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UNDERGROUND GRAVITY SURVEY IN A COAL MINE

PODZEMNA GRAVIMETRIJSKA ISTRAŽIVANJA U RUDNIKU UGLJA

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Abstract: Underground gravity surveys are usually conducted in order to define geological structures and to locate and delineate ore bodies. In the coal mines, on the other hand, these surveys are often applied in solving stability and safety problems of the mine. Basic principals of underground gravity measurements and examples of application in coal mining are presented. Complex geophysical and geological investigations were conducted in a wider area of the coal mine "Trbovlje – Hrastnik" (Slovenia) in purpose to define geological features and delineate potentially dangerous zones, connected to the subsidence, rockslides and water penetrations into exploitation galleries of the mine. Gravity and micro-tremor measurements were conducted in the mine galleries. Compilation and interpretation of subsurface gravity anomaly maps and interval density map is presented.

Key words: underground gravity measurements, coal mines, safety

Apstrakt: Podzemna gravimetrijska istraživanja u rudnicima se, obično, izvode u cilju definisanja geološke građe i lociranja i okonturivanja rudnih tela. U rudnicima uglja, sa druge strane, ova istraživanja se najčešće primenjuju za rešavanje problema stabilnosti i bezbednosti rudnika. Prikazani su osnovni principi podzemnih gravimetrijskih merenja i primeri primene dobijenih rezultata u rudnicima uglja. Na širem prostoru rudnika "Trbovlje - Hrastnik" (Slovenija) izvedena su kompleksna geofizička istraživanja u cilju određivanja geoloških karakteristika ispitivanog područja i definisanja i okonturivanja zona različitog stepena rizika, vezanih za sleganje, akcidentne odrone i prodore vode u delove eksploatacionih galerija rudnika. U samom rudniku izvršena su gravimetrijska merenja i merenja mikrotremora. Prikazan je način izrade i interpretacija potpovršinskih karata gravimetrijskih anomalija i karte intervalnih gustina.

Ključne reči: podzemna gravimetrijska merenja, rudnici uglja, bezbednost

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1. INTRODUCTION

Basic aim of gravity surveys is to define rock density distribution in purpose to construct geological model of the investigated area. Underground gravity measurements in the mines are usually conducted in purpose to determine interval densities of layers at different depth. In the case of complex geology and significant lateral density variations, application of this method requires gravity measurements in a larger number of vertical shafts (that is often impossible, especially in the small or deep mines). On the other hand, if there is a possibility to conduct gravity measurements in parallel horizontal galleries in a mine, as well as at the terrain surface, compilation of underground and surface gravity profiles and interval density profiles enables better definition of horizontal density variations. Interval density maps and cross sections, or even 3D model of interval density distribution, can be obtained for the mines with larger number of accessible shafts and galleries, where complex gravity survey can be conducted.

Underground gravity measurements are differently influenced by density variations below and above measurement station, so it is often hard to separate those influences. Abrupt density changes in a vicinity of a gallery have a significant influence on measured gravity data, but the distribution and densities of anomalous masses are usually partially known. When measurements are conducted at a horizontal gallery in a deep mine, density variations in the area surrounding the gallery usually have a very small influence on surface gravity data, but their influence on calculated interval densities is significant.

Coal mines are characterized by intensive activity, so they represent zones of increased risk connected to object stability, as well as to safety of staff and equipment. Surface and subsurface gravity investigations can be successfully applied for detection and monitoring of variations in the condition of rock masses in the area around the coal mine.

Variations of stress and strain in rock masses, repositioning of rock material due to subsidence and slides, intrusions of water in fractured parts of rock mass, as well as other similar phenomena, that are influenced by activities in a coal mine, are causing variations in rock density distribution and, as well, in gravity. Gravity measurements in coal mines can be conducted as single-time measurements or measurements repeated in time intervals. Single-time measurements can be used for construction of geological terrain model, but only repeated measurements (gravity monitoring) can insure data for tracing of variations in gravimetric parameters at the field.

Density model, formed on the bases of surface and underground gravity measurements (Vasiljević, 2005), can be transformed into a geological model, according to the known geological and petrologic characteristics of the investigated area. Results of density measurements in the laboratory, conducted on rock samples from all parts of a mine and from the terrain surface, should be included in the model. Ones the density model is formed, gravity monitoring is used to detect the occurrences of density variations that might be connected to a development of degradation or other process in rock masses. Such a process can endanger the mine safety, so the early detection of any change in rock masses is very important.

2. APPLICATION OF GRAVITY SURVEYS FOR THE SAFETY OF COAL MINES

Gravity measurements can be used for detection of abrupt density changes or any kind of unusual density distribution in a vicinity of a coal mine galleries. Density variations can be caused by the presence of cavities or fractured zones, as well as by the intrusions of water in fractured parts of the rock mass. Gravity measurements are also used for detection and positioning of old mine works.

Numerous examples show that the results of surface and subsurface gravity surveys can represent a significant contribution to a successful analysis of the stability and safety of coal mines. Gravity monitoring in a coal mine was used for rock-burst forecasting (Fajklewicz, 1983). The mean density change of the rock mass, which was threatened with rock burst, was estimated from gravity measurements and the depth of rock-burst focus was determined using the analytical continuation of gravity field.

Presence of the erosion pockets filled with material and water under high pressure near the gallery of a coal mine can be detected by gravity measurements (Fajklewicz et al., 1982). If such a phenomenon is not under control, consequences for mining crews and equipment can be disastrous. In many cases, gravity measurements can be a substitute for extensive investigation boreholes drilling.

Monitoring of mining subsidence is especially important for the safety of a coal mine, as well as for environmental protection. Gravity measurements at the terrain surface should be conducted before, during and after coal-seam extraction. Gravity measurements are strongly influenced by the change of station height, so the amount of that change can be calculated from the variations of measured gravity values. Results of such a survey (Lyness, 1985) showed good correlation between results of gravity measurements and results of precise leveling. One method does not exclude another, but it is preferable that they are combined. Gravity measurements can be repeated at all stations in a short period of time and that improves the quality of the subsidence effects monitoring.

Another approach to the gravity monitoring of coal mining subsidence is based on joint analysis of surface and subsurface gravity data (Vasiljević et al. 2005). Monitoring of variations in measured gravity values, gravity anomalies and interval densities during the different phases of subsidence enables monitoring of changes in rock masses and modeling of subsidence process, as well as a prediction of further changes in rock masses (forward modeling). Method can be applied in a situation when the active mine works are placed below the old mine works, so there is a successive subsidence due to current coal extraction, as well as to compaction of parts of rock masses, disturbed by previous mining activities in upper part of investigated area.

3. UNDERGROUND GRAVITY MEASUREMENT TECHNIQUES

Underground gravity measurements can be conducted in all types of mines at different depths, as long as the shafts and galleries of the mine are accessible and safe. Maps and cross sections of the mine are used to plan efficient and precise geodetic and gravity measurement. Different types of portable gravitymeters, constructed for the surface surveys, are the most often used instruments for subsurface gravity measurements.

Gravity survey in the mine can be performed as a single-time measurement or monitoring (measurements in permanent gravity net, repeated in time intervals). Gravity monitoring is applied for tracing variations in gravimetric parameters, connected to the processes in the rock masses. Time intervals are adjusted depending to the dynamics of the observed process.

There are two basic conditions necessary for successful underground gravity measurements:

1. Density contrast and the position of the source of gravity anomalies should induce detectable values of anomalies;
2. Distribution of the shafts and galleries should be suitable for the positioning of gravity station's net.

Gravity net is carefully designed. At least two base stations are necessary, one at the surface and the other in the mine. They are usually located in the shaft or in its immediate vicinity and their main purpose is to connect surface and subsurface gravity measurements. In the mines that are large or complex, additional base stations are included at every level or separated part of the mine, in order to connect measurements at all stations. Quality control of the underground gravity survey is achieved by repeated measurements at the base stations (Murty et al. 1982).

Distribution of gravity stations in the net depends upon the specific task of the survey. Distance between the stations depends on the magnitude and expanse of expected gravity anomalies. The gravity influence of underground constructions is smallest when the station (gravitymeter) is positioned along the axes of the shaft or gallery. Station should be sheltered from the influence of intensive ventilation, often present in the coal mines.

Stations can be distributed along horizontal and vertical profiles and planes or in full space, depending upon the characteristics of the mine (Figure 1). Measurements along vertical profiles or planes (Figure 1a) are used to calculate interval densities (density of the layer between two levels of measurement). In this case, gravity net is designed to contain pairs or groups of stations (surface and subsurface) distributed along the same vertical direction. Measurements along horizontal profiles or planes (Figure 1b) are used to create subsurface gravity anomaly profiles and maps. The best results are obtained by measurements in full space (Figure 1c), for they enable creation of 3D models.

Coordinates and height of every station are determined by high-precision geodetic measurements. In order to insure correct positioning of pairs or groups of stations along chosen vertical directions, geodetic survey is conducted before the gravity measurements. It is also necessary to measure or estimate distances from the every station (gravitymeter) to the walls of the shaft or gallery. These data, together with the dimensions of all underground constructions, are used to calculate the correction for the gravity influence of artificial underground features.

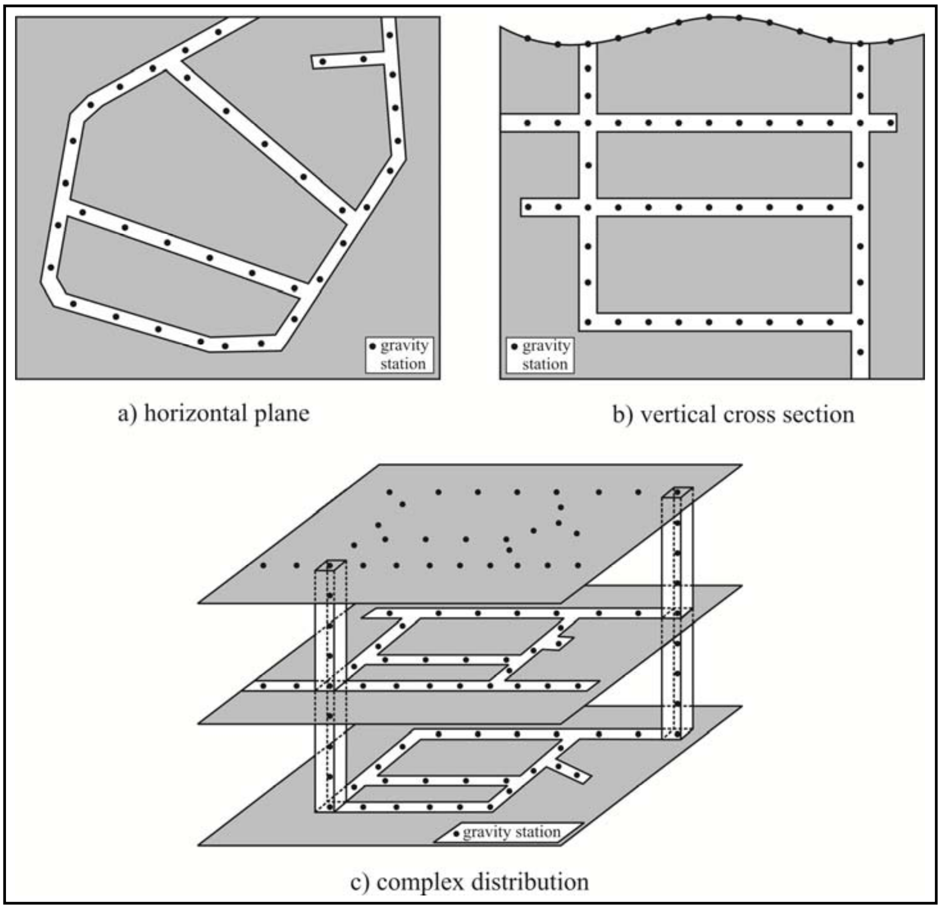

Figure 1 - Distribution of gravity stations: a) in the horizontal plane; b) in the vertical plane (cross section) and c) complex distribution

4. UNDERGROUND GRAVITY SURVEY IN "TRBOVLJE - HRASTNIK" COAL MINE

Underground gravity survey was a part of complex geophysical and geological investigations, conducted in a purpose to define geological features and delineate potentially dangerous zones, connected to the subsidence, rockslides and water penetrations into exploitation galleries of a coal mine "Trbovlje – Hrastnik" in Slovenia (Starčević et al. 2002). Surface geophysical investigations of the wider area around the coal mine included gravity, geomagnetic, electrical and micro-tremor measurements. Subsurface gravity and micro-tremor measurements were conducted in the mine galleries.

Geology of the area surrounding the coal mine is rather complex. West, central and north zones are composed mainly of marls and coal, though most of coal in upper parts was excavated. Composition of east and south-east zone is determined by faulting, so upper parts are composed mostly of marls and limestone and lower parts are mainly composed of marls. Dolomites form the base of considered formations. Density variations are present, both in vertical and horizontal direction. Unstable zones are formed as a consequence of shutting down galleries at different levels above the present active mining zone.

La Coste-Romberg model D-150 gravity meter was used for measurements. Surface gravity measurements were conducted at 183 stations in wider area above mining zone. Subsurface gravity measurements (Figure 2) were conducted at 19 stations in the mine galleries, on several levels. Most of the measurement stations (J1-J14) are distributed at the mean height of 89 m (at mean depth of 325 m); four stations are above this level at different heights (116 m - 130 m), while one station (J18) is below this level (58 m).

Figure 2 - Underground gravity measurements in "Trbovlje – Hrastnik" coal mine

Position of stations J1 - J18 is shown at the presented maps (Figures 3-7). Station J19 is outside of presented area (about 140 m east from the station J7) and it was used as the base station in the mine. Shallower galleries of the mine are mostly closed or unsafe. Entering shaft is located outside of presented area and it is not suitable for gravity measurements.

Measured gravity values were reduced to absolute level and corrected for instrumental drift and tidal effect. Accuracy of absolute gravity values is 0.3 μm/s^2. Normal gravity values were determined using formula by Cassinis. Terrain corrections for surface and subsurface (Hearst, 1968) stations were calculated. Corrections for the mine galleries were calculated using formula by Hussain (Hussain et al. 1981).

Rock samples were collected from each subsurface gravity station. Results of the laboratory density measurements of the samples from the mine galleries are shown in Table 1.

Table 1 - Density measurements of rock samples from the mine

Station	**Height *h* [m]**	**Number of samples**		**Rock type**	**Average density at the station [t/m^3]**	**Average density of the rock type [t/m^3]**
J1	86.96	1	18	coal	1.37	1.43
J2	87.21	3			1.32	
J3	87.31	3			1.41	
J4	87.01	3			1.54	
J5	88.29	5			1.53	
J14	96.95	3			1.42	
J6	88.89	2	3	limestone	2.45	2.45
J19	115.88	1			2.44	
J7	89.24	1	34	dolomite	2.67	2.69
J8	89.24	2			2.62	
J9	88.07	3			2.66	
J10	88.57	2			2.64	
J11	88.30	3			2.67	
J12	90.55	2			2.76	
J13	90.80	2			2.68	
J14	96.95	5			2.75	
J15	129.76	7			2.79	
J16	119.32	3			2.81	
J17	117.58	2			2.63	
J18	58.18	2			2.66	

Distribution of the rock sample densities at the mean height of 89 m (stations J1-J14, marked by black dots) is presented on Figure 3. Faults are marked by red lines. Shaded areas are the zones of increased safety risk, delineated on the base of complex geophysical investigations. West shaded area is determined as an active zone of high safety risk, while south-east area is potentially dangerous and further investigations are needed to determine the level of safety risk.

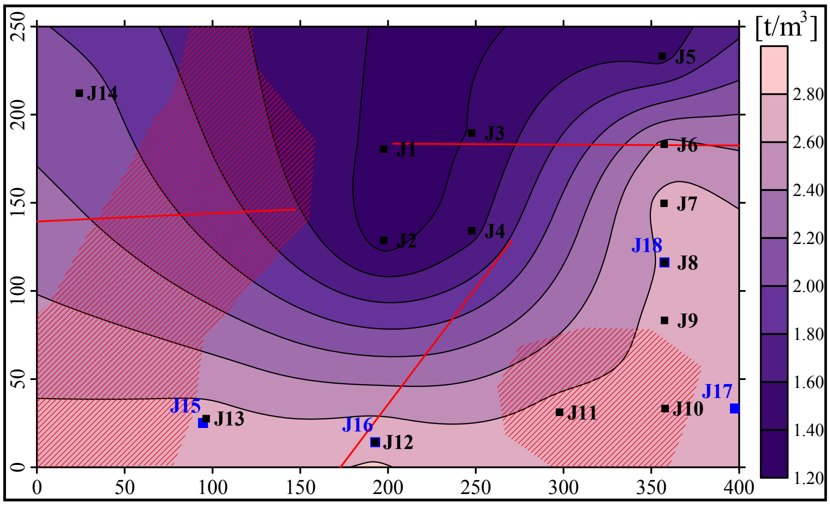

Figure 3 - Distribution of the rock sample densities at the mean height of 89 m

Interval densities are calculated using classical formula (Hammer, 1950). Corrections were made for topography on surface and subsurface stations and for mine galleries (Vasiljević, 2006). Obtained interval density map (for the interval layer between the surface and underground level at the mean height of 89 m) is presented on Figure 4. Mean thickness of the interval layer is 328 m. Distribution of interval densities of the tick layer is mainly influenced by density variations in the vicinity of surface and underground level of measurements. Range of interval densities is much smaller than the range of sample densities, because they are influenced by large rock masses.

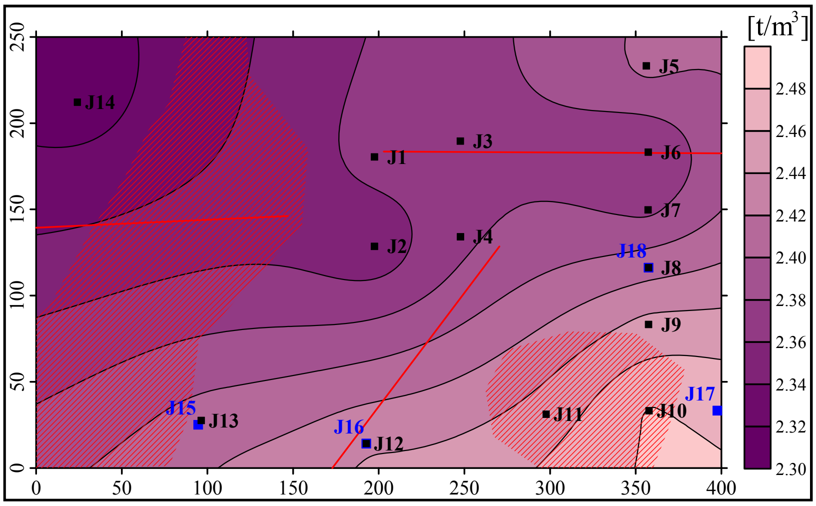

Figure 4 - Interval density map

Lower interval density values generally correspond to the coal formations at the north area of the map at Figure 3, while higher values correspond to carbonates (mainly dolomites) at the south. Differences of density distribution in maps on Figures 3 and 4 are caused mainly by near-surface density variations. West safety risk zone (shaded area) is not covered by underground gravity measurements, but general decrease of densities toward east is in accordance with other geophysical data that suggest possibility of increased risk.

Interval density determination for other pairs of subsurface stations (positions of stations J15-J18 are marked by blue dots on all maps) is presented in Table 2. Obtained interval density values correspond to the measured densities of dolomite samples from the galleries (Table 2).

Table 2 - Interval densities for other pairs of gravity stations

Station	**Height h [m]**	**Δh [m]**	**Interval density [t/m³]**	**Rock type**
J8	89.24	31.06	2.67	dolomite
J18	58.18			
J16	119.32	28.77	2.66	
J12	90.55			
J15	129.76	38.96	2.67	
J13	90.80			

Gravity anomalies on surface and subsurface level are calculated using mean interval density of 2.40 t/m^3. Obtained maps are presented at Figures 5 and 6. Comparison of the maps shows that anomalies are significantly different at presented levels and that implicates different density distribution in the vicinity of each level.

Intensity of surface gravity anomalies (Figure 5) increases from north to south and south-east. Terrain surface of the north area is covered by various Triassic sediments. Water penetrations into exploitation galleries of a coal mine were detected north from the area showed in the maps. Low values of the anomalies are probably caused by fractured surface sediments of decreased density near the surface and coal formations below. Terrain surface of the south area is covered by low density Oligocene and Miocene sediments. Increase of the gravity anomalies is caused by higher density dolomites that form the base of Tertiary formations.

Distribution of subsurface gravity anomalies (Figure 6) is more complex. It is influenced by rock density distribution both below and above subsurface level (at the mean height of 89 m) and that complicates the interpretation. The main problem is that the anomaly sources of same parameters, located below and above subsurface level, would cause gravity anomalies of the same absolute intensity, but of opposite sign. Gravity minima near station J3, for instance, could be caused by low density source below or high density source above measurement level.

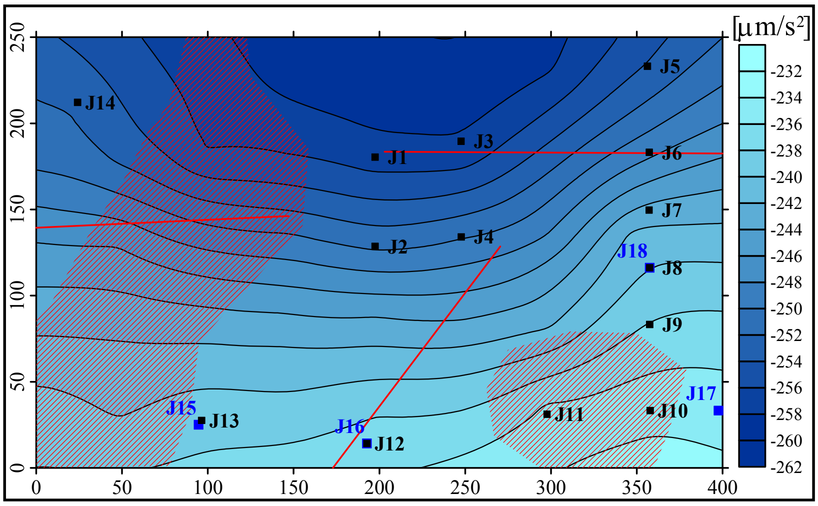

Figure 5 - Surface gravity anomaly map

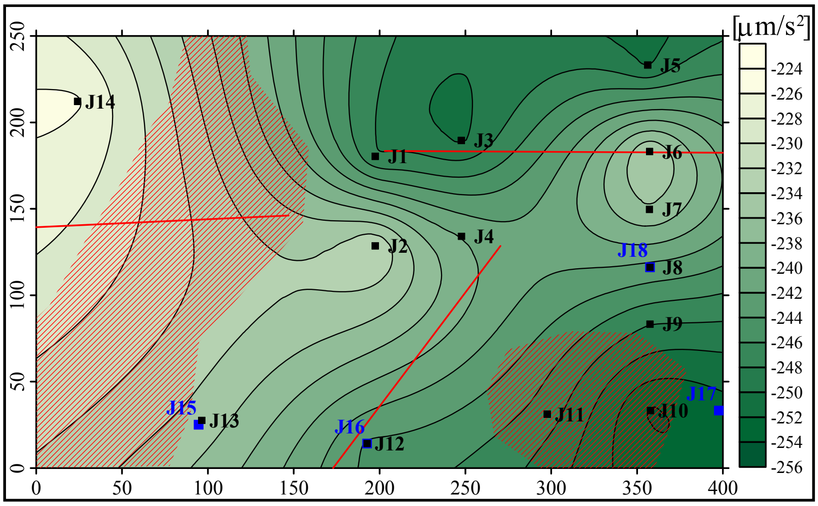

Figure 6 - Subsurface gravity anomaly map

In order to partially separate gravity sources located below and above subsurface level (Vasiljević, 2006), gravity anomalies were corrected using interval densities for the calculation of Bouguer correction for interval layer. Subsurface gravity anomaly map corrected using interval densities (Figure 7) mostly represents gravity influences below the subsurface level and it is generally in correlation with the distribution of rock sample densities (map on Figure 3).

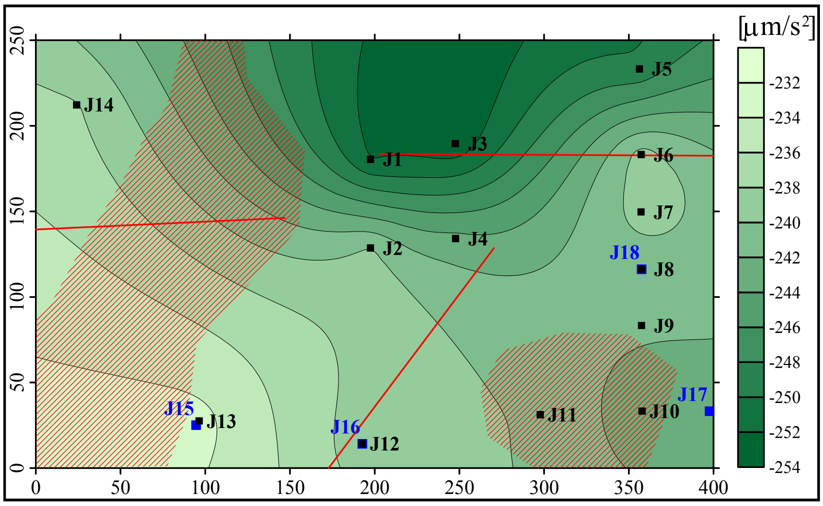

Figure 7 - Subsurface gravity anomaly map corrected using interval densities

Subsurface gravity anomaly map of the interval layer (Figure 8) was obtained as a difference between subsurface gravity anomalies (Figure 6) and corrected subsurface gravity anomalies (Figure 6). The shape of anomalies is in correlation with the distribution of interval densities (Figure 4), but this is also a consequence of using interval densities for calculation of corrected subsurface gravity anomalies. Purpose of this map is to show gravity influence of anomaly sources located above subsurface measurement level. Sign of the anomaly is reversed, comparing to surface gravity anomaly map. Positive anomalies are connected to low density formations, while high density rocks cause negative anomalies.

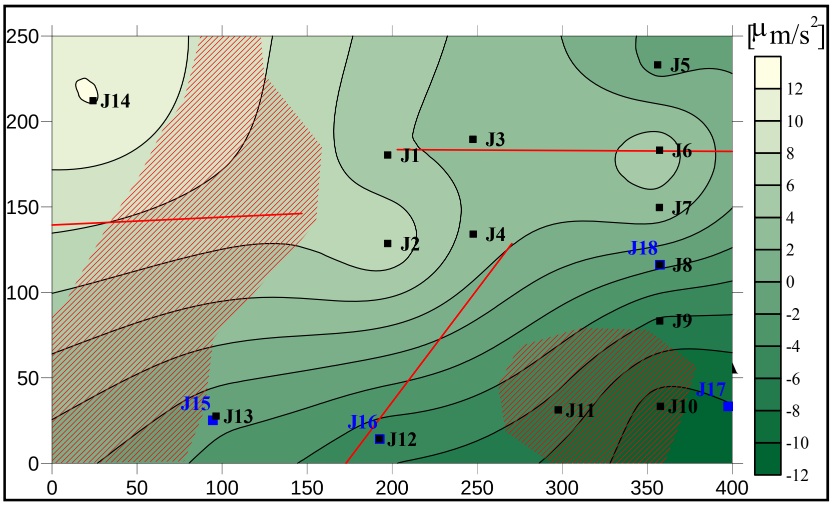

Figure 8 - Subsurface gravity anomaly map of the interval layer

Another approach to separation of gravity sources located below and above subsurface level is correlation between surface and subsurface gravity anomalies. High negative correlation coefficient is connected to significant density variations inside the interval layer. High positive values of correlation coefficient implicate abrupt density changes below interval layer. This method is more suitable for profiles, but it can also be used on maps.

5. CONCLUSIONS

Results of combined surface and underground gravity measurements in mines can represent a significant contribution to analysis of stability and safety of the coal mines. Different types of underground gravity surveys are designed for detecting specific safety problems (cavities, fractured zones, subsidence, slides, water intrusions, rock-burst).

Interval density distribution and subsurface gravity anomalies enable precise detection of gravity anomaly sources and better geological interpretation of gravity data. Gravity models based on joint analysis of surface and subsurface gravity data, as well as interval and rock samples densities, are more accurate than standard gravity models.

Underground gravity survey in the coal mine "Trbovlje – Hrastnik" (Slovenia) was a part of complex geophysical investigations, conducted in a purpose to delineate potentially dangerous zones, connected to the subsidence, rockslides and water penetrations into exploitation galleries. Interval density data are, generally, in accordance with other geophysical data that suggest possibility of increased risk in one of delineated zones. Subsurface gravity maps were used for the separation of shallow and deep anomaly sources and geological interpretation. Better results might be obtained by designing gravity net with greater number of stations at all levels and by applying gravity monitoring.

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