum_j \frac{h_j^k(x_i)}{\sigma_j(x_i)}; \tag{4}$$

k – destruction isodense ($\Delta\sigma_k$) index; *j* – layer index; x_i – arbitrary point along the profile.

Taking $\Delta\sigma_{k-1} - \Delta\sigma_k \rightarrow 0$, that is intersection of isodense is going to zero, and taking into account homogeneity of mass in the model before destruction, then:

$$\Delta h(x_i) \le \sum_j \frac{1}{\sigma_j(x_i)} \int_{h_{j-1}}^{h_j} \Delta\sigma(x_i, h)dh, \tag{5}$$

which results from the equations (3) and (4).

On one of the profiles of the Novo-Golyn section, a quantitative interpretation of gravimetric data was carried out - the solution of the inverse task of gravity exploration, the purpose of which was to identify and localize destruction zones associated with salt chambers: local changes in solution density of the conserved mine chambers, development of integrity violation of chambers and rocks above the chambers, etc. Obviously, the destruction zones cause the appearance of negative local anomalies of the gravitational field.

The geological section along the profile consists of sediments of the Stebnyk suite (N_1stb), which are represented by interstratified clays with layers of gypsum and siltstone, underlying saline clays, breccias with lenses and layers of potassium salts of the Lower Baltic suite (N_1bl_1); above them, there are rocks of the Upper Baltic suite (N_1bl_2), which are represented by clays. For ore kainite formation, which is located in the sediments of the Lower Baltic suite (N_1bl_1), the density is 2.25×10^3 kg/m^3, and for mine workings (chambers) filled with pulp and brine, it is 1.27×10^3 kg/m^3. For the zone of destruction of the saline Lower Baltic suite (N_1bl_1), which is located in the ore layer and above it, the density is taken to be 2.20–10^3 kg/m^3 (Table 1).

As a result of interpretation of gravimetric observations (solution of the inverse problem of gravity exploration), the predicted distribution of densities within the geological section is obtained, which is presented in two variants: the first - survey of 2007, the second - 2008 (Fig. 2). The initial values of rock densities are given in Table 1.

Destruction of rocks is observed at depths of +200 ÷ +270 m (according to absolute marks). The dimensions of these destruction zones increase in the direction to the central part of the profile under research. The intensity of destruction according to gravimetric exploration in 2008 compared to 2007 increased. Thus, the process of karst formation was continuing.

***Table 1** Density of rocks at the Novo-Golyn mine*

	Rock	Stage	Density limits for laboratory studies, 10^3 kg/m^3	Initial model values, 10^3 kg/m^3
1	*Clay with a content of sand*	*Q*	*2.0 – 2.1*	*2.05*
2	*Gravel and pebbles horizon*	*Q*	*2.0 – 2.4*	*2.3*
3	*Gypsum-clay cap*	*Q*	*2.2 – 2.2*	*2.2*
4	*Schist and fractured clays with interbeds of sandstones, siltstones*	N_1bl_2	*1.95 – 2.3*	*2.12*
5	*Clay with a high content of salt and breccia, lenses and layers of potash and rock salt*	N_1bl_1	*1.95 – 2.3*	*2.12*
6	*Potassium salt*	N_1bl_1	*2.1 – 2.25*	*2.25*
7	*Shally and fractured clays with gypsum and anhydride, fine-grained sandstones and aleurolites*	N_1stb	*2.0 – 2.35*	*2.2*
8	*Concentrated brines*		*1.27*	*1.27*
9	*Unfilled mines*		*0*	*0*

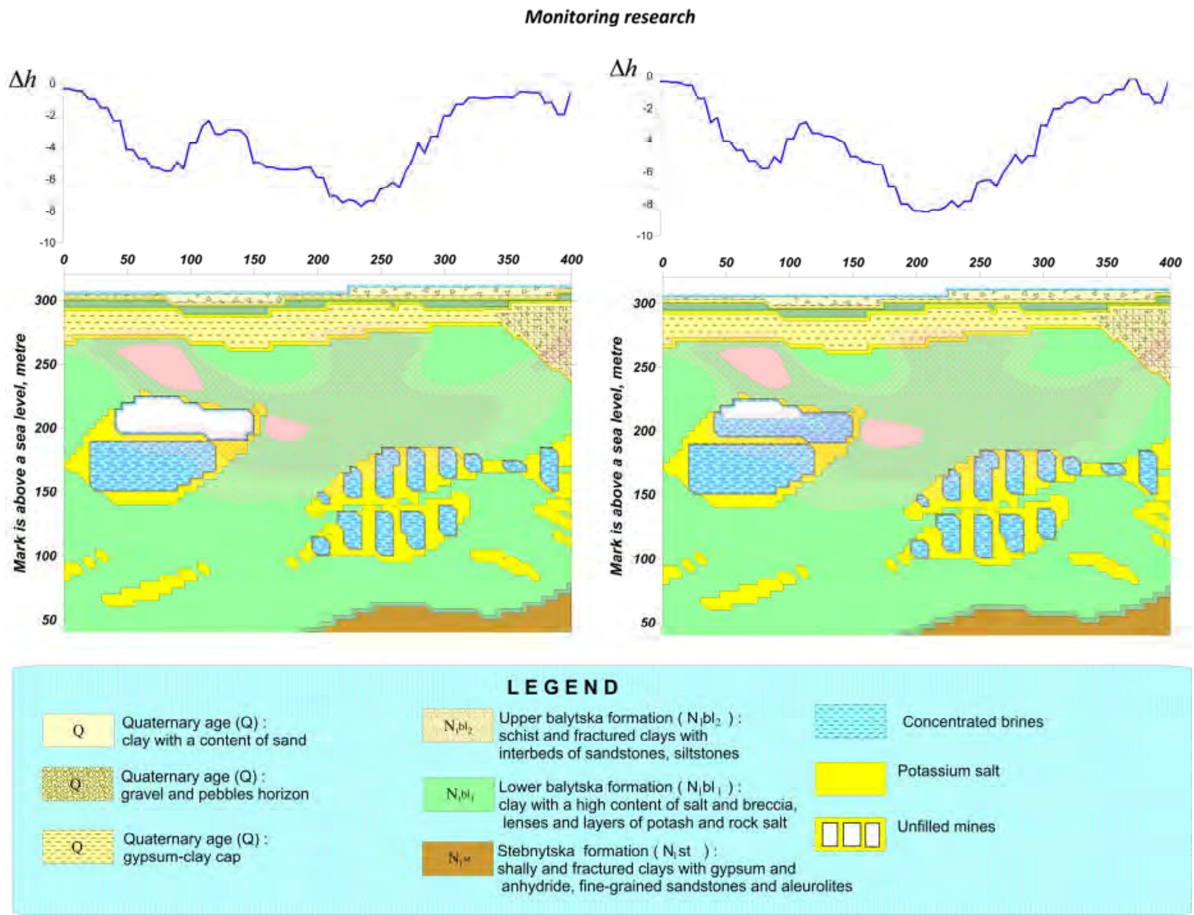

***Figure 2** Mine field East Golyn, mine “Novo-Golyn”. Geological-petrophysical models.*

According to the results of interpretation of geological and geophysical data, we have identified types of dense anomalies (zones of decompaction) associated with the following geological processes:

infiltration of rocks, the erosion of the surface of the salt mirror, destruction of interchamber bearing blocks and ceiling of the chambers. Characteristics of anomalies are presented in Table 2.

Table 2 *Geological interpretation and classification of decompaction zones*

Attribution of zones of decompaction	**Intensity of decompaction, 10^3 kg/m^3**	**Dimensions of gravitational anomalies, m^2**	**Intensity of gravitational anomalies, 10^{-5} m/s^2**	**Nature of the phenomenon**
Associated with chambers	*0,1–0,4*	*50÷200 ×50÷200*	*0÷–0,2*	*Development of chambers and violation of the integrity of the mass*
Associated with salt mirrors	*0,15–0,45*	*25÷150 ×25÷150*	*0÷–0,1*	*Erosion of the surface of the salt mirror*
Associated with the top part of the section	*0,05–0,35*	*≤50×50*	*0÷–0,05*	*Infiltration of rocks*

Additionally, based on the proposed method (formulas 3-5), we performed an assessment of the degree of subsidence of the earth surface according to decompaction, which was calculated by the results of the inverse task of gravity exploration. The subsidence evaluation (in meters) is illustrated in graphs over the sections of the predicted distribution of decompaction (Fig. 2). The maximum subsidence up to 6.2 m is to be expected above the layers of potassium salts.

Conclusions

1. It has been proved that the only mobile non-destructive method for estimating the decompaction of rocks due to the leaching of their salt components in the mine fields of the Kalush mining industrial area is the geophysical method of gravimetric exploration.
2. Model experiments of solving the direct problem of gravity exploration for real objects of different densities and different degrees of decompaction have allowed to confirm the sufficient resolution of the gravimetric method and to classify density anomalies in accordance with certain types of objects.
3. Estimation of the size of the decompacted objects and the changes in their density over the time according to high-precision gravity exploration makes it possible to calculate the degree of maximum predicted subsidence and sinkholes of the earth surface, which will be the information basis for further planning management decisions about monitoring the ecological condition of potassium salt deposits.

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