

## Article

# Microgravity Survey to Detect Voids and Loosening Zones in the Vicinity of the Mine Shaft

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**Abstract:** In mining and post-mining areas, the assessment of the risks to the surface and its infrastructure from the opening or closed mine is of the utmost importance; particular attention should be paid to mine shafts. The risks include the occurrence of undetected voids or loosening zones in the rock mass. Their detection makes it possible to prevent their impact on a mine shaft and surface infrastructure. Geophysical methods, and in particular, a microgravity method lend themselves for the detection of changes in the distribution of masses (i.e., the density) due to voids and loosening zones. The paper presents the results of surface microgravity surveys in the vicinity of three mine shafts: under construction, working, and a liquidated one. Based on the gravity anomalies, the density distribution of the rock mass for all three cases was recognized. The properties of the anomalies allowed to determine which of the identified decreased density zones may pose a threat to the surface infrastructure or a mine shaft. The microgravity survey made inside the working mining shaft provided information on the density of rocks outside the shaft lining, regardless of the type of lining. No significant decrease of density was found, which means that there are no larger voids outside the shaft lining. Nevertheless, at a depth of 42 m in running sands layer, the decreasing density zone was located, which should be controlled. Additionally, measurements in two vertical profiles gave the possibility of directional tracking of density changes outside shaft lining. Such changes were observed on three boundaries of geological layers, with two of them being on the boundary of gypsum and other rocks.

**Keywords:** geophysics; microgravity; hard coal mine; mine shaft; mining and post-mining area; rock density; voids and loosening zones



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## 1. Introduction

Deep mining is one of the methods for exploiting mineral deposits. Shafts are the most important infrastructure as they play a key role in such mines. They allow not only to excavate the minerals but to transport people and equipment necessary for the mine to operate. Shafts play a vital role in ventilation; they also convey electricity and water. This is why it is important to regularly monitor mine shafts in order to prevent the events that could lead to their damage or, even worse, destruction. Unfortunately, despite all the safety measures and precautions, shafts may become damaged or destroyed with dramatic consequences [1]. The causes may vary but ultimately the failure is usually a result of a human error such as insufficient monitoring, routine, or inappropriate investigation methods.

Many factors may threaten the stability of a mine shaft and the entire infrastructure related to it. One of them is damage to shaft lining, which apart from common causes such as inappropriate exploitation and maintenance of the shaft, may be a result of causes that are described by Lecomte et al. [1]. One of such cause is excessive pressure of water on the shaft lining, which may lead to ruptures (shaft located at Tirphil, New Tredegar, England, 2010). Underground water may also lead to chemical or mechanical suffusion, i.e., sliding

of the material outside of the shaft lining, which results in voids and loosening zones; it also leads to tensions in the shaft lining, which may cause fracturing. A similar phenomenon but at a larger scale may occur near the surface, posing a threat to the shaft and the surrounding infrastructure (coal shaft V, Knurów-Szczygłowice colliery in Poland) [2]. Another hazard may be posed by an unfavorable geological structure, as was the case with the collapse of the shaft at the Jinchuan Nickel Mine, Gansu Province, China, 2005 [3,4] or the coal shaft V in Pniówek colliery, Poland, 2007 [5].

When a mine is closed, the shafts are liquidated in a manner that depends on the country and time. Unfortunately, liquidated shafts pose danger to the surrounding area due to the factors indicated above as well as the following [1,6]:

- a collapse of the material filling the shaft (shafts n°8 and n°8 bis, at Noeux-les-Mines, France, 2007),
- a failure of the shaft head (West Midlands Shaft, England, 2000 and shaft III Matylda-East colliery, Swietochłowice, Poland, 2008),
- a failure of deep closure structure located in the shaft galleries (shaft n°2, Vieux Condé, France, 1987),
- a risk of subsidence due to remobilisation of filling material or surface development (coal shaft Nord at Noyant d'Allier, France, 2001),
- a specific focus on surface development (Low Hall n°7, New Zealand Pit at Abrams Lancashire, England, 1945).

Hazards to a shaft and its surrounding areas may be identified using many methods that determine the condition of the shaft lining, its damage or horizontal or vertical dislodgments of the shaft elements, and the surface or surface infrastructure. These methods, however, are limited to detecting certain occurrences and usually do not determine their direct causes, which in the cases indicated above are related to the condition of the rock mass. In order to identify the sources of hazards for the shaft and its infrastructure, geophysical methods should be applied.

Geophysical methods are widely used to identify shallow rock mass, but their application is determined by the shallow geological setting, specific purpose, and the location. In the case of hazards related to mine shafts, the geophysical surveys may be applied to the surface surrounding the shaft and the shaft's interior. Surface surveys can be applied to operating and liquidated shafts.

Theoretically, almost all geophysical methods can be applied for surface surveys, but in practice there are limitations to the applicability of a given method.

Seismic method is characterized by very good vertical and horizontal resolution and is frequently used to identify shallow geological structures and detect voids and loosening zones [7–9]. Unfortunately it requires profile surveying, which renders it inapplicable for investigating mine shafts due to the surface infrastructure of the surveyed areas and the fact that it is impossible to run profiles that would allow for area-wide reconnaissance of the rock mass. Another issue is multiple distortions resulting from the operations of the shaft and its infrastructure. Seismic method can be applied to liquidated shafts, although it is applicable only along profiles and it is not always economical to increase the number of profiles.

Geoelectrical methods, including electrical and electromagnetic (including Ground Penetration Radar) ones, allow for examination of shallow parts of the rock mass [10–12]. However, as is the case with the seismic method, the measurements are taken along profiles, which means that both methods have similar limitations. Additionally, many distortions occur that are a result of buried utilities such as water, electricity, gas, telecommunications, and more. This is why, while geoelectrical methods give good results in undeveloped areas [13,14], they are of limited use in the case of mass rock surrounding the shaft accompanied by the broadly-understood infrastructure.

The limitations of both geophysical methods render a magnetic method useless for the purpose of surveying the rock mass surrounding the shaft that carries any infrastructure. The method is inapplicable also due to many electromagnetic distortions. Outside of

urbanized areas, the method can be used to detect buried shafts on the condition that near-surface elements of the shaft contain iron.

The last geophysical method, gravity method, registers the spatial distribution of masses, and consequently, the distribution of density [15]. The advantage of this method is its low susceptibility to external interference. Since the method is based on the common phenomenon of gravity, the only errors come from the observation device, i.e., the gravimeter. Due to the construction of the gravimeter, significant measurement errors come from instrument vibrations, coming from ground vibrations or vibrations caused by strong wind gusts. The appropriate method allows, however, to reduce such errors. For near-surface surveys, a variant of gravity method, i.e., microgravity, is applied. The prefix micro points to low anomalies generated by distortion and small distances between observation points.

Microgravity method is widely used for the detection of objects whose density differs from the density of surrounding forms, which renders it particularly applicable for detection of voids and loosening in the rock mass [16–18], posing a risk to the stability of the shaft and its surrounding infrastructure. As the measurements are taken at observation points, the method is applicable to surveys conducted in the areas covered by infrastructure or urban areas [19–21]. The measurements can be taken inside facilities such as halls and sheds, allowing for more complete coverage of the surveyed area. For this reason, the method can be applied to operating shafts as well as liquidated ones [22,23].

As has already been mentioned, geophysical surveys conducted in a working mine shaft, aimed at examining the rock mass outside of the shaft lining, are a separate issue. Voids and loosening zones outside of the shaft lining pose a particular risk to the shaft as they may lead to damage of the lining. Due to specific construction of the shaft and conditions inside the shaft, the only applicable method that can provide the desired results is the gravity (microgravity) method. As Hammer demonstrated in 1950 [24] and McCulloh confirmed in 1965 [25], this method allows to assess medium density rock mass outside of the shaft lining. On this basis, the loosening zones and voids outside of lining were detected as they lower the average density calculated from observation points located in the shaft. Madej has presented many examples in detail in his work [26].

For the above reasons, the authors present the application of microgravity method to assess risks related to mine shaft, while it is still operating as well after its liquidation. They also present the example where the risk was assessed during the sinking of the shaft. As the method registers the distribution of density in the rock mass, it gives good results in detecting voids and loosening zones in the rock mass. It can also be applied for detecting buried shafts and reconnaissance of rock mass surrounding the identified liquidated mine shafts. It also allows to assess the degree to which the liquidated mine shaft is backfilled in its near-surface part. Before shaft sinking, the seismic methods allows to recognize deeper parts of the rock mass [27], but the microgravity method allows to recognize the shallow part. Unfortunately, due to the lack of shaft infrastructure, there is no possibility to perform a survey inside the shaft during its sinking.

As it is relatively straightforward, microgravity method can be applied for monitoring the safety of shaft during its construction, exploitation, and after its liquidation [26,28,29]. The results can be used to vary mining modellings and simulations [30,31].

## 2. Materials and Methods

Geophysics is a field of science related to the problems connected with the Earth's structure and the processes that take place in there, using the analysis of natural and unnatural induced physical fields. A gravity method, based on the Earth's natural gravity field, is one of the passive methods. It means that the devices only register the received signal. Gravity surveys are based on measuring the changes in the gravity field, which reflect the changes in the distribution of masses (and, consequently density) in the rock mass. In fact, the measured value is the value of the vertical component of Earth's acceleration ( $g_M$ ). As it follows from the Newton's Law of Universal Gravitation and Second Newton's Law of Motion [32], acceleration caused by Earth's gravity field is directly proportional to

its mass and inversely proportional to the square of the distance. In light of the above the observed changes in gravity, forces may be used for a broadly understood reconnaissance of the distribution of masses in the rock mass.

In applied geophysics, the gravity method is applied to identify a geological structure frequently in order to detect mineral or oil and gas deposits. In engineering, a microgravity method is used to determine the condition of near-surface rock mass, particularly to detect loosening zones and natural and anthropogenic voids [16,18,33]. Gravity method also allows to determine the volume density of the rock mass “in situ”.

The change in gravity between observation points can have two primary sources. The first one is related to the distribution of density in the rock mass and the other to the observation point elevation and the terrain topography. While the first cause is the subject of the investigation, the other is undesired and should be eliminated.

For this purpose, the terrain correction  $\delta g_T$  is calculated. It eliminates the gravity impact of the terrain surrounding the observation point. Thanks to this correction, the excess of masses (above the observation point) and the deficit of masses (below this point) are eliminated. In both cases, the vertical component of this impact leads to the reduction of the gravity value, so the correction is always added to observation value. Introducing a correction renders the surrounding terrain flat from the point of view of each measurement point. In the case of geological investigations, the correction is calculated up to 25 km from the observation point and in the case of microgravity surveys the distance of 25 m is usually sufficient [34]. Obviously, if the terrain is not very varied, there is no need to introduce the correction.

The impact of the elevation on the measured gravity is consistent with Newton’s Universal Law of Gravitation: The gravity lessens in inverse proportion to the square of the distance between the observation point and the element of the Earth. For this reason, the measured values of gravity must be reduced to some assumed reference level (datum) with some fixed equipotential surface. The basic datum in gravity studies is the surface of the Earth model, i.e., the surface of the oblate ellipsoid.

In order to reduce gravity measurements, corrections are introduced to eliminate individual factors related to the difference in elevation between the physical Earth surface (the observation point) and the datum, as well as the deposition of different rock masses between them.

The first correction is the free-air correction  $\delta g_F$ , which eliminates the effect of elevation difference between the location of the observation point and the datum. Using the Earth model, the average vertical gradient of gravity can be calculated, which is  $3.086 \text{ nm}\cdot\text{s}^{-2}$  per meter. Therefore, the measured value of the gravity force transferred to a datum that is closer to the center of mass (Earth) must be increased.

The gravity impact generated by an infinite slab with a thickness equal to the distance between the observation point and the datum and a certain average density is eliminated with the Bouguer correction  $\delta g_B$ . The value of the Bouguer correction is negative as the gravity impact of the mass of the slab located below the observation point is eliminated.

The sum of all the corrections described above is called Bouguer reduction and it allows to calculate the value of the Bouguer anomaly, which is caused solely by the changes in the density distribution in the Earth’s crust. The Bouguer anomaly stands for the difference between the measured gravity reduced to a datum and the normal gravity calculated at that level also called latitude correction.

The normal gravity value  $g_N$  is calculated using the International Gravity Formula derived from the Geodetic Reference System 1980 Earth model [35].

$$\Delta g = g_M + \delta g_F + \delta g_B + \delta g_T - g_N \quad (1)$$

Micrgravity surveys are frequently carried out in urban areas and in many such cases it is necessary to take into account one more correction, as buildings and other structures located in the vicinity of observation points also have a certain mass. When such masses are close to the observation points they have an impact on the gravity value, in a similar



way as terrain relief does. In order to eliminate this impact, the building correction  $\delta g_U$  is calculated [19,20].

In mining areas, microgravity measurements are conducted both at the surface and in mine shafts and mining galleries. Each of the underground workings constitute a mass deficiency that affects the measured gravity values at the observation points in or near them. It is therefore necessary to eliminate this influence by introducing mining correction  $\delta g_G$  corresponding to gravity effects from the shaft (shaft correction) or galleries (gallery correction). New geodetic methods allow you to model the shape of the above objects with very high accuracy [36].

The Bouguer anomaly is a superposition of the gravity impact of all the rock masses in the geologic medium. However, from the point of view of engineering investigations, the most interesting part is the one concerning the changes in density distribution in the most near-surface part of the rock mass, called local anomalies. Anomalies originating from sources outside the surveyed area are called regional anomalies [37]. There are several different analytical methods by which the distribution of regional anomalies is calculated from the Bouguer anomaly distribution. The difference between the Bouguer anomaly and the regional anomaly results in a residual anomaly [38], which is a mathematical approximation of the local anomaly.

The authors of this paper used three methods to calculate regional anomalies, such as approximating the regional field with a low-order polynomial, Butterworth and Gauss filtering. The calculation of the regional field using the polynomial method involves approximating the trend seen in the Bouguer anomaly distribution using the polynomial order 1–4. The filtering methods, on the other hand, are performed in the wavenumber domain by transforming the Bouguer anomalies, usually with Fast Fourier Transformation. The transformation allows for the calculation of the power spectrum, which is used to determine the wavelengths representing the regional and residual anomalies. The wavelength depends on how deep the source of the anomaly is located and how large it is. It provides the basis for filtering methods. In gravity, the Butterworth and Gauss filter is most commonly used to separate both types of anomalies.

The gravity method also allows for the determination of bulk density values “in situ”. This task can be performed in two ways: using surface measurements [39,40] and using measurements in boreholes. In the second case, two types of gravity surveys are available, i.e., surveys in small-diameter boreholes [41] and in mine shafts [24].

In order to determine the bulk density of the rock medium surrounding a mine shaft, the “in situ” interval density method is applied, in which the microgravity observations are made inside the mine shaft, in observation points along the vertical profile [26,42].

A regularity discovered by McCulloh [24] underlies the use of the gravity method, in its vertical profiling version. It indicates that the gravity impact from a horizontal, infinite rock layer limited from above and below by observation points is generated by that part of the layer that is adjacent to the measurement profile within a radius equal to five times its thickness. It is known that in the measured values, up to 90% of the information comes from the structure of the geological medium located immediately behind the shaft lining [26].

The gravity values ( $g_M$ ) recorded in the shaft are influenced by gravity impact of the shaft, its lining, and other shaft bottom and mine workings occurring nearby. For this reason, the mining correction  $\delta g_G$  needs to be applied. The topography of the terrain around the shaft has a similar effect, which sometimes necessitates the introduction of terrain correction  $\delta g_T$ .

On the basis of the measured gravity values with corrections ( $g$ ), the density  $\rho_i$  of the rock slab is determined, with the slab delineated from the top and bottom by the following observation points [24,25]:

$$\rho = 3.682 - 1.193 \cdot (\Delta g / \Delta h) \quad (2)$$

$\Delta g = g_{i+1} - g_i$ —gravity difference between a roof and a foot of a slab,  $\text{nm} \cdot \text{s}^{-2}$ ,  $g_i = g_{M,i} + \delta g_{G,i} + \delta g_{T,i}$ ,  $\Delta h = h_{i+1} - h_i$ —rock slab thickness, m.

Density error is calculated according to the formula:

$$\delta\rho = |1.193 \cdot \delta g / \Delta h| \quad (3)$$

$\delta g$ —mean square measurement error,  $\text{nm}\cdot\text{s}^{-2}$ .

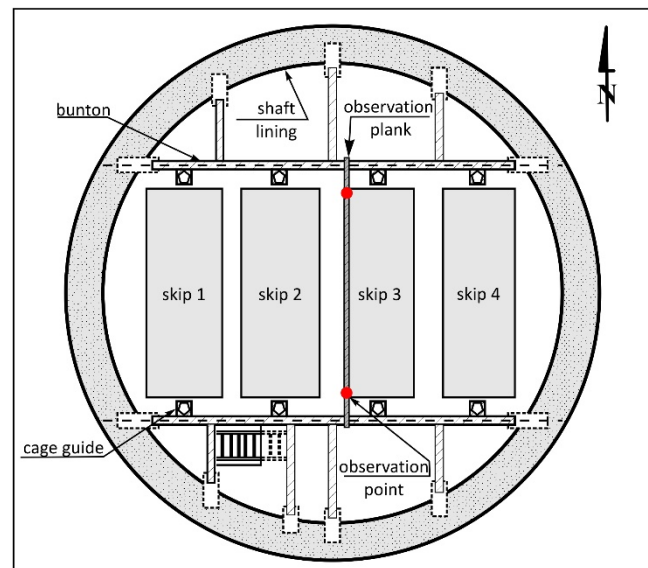
Microgravity surveys for geological and engineering purposes use gravimeters that measure relative values of gravity. It is not necessary to determine the absolute value of gravity in these surveys because the key information does not concern the specific value at the observation point, but the change of gravity between the observation points. All gravity measurements taken during gravity surveys are reduced relative to a fixed reference base. The reference base is the point at which the gravity force value has been predetermined. This value can be set arbitrarily or measurements can be referred to a point with an established absolute value of gravity, thus assigning absolute values to the measured values.

Relative gravimeters, due to their construction, are characterized by the occurrence of drift, which means a change of the measured gravity value with time. In order to eliminate the drift, its magnitude is examined with the passage of time on a single assumed point called a drift base. In the case of engineering surveys, one and the same point is used as a drift and reference base at the same time. In order to eliminate the drift effectively, gravity measurements are performed in the system of survey loops, starting and ending at the drift/reference base. In order to increase the quality of results, survey loops are not longer than 1–2 h.

Two procedures are used to obtain high quality gravity measurement results. The first one consists in taking at least two or three measurements of the gravity values at each observation point. If the difference between the obtained results does not exceed  $0.05 \text{ nm}\cdot\text{s}^{-2}$ , the average value is calculated, otherwise additional measurements are taken. The other procedure consists of repeating the gravity observations for at least 5% of all observation points, and in the case of microgravity surveys, even at two to four observation points from each survey loop.

The procedures described above are applicable in surface gravity surveys and in surveys carried out in vertical profiles in mine shafts. The difference in both cases is related to the manner of distribution of observation points within the survey area. In the case of surface surveys, the points are usually located at regular intervals in the form of a survey grid. The distance between points depends on the expected depth of the source generating the anomaly. In microgravity surveys, these distances range from 1 to 25 m.

In mine shafts, gravity is measured along vertical profiles located on the edges of the mine cage (a skip) or along the shaft axis. The distance between the observation points depends on the distance between the shaft bunton. A spatial measurement plank is placed on the bunton, thanks to which gravity measurements are not affected by the vibrations of the skip (Figure 1).



**Figure 1.** The mine shaft cross-section.

### 3. Results

Here we would like to present how the microgravity method can give an answer about the state of rock mass around a mine shaft. We have selected three examples of a gravity survey, each from a different stage of mining activity—before, during and after the operations of a mine shaft.

#### 3.1. Working Mine Shaft

One of the main challenges posed before mining operations is ensuring the safety of workers and mining infrastructure. It is particularly important to ensure safe exploitation of mine shafts. In order to identify the causes of mass rock distortions that have an impact on the safety of a mine shaft, the current structure of the rock mass has to be investigated. This can be performed using microgravity method in the form of vertical gravity profiling and surface microgravity method. The application of a surface microgravity survey allows for a reconnaissance of the state of the rock mass surrounding the mine shaft in terms of the existence of possible loosening zones, crack zones, or directions of water migration towards the shaft. Certain issues related to the safety of shafts, such as the state of the shaft lining resulting from the influence of physical phenomena on the shaft, are investigated by means of vertical gravity profiling.

The authors present the application of the above-mentioned methods on the example of research carried out in and around the mine shaft in the area of one of the collieries in Upper Silesia, Poland.

##### 3.1.1. General Geological Setting

The examined shaft is surrounded by rock complexes from three periods at the following depths:

- 0.0–61.8 m—Quaternary,
- 61.8–139.0 m—Neogene,
- from 139.0 m—Carboniferous with coal seams.

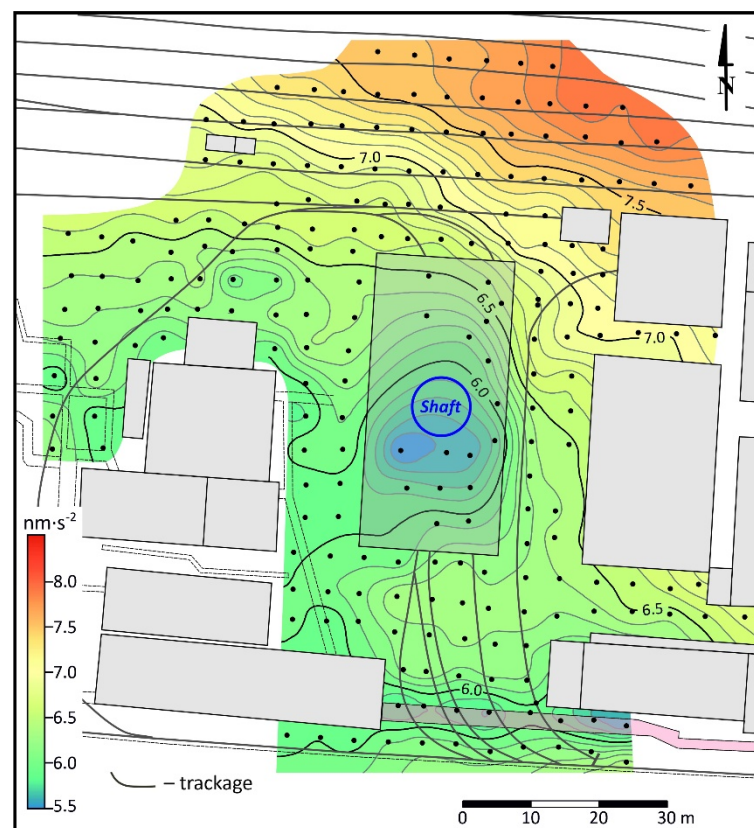
The Quaternary sediments lying horizontally and reaching a thickness of 31.5 m are developed in the form of silt over a sandy clay layer and very wet silt. Below there is a 25-m-thick layer of fine sand over medium sand, which occurs as running sand. The last layer of Quaternary sediments is loam with gravel lying at the depth of 56–62 m.

The thickness of the Neogene formations around the shaft is 77 m. In their roof there are 18-m-thick layers of loam and gypsum, below which lies a 30-m-thick layer of sandy loam. The other Neogene formations are layers of sandstone and shale.

The Coal Measures begin at a depth of 139 m and consist of alternating layers of sandstone and shale and coal seams. The direction of extension of the Carboniferous strata is northwestern–southeastern (NW–SE), which dips sharply towards the southwestern (SW).

### 3.1.2. Microgravity Survey

Surface microgravity surveys were made around the shaft, in a radius of approx. 50 m. Observation points were supposed to be set in a  $5 \times 5$  grid but only in accessible locations (Figure 2). The measurement was repeated at about 5% of the points and the mean square error stood at  $0.07 \text{ nm}\cdot\text{s}^{-2}$ . The obtained error value is close to the nominal error of the gravimeter and is slightly higher due to ground vibrations caused by the working shaft and the surrounding equipment.



**Figure 2.** The distribution of Bouguer anomalies (black dots—the observation points).

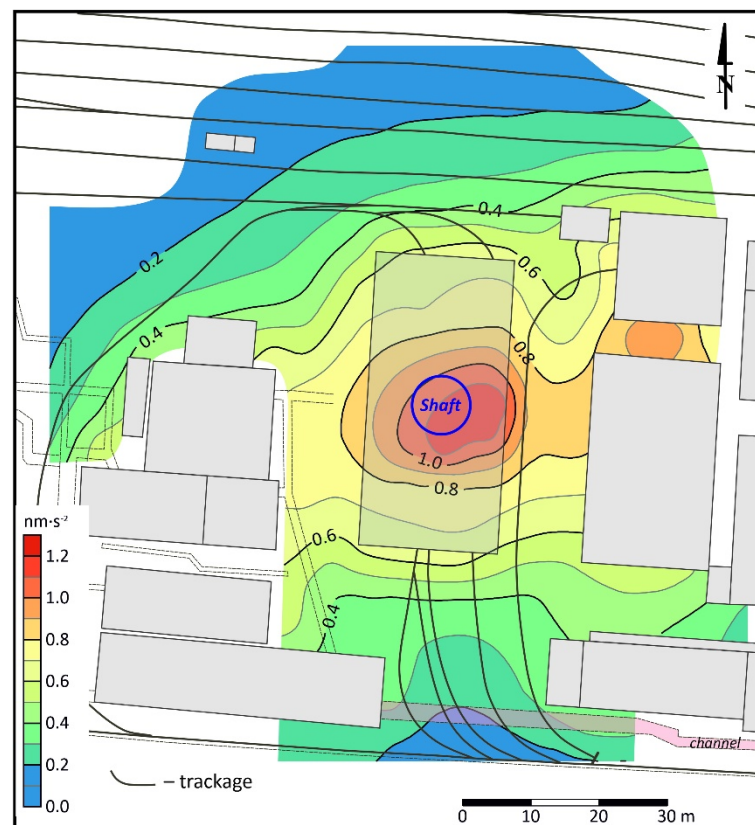
On the basis of microgravity and geodesy data, Bouguer anomaly values were calculated in accordance with the Formula (1), which provides the starting point for interpretation and subsequent data processing. First, Bouguer anomalies were subjected to Butterworth filtering in order to eliminate unwanted interferences caused by ground vibrations, measurement errors, and geodesic errors. This allowed us to obtain the distribution of Bouguer anomalies shown in Figure 2.

In the presented anomaly distribution, the influence of the gravitational influence of the shaft is clearly visible, manifested by strong, relatively negative values in its vicinity. Since some points were located close to buildings, they undoubtedly also influenced the measured values. The influence of buildings was eliminated using building correction.

Buildings were approximated by a rectangular prism, using geodetic data and information about the materials used in the construction of each building [20].

Mining correction was used to eliminate the influence of the shaft. Mining (shaft) correction was calculated using archival information from the excavation of the shaft. The mine shaft with diameter of 7 m had a brick and concrete lining to a depth of 65 m and a tubing lining below this depth. The different sections of the shaft were approximated by vertical cylinders. The foot and roof of each cylinder corresponded to the position of the rock layers surrounding the shaft pipe. The densities of each cylinder were chosen according to the layers that each cylinder corresponded to. The influence of variable shaft lining was also taken into account in the calculation of the correction. The correction was calculated at all points on the ground surface as well as at observation points inside the shaft (which will be described later).

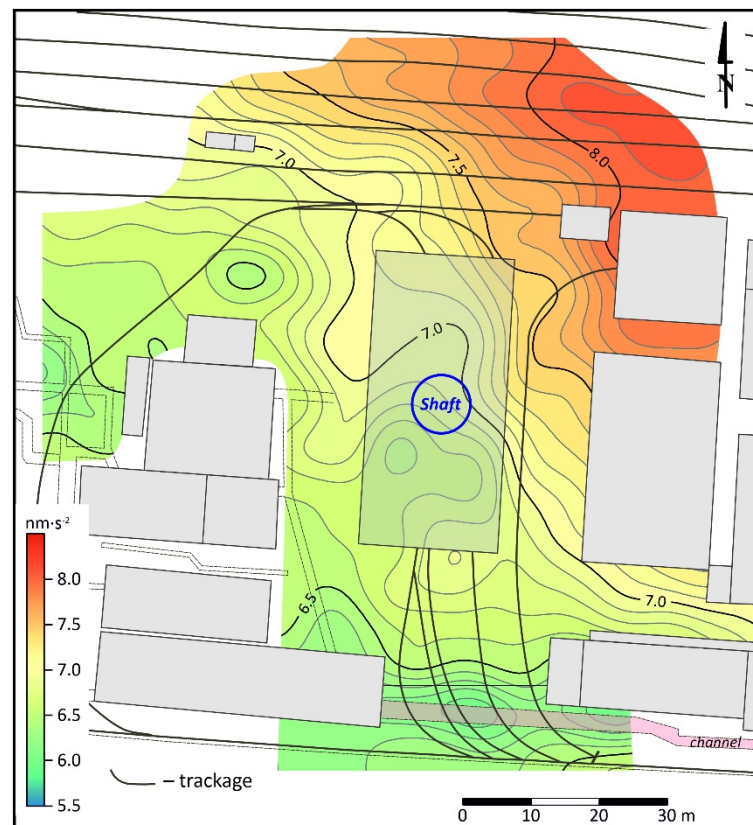
It follows from the calculations that the total gravitational influence of the shaft and buildings on the ground surface reaches a maximum value of slightly more than  $1.1 \text{ nm}\cdot\text{s}^{-2}$  (Figure 3). For a microgravity survey, this value is significant and its disregard would have a significant impact on the interpretation.



**Figure 3.** Distribution of the sum of building and mining correction.

After taking into account both gravity corrections above, the distribution of Bouguer anomalies is as shown in Figure 4. In general, the course of the anomalous field is from NW to SE, and the values of the anomalies increase from SW to NE (northeastern), and the total range of Bouguer anomalies is  $2.2 \text{ nm}\cdot\text{s}^{-2}$ . Thus, the course of the field is closely related to the geological structure described earlier, i.e., the course and dip of the Carboniferous strata.



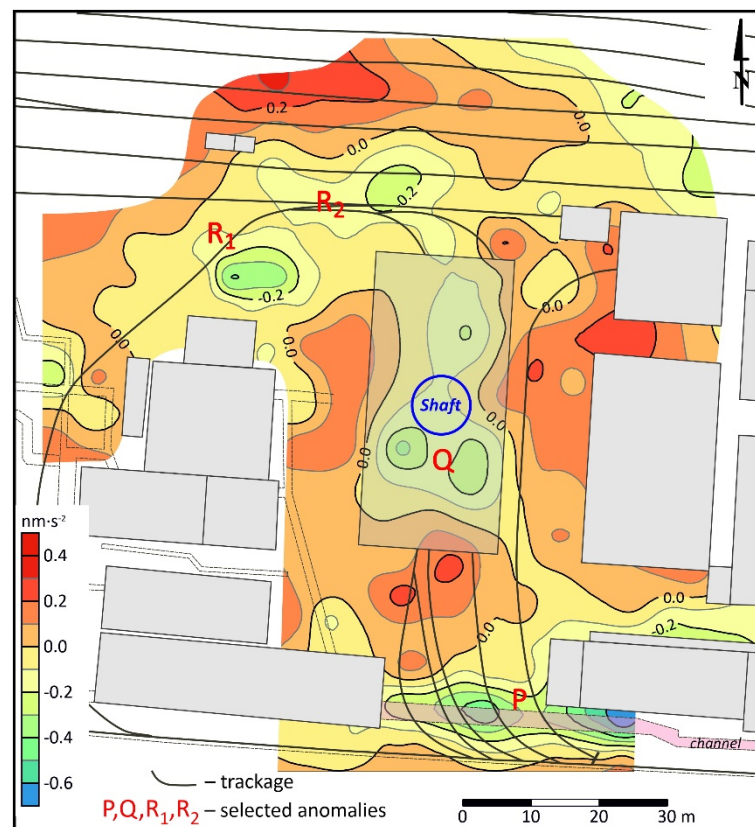


**Figure 4.** Distribution of Bouguer anomalies with building and mining correction.

In the obtained distribution of Bouguer anomalies compared to the general trend of changes in Bouguer anomalies, local changes of small horizontal extent and small amplitude (in relation to the whole field) can also be observed. These local anomalies provide information on the condition of the rock medium around the shaft. In order to separate them, a regional anomaly corresponding to the influence of the general geological structure was calculated. The regional anomaly was approximated using the surface polynomial order 2, which allowed the calculation of residual anomalies (Figure 5). The residual anomalies reflect the actual local anomalies, but are only an approximation of them.

In the obtained distribution of residual anomalies, the most visible is a sequence of relatively negative gravity anomalies P located in the southern part of the image. It is characterized by a small horizontal extent but significant amplitude. Its course coincides with that of a drainage channel located shallowly underground.

A relatively negative gravity anomaly Q was recorded in the direct vicinity of the shaft. This anomaly is a culmination of a zone of lower gravity values, which runs in the northern direction and joins a sequence of negative anomalies stretching East–West. Within the zone, two small anomalies with amplitudes larger than their surroundings  $R_1$  and  $R_2$  are also observed. The small amplitude and small horizontal extent of the entire zone of relatively negative gravity anomalies indicate that they are related to near-surface local density changes and do not affect the safety of the shaft. The anomalies P and  $R_2$  are associated with railroad infrastructure located in the vicinity of the shaft. The anomaly  $R_1$  occurs in an area devoid of any technical utilities. Therefore, it is caused by a local decrease in the density of the rock medium. This decrease is small and occurs in a limited area. Due to the relatively large distance of this anomaly from the shaft, it does not pose a threat to the investigated object.

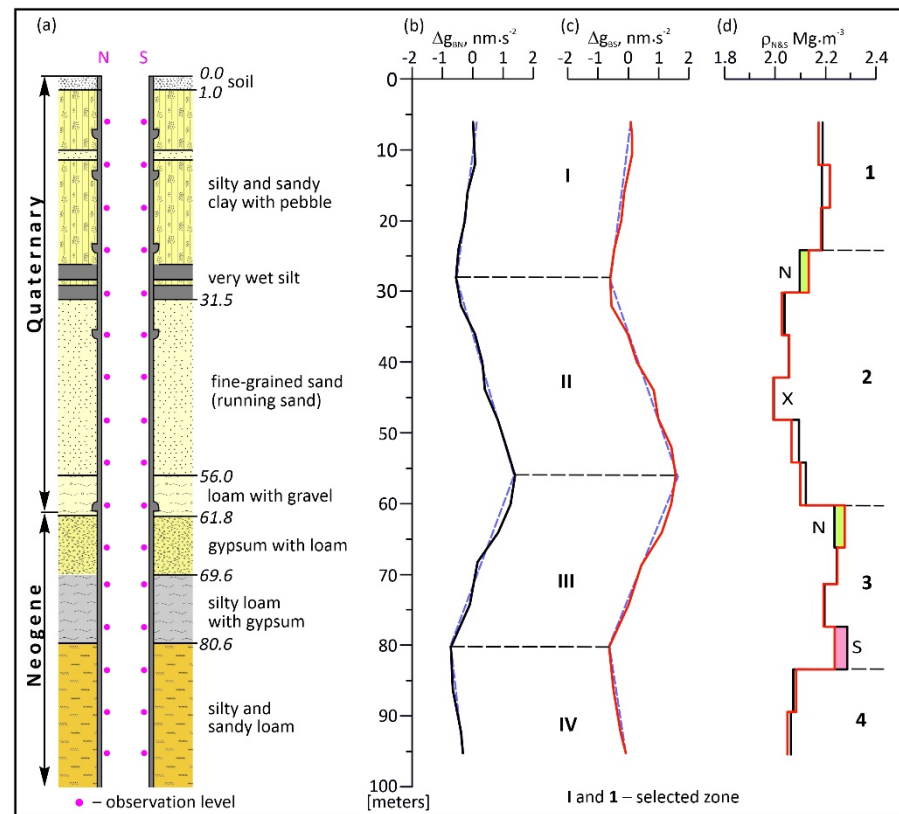


**Figure 5.** Distribution of the residual anomalies.

### 3.1.3. Gravity Vertical Profiling

Gravity surveys of the rock medium behind the shaft lining were carried out inside materials and personnel transport shaft. Vertical gravity profiling was performed along two vertical measuring profiles located on the northern and southern side of the shaft (Figure 1). Observations of gravity changes with depth were started from the depth of 6 m below the pit bank (outset) to the depth of 96 m. The gravity measurements were performed according to the rule that the gravimeter should be located in the same position relative to the shaft axis. The average vertical distance between successive buntons was 6 m.

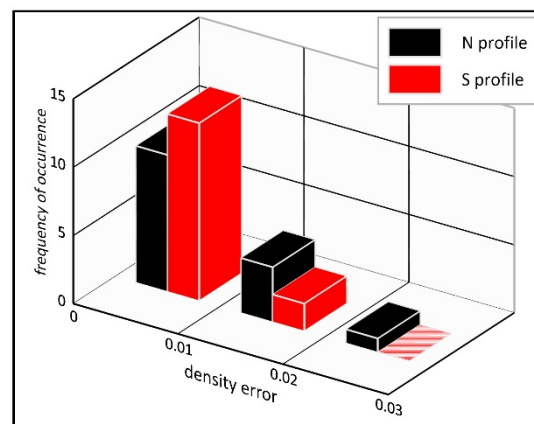
The basis for interpretation of results of a vertical gravity profiling in a mine shaft is the vertical distribution of Bouguer anomalies, taking into account relevant gravity corrections, among which the most important is the shaft correction (a variant of mining correction), which was described earlier. The analysis of the Bouguer anomaly distributions along the north and south profiles shows that the shapes of both distributions are very similar to each other (Figure 6a–c), as they both reflect general changes in gravity due to depth.



**Figure 6.** The results of vertical gravity profiling: (a) lithology, (b,c) “Bouguer anomaly”, (d) densi-gram.

Four almost linear variations can be distinguished on both distributions, which correspond to four rock complexes (I–IV) that vary in density. The first density boundary occurs at the depth of 28 m. It separates a predominantly clay complex (I) located higher from the very wet sand located below (II). The next density boundary lies at a depth of 56 m and corresponds to the floor of the above-mentioned sands. The third density boundary lies at the depth of 80 m and marks the bottom of the loam and gypsum (III). Below the depth of 83 m, there is loam of lower density than the gypsum complex located above.

On the background of the general trends of the Bouguer anomalies, local changes in gravity are visible, which correspond to local changes in density within the described complexes I–IV. These changes can be observed in the distribution of interval densities calculated for both profiles (Figure 6d). The thickness of each interval is the distance between the observation points, which was about 6 m. For each interval density, an error was calculated that ranged from  $0.002 \text{ Mg}\cdot\text{m}^{-3}$  to  $0.024 \text{ Mg}\cdot\text{m}^{-3}$ , with most of them not exceeding  $0.01 \cdot \text{Mg}\cdot\text{m}^{-3}$  (Figure 7).



**Figure 7.** Frequency of density error occurrence.

On the densigram (Figure 6d), we can also distinguish four zones with similar density values. It should be noted, however, that the position of borders of these zones differs slightly from the position of borders determined on the basis of “Bouguer anomaly”. This has to do with the fact that density is calculated for constant intervals imposed by the distance between buntons, while boundaries on the densigram are determined on the basis of interval levels. Similarly, density interval boundaries are related to lithological boundaries. Sometimes an interval falls on a lithological boundary, making the calculated density the average of the two boundary layers.

Thus, the first zone (1) reaching the depth of about 24 m is characterized by nearly constant density with an average value of  $2.19 \text{ Mg}\cdot\text{m}^{-3}$  and corresponds to the layer of silty clays. The second zone (2) extends to the depth of 60 m, i.e., to the border of the quaternary and is not as homogeneous in terms of density. In both profiles, interval densities vary between  $2.00$  and  $2.11 \text{ Mg}\cdot\text{m}^{-3}$ . They may represent facial changes within the fine and medium sand layer. There is only one interval density (X) at the depth of 42 m that has a noticeably lower density than the average density of the zone (2). It is clearly visible one both vertical profiles, and this indicates that loosening exists around the shaft. It is possible because the density is in the running sand layer. Just below the quaternary boundary, the third zone (3) is located with the varied density of between  $2.20$  and  $2.28 \text{ Mg}\cdot\text{m}^{-3}$ . It is composed of loam and gypsum layers, i.e., it is heterogeneous in terms of density. Below, at the end of the measurement profile lies the fourth zone (4) with silty and sandy loam with nearly uniform density of  $2.08 \text{ Mg}\cdot\text{m}^{-3}$ .

On the background of the described zones, some horizontal differentiation can also be observed in the northern-southern (N–S) direction. The first differentiation can be seen at the depth of 24–30 m, where a decrease of density can be observed on the northern side. This zone is located within the layer of very wet silt and may be related to leaching of rock material beyond the shaft lining. Within the Neogene formations, two intervals with horizontal density variation are observed, the first one under the quaternary–Neogene boundary (60–66 m) within the gypsum layer (lower density on the northern side) and the second one in the interval at a depth of 78–84 m, at the boundary of silty loam with gypsum and silty loam (lower density on the southern side). It seems that both density variations can be related to the occurrence of minor karst in these intervals. There are also other density differences visible in the densigram, but their magnitude falls within the error limits and there are no grounds to treat it as a loosening zone.

In general, the calculated density distributions indicate that there are no significant loosening zones in the surrounding rock mass in the studied shaft section that could threaten its safety.

### 3.2. Closed Mine Shaft

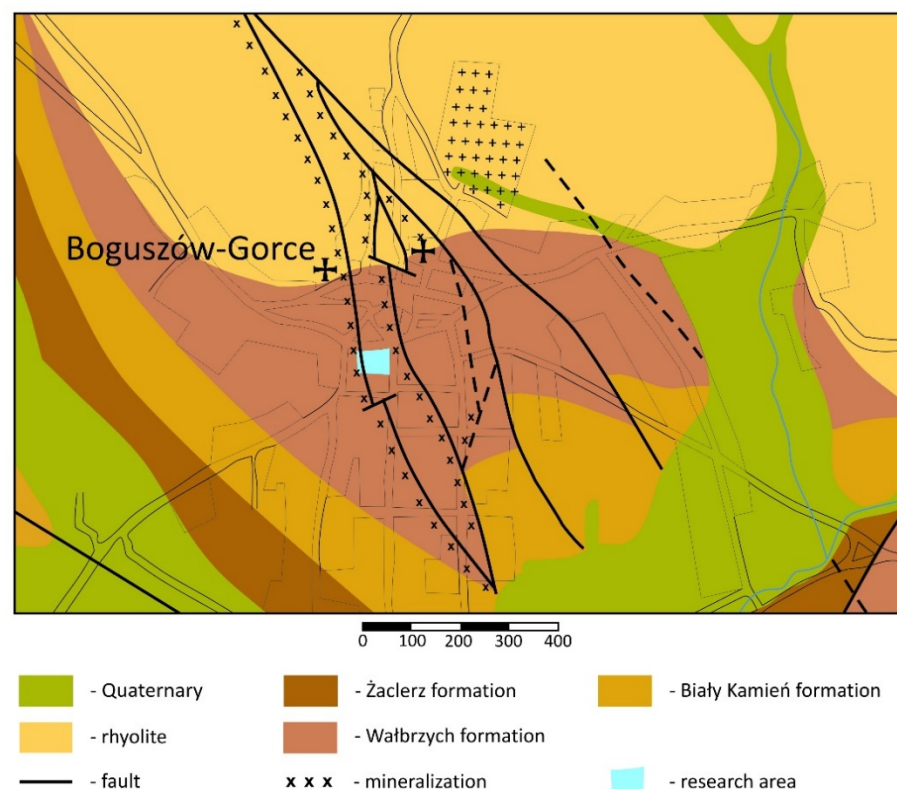
A microgravity study was conducted on a plot of land occupied by the Fire Department in Boguszów Gorce, Lower Silesia, Poland. The purpose of the study was to determine

the safety of the land surface and urban infrastructure in the area. This was due to the fact that after one of the November rainfalls, two sinkholes with a small horizontal extent were formed, located on the opposite sides of a garage building. These sinkholes were eliminated as they were filled in to make way for fire trucks.

Between the 14th and 19th centuries, silver ore was mined in the town. At the distance of several tens of meters from the sinkholes, there was an old mine shaft “Ludwig”, which, according to reports, was liquidated by covering it with a concrete slab and is now probably located under a building [43]. Therefore, it was necessary to investigate if there was a connection between the sinkholes, the mine shaft and shallow exploitation of silver ores.

### 3.2.1. General Geological Setting

The major part of the town lies on steeply sloping strata of Upper Carboniferous system, Silesian series, Namurian, and Westphalian stage (according to the regional stratigraphy of northwest Europe)—Figure 8. According to Polish stratigraphy, in the research area there are three rock formations: Wałbrzych (Namurian A-B substages), Biały Kamień (Namurian C and some part of Westphalian A substages) and Żalcerz (Westphalian substage). Lithologically, all of them are formed almost in the same way: quartz puddingstone, sandstone, mudstone, claystone, and hard coal. They are bordered on the north by a large rhyolite laccolith. These formations are cut by NW–SE extensional faults with opposite slopes to the Carboniferous strata.



**Figure 8.** Simplified geological setting in Boguszów-Gorce area.

In the fault zones, in the near-surface part of the rock mass, mineralization of silver ore occurs, while barite is observed at a greater depth. There are four zones in the city area. Two of them and partly the third one are mineralized, and the extreme southern one runs through the surveyed area.

### 3.2.2. A Brief History of Mining in the Studied Area

The history of Boguszów-Gorce is closely connected with silver mining. The beginnings of exploitation date back to the 14th century, but an important date is 1529 when



the “Wags mit Gott” mine was build [43]. The mining history of the town is a story of ups and downs, largely dependent on the wars affecting the area. The end of the 16th century saw the end of the first stage of the town’s development, followed by stagnation, and as late as in the second half of the 17th century, timid attempts were made to reactivate mining. The exploitation was carried out through mining galleries with a cross-section of about  $1.2 \times 0.8$  m, and the small lighting shafts had a square cross-section of  $1.1 \times 1.1$  m. It was not until the early 18th century, after the discovery of a new rich vein, that mining flourished again, but by the end of that century it had practically died out. In the second half of the century, attempts were made to reactivate mining, among others by digging a new shaft “Ludwig”, but the project was discontinued as soon as 1865. The “Ludwig” shaft was 132 m deep and the shallowest exploitation level was located at a depth of approximately 40 m.

### 3.2.3. Microgravity Survey

Microgravity survey, aimed at identifying possible loosening zones and voids in the near-surface part of the rock mass, were carried out in an area of approximately  $65 \times 70$  m (Figure 8). This area included both sinkholes and the area adjacent to the decommissioned “Ludwig” shaft, and the measurements were made in a grid of  $2.5 \times 2.5$  m, and twice as densely near the sinkholes. The number of points was limited by buildings and slopes.

Just because of the buildings and escarpments, it was necessary to apply the building and terrain correction. On the basis of the elevation of the land surface around and in the studied area, the terrain correction was calculated assuming an average density of  $2 \text{ Mg}\cdot\text{m}^{-3}$ . On the basis of maps and geodetic measurements, buildings were mapped and building correction was calculated. The total result of both corrections is shown in Figure 9.

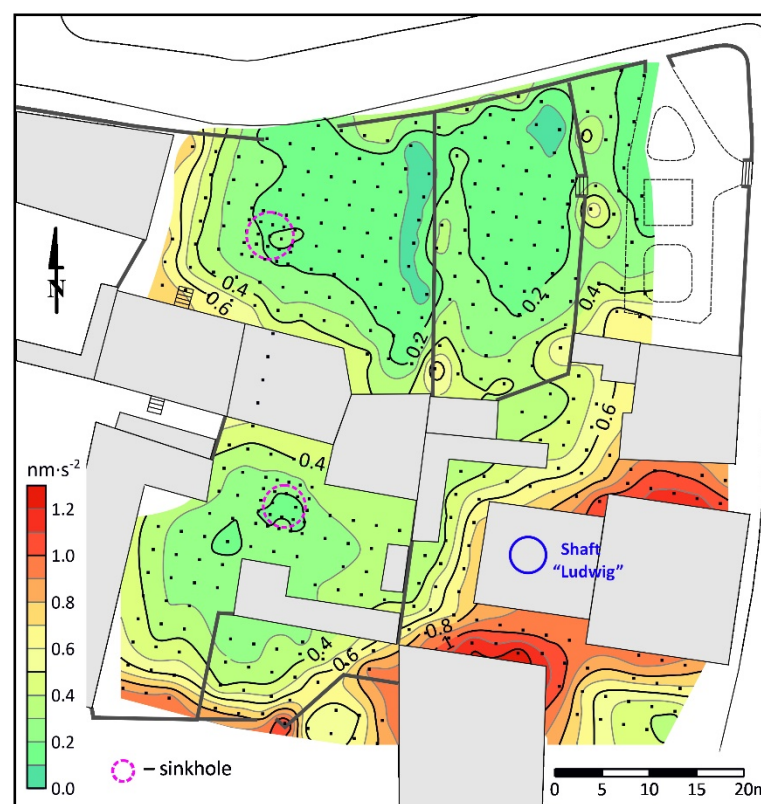
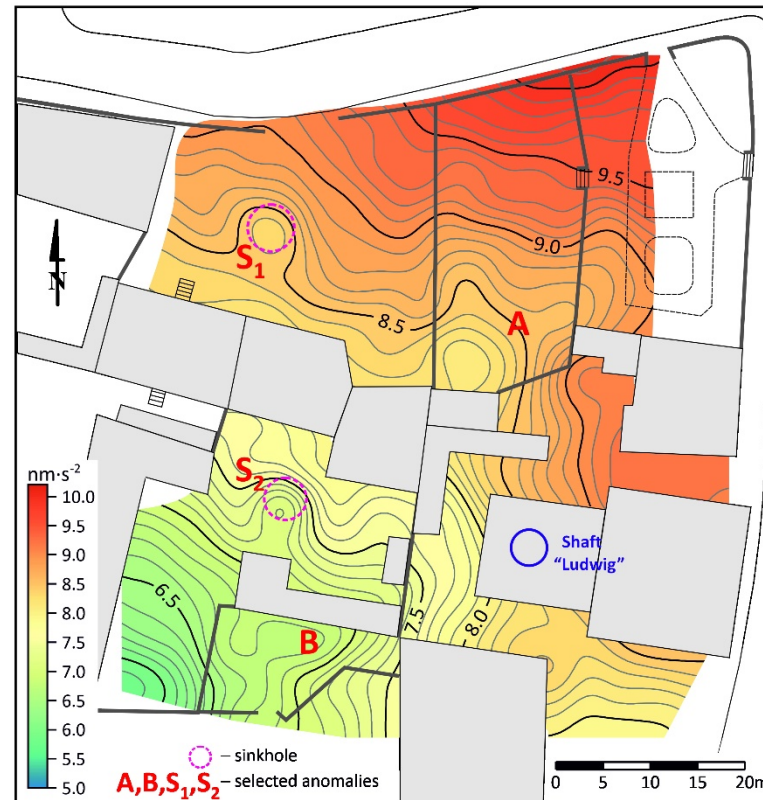


Figure 9. Distribution of a sum of building and terrain corrections.

The maximum value of corrections was about  $1.2 \text{ nm}\cdot\text{s}^{-2}$ , reaching the highest values at the points located near buildings and slopes. It is worth noting that these corrections significantly impact on the measured gravity value and, consequently, need further inter-

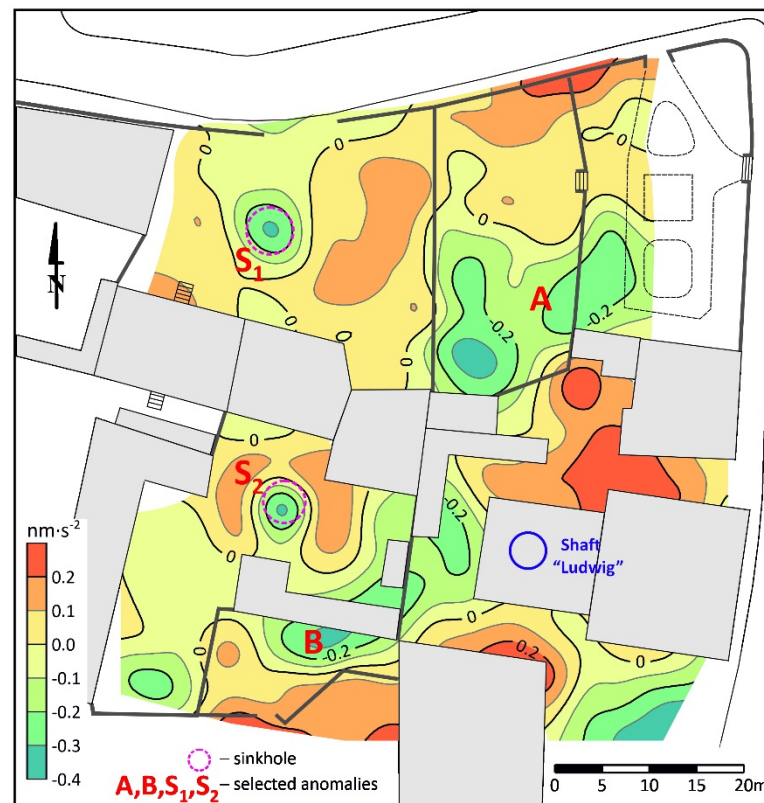
pretation. At the next stage, Bouguer anomaly values were calculated, which were then filtered with Butterworth formula to remove small, random errors. The distribution of the obtained values is shown in Figure 10.



**Figure 10.** Distribution of Bouguer anomalies with corrections.

The general course of the contours on the Bouguer anomaly distribution is from NW to SE, which is consistent with the extension of the geologic strata of the studied area. The steeply southward collapsing Carboniferous strata cause a significant horizontal gradient, so the Bouguer anomaly values vary by about  $5 \text{ nm}\cdot\text{s}^{-2}$  in such a small area. The two sinkholes that generate the two anomalies S1 and S2 are very prominent in the distribution. Both anomalies are characterized by relatively negative values, which indicates the scarcity of masses in these areas and thus decreased density. Two other anomalies A and B, also with reduced values relative to the surroundings, can be easily distinguished in the distribution. Like the earlier anomalies, these anomalies also indicate mass shortages in the near-surface part of the rock mass.

There is a strong horizontal gradient in the studied area that can mask other anomalies and makes it difficult to define the boundaries described above. For this reason, it was necessary to eliminate this gradient as a regional factor from the large geological structures, which are the Carboniferous strata (Figure 8). Different variants of the calculation of the regional field were performed and finally the Gauss low-pass filter was selected. By subtracting the thus approximated regional field from the Bouguer anomaly, the values of residual anomalies were obtained, the distribution of which is presented in Figure 11.



**Figure 11.** Distribution of residual anomalies.

The boundaries of S1 and S2 are clearly visible on the distribution of residual anomalies. Their horizontal extent is small, almost equal to the area of sinkholes. This means that the density around the sinkholes is not reduced, which indicates that the rock mass was not disturbed there, i.e., there are no cracks and fractures. It can be assumed that the sinkholes were formed by vertical collapses of rock masses only in their area. The collapses most likely occurred only in the area of the shafts, which are the remnants of shallow silver ore mining. Analyzing the simplified geological map (Figure 7), it can be noted that the line connecting the two small shafts coincides with the course of the fault in this area, which contains silver ore mineralization. Thus, it is highly probable that the small shafts define the course of an unknown adit, and were used to illuminate it or exploit the ore.

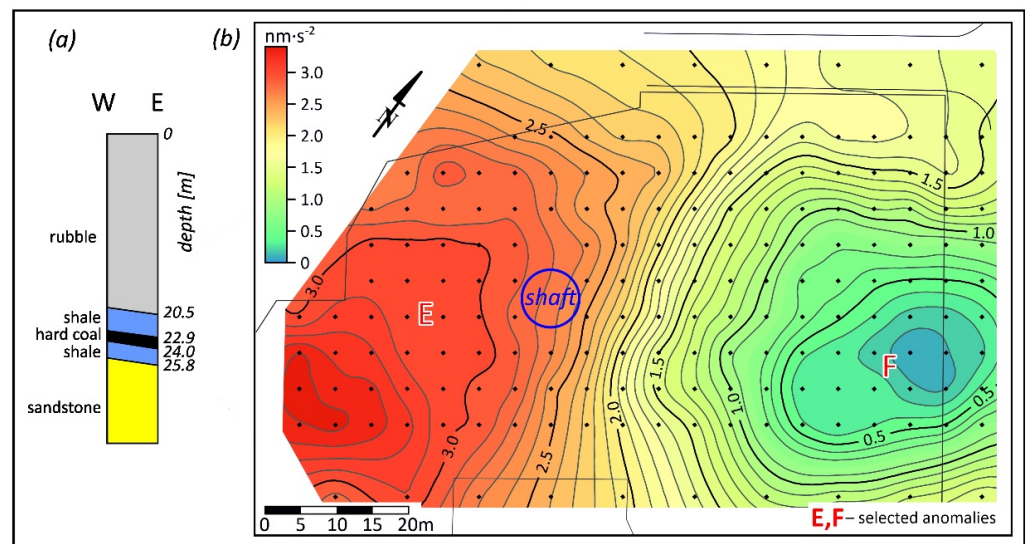
The separation of the residual anomalies allowed for determination of the horizontal extent of the boundaries of anomalies A and B described earlier (Figure 11). The decomposition shows that anomaly B is larger than it would appear from the Bouguer anomaly distribution and continues in the NE direction. It merges with anomaly A, whose horizontal extent is now more clearly visible.

The distribution of anomaly A does not indicate that it is related with the decommissioned “Ludwig” shaft, which cannot be excluded in the case of anomaly B. Nevertheless, it seems more likely that the sequence of anomalies A and B has a common origin, which may have two causes. The first cause may be a sequence of old mining that has affected the shallow part of the rock mass and thus affected its density. The second cause may be a near-surface loosening of the rock mass caused by water flow along the land surface sloping in a nearly southerly direction. Anomalies A and B lie on the plots with different elevations, separated by retaining walls. Thus, there are grounds for the occurrence of a suffosion phenomenon leading to a decrease in density and thus the formation of anomalies.

### 3.3. The Shaft under Construction

Microgravity surveys in the area surrounding the drilling site of the new mine shaft were carried out to examine the shallow parts of the rock mass and identify the areas of

lower density, which might pose a threat to the shaft itself and the future infrastructure around it. The research was prompted by the discovery of old mining cavities at a depth of approx. 23 m, which indicates that at this depth, previously hard coal was mined in the seam with a thickness of approx. 1.1 m (Figure 12a). The mounds consisting of rock debris, shale, and hard coal were found at a depth of 20 m.



**Figure 12.** The results of survey: (a) main shaft lithology and (b) distribution of Bouguer anomalies.

Microgravity measurements were performed around the shaft in the area of  $95 \times 60$  m, in a regular grid of  $5 \times 5$  m, and additionally, in accessible places, points located every 10 m were added on the outside. The studied area was virtually flat, therefore, there was no need to calculate a terrain correction. However, it was necessary to calculate the correction eliminating the gravity impact of the shaft. The distribution of Bouguer anomalies after the correction is shown in Figure 12b. The analysis of the obtained distribution reveals two opposing anomalies: relatively positive E and a relatively negative F. Due to the horizontal extent of both anomalies relative to the entire studied area and the amplitude of both anomalies, it is not possible to calculate the regional anomaly, and both anomalies should be treated as local. Anomaly E, being relatively positive, is not interesting from the point of view of the task at hand. However, the relatively negative anomaly F with an amplitude of about  $1.5 \text{ nm} \cdot \text{s}^{-2}$  indicates a significant mass shortage in its area. Based on the information about the occurrence of old workings, it should be believed that its cause is related to the exploitation of shallow coal seam. Given that the dip of the strata is about  $9^\circ$ , it is possible that the anomaly reflects shallow, uncontrolled hard coal mining. Nevertheless, the reduced density of the rock mass poses a threat to the shaft and future infrastructure, so it should be further investigated by drilling.

#### 4. Discussion

The presented examples of surveys demonstrate that the microgravity method can be used in an area that is not easy to measure, the mining area, and, particularly, in the close vicinity of the mine shaft. Despite the shaft and its infrastructure, this method allows to take measurements in the areas where other geophysical methods cannot be applied. What makes it possible are formulas that allow for calculation of corrections that eliminate the gravity impact of the shaft, the underground infrastructure, and the buildings on the surface [19]. The negative anomalies obtained from the processed measurements are always associated with decreased density in the rock mass. Some of these anomalies are easy to interpret as they are related to the existence of identified underground infrastructure, such as an underground channel observed in the gravity distribution near an operating shaft. The other negative anomalies, on the other hand, are due to the presence of voids and



loosening zones in the rock mass. Due to the complex geomechanical processes occurring in the rock mass, in most cases, it is difficult to answer unambiguously whether an anomaly is caused solely by a loosening zone, a void, or a void and a loosening zone above it [31,44]. However the analysis of the parameters of the anomaly, especially its amplitude and horizontal extent, allows to determine whether its source can pose a threat to the surface and objects in its vicinity [36]. What is more, an analysis of the knowable shallow geological structure and landforms may point to the anomalies being linked to the hydrogeological conditions in the studied area [45,46].

The presented examples of surface surveys clearly demonstrate how microgravity method can be applied to detect risks related to a mine shaft. Each case was resolved in a different manner. The study in the area of the liquidated shaft “Ludwig” confirmed that the shaft had been liquidated properly and the risk related to the shallow silver ore goafs. The surveys carried out in the vicinity of the working shaft showed that during the surveys there were no density changes that could threaten the stability of the shaft. However, the course of the negative anomaly of (presently) low amplitude in the vicinity of the shaft should be regularly monitored [28,29], as it may be related to leaching, potentially leading to further loss of density. The case of the shaft under construction is an example of the situation where high amplitude indicates the existence of voids in the rock mass, which could threaten the shaft infrastructure and must be investigated further by drilling.

An additional advantage of the microgravity method is that it can be used inside the mine shaft and it is the only geophysical method that can be used when the mine shaft lining is made of steel. As shown in the example described above, the method makes it possible to determine the density of the rock mass outside the shaft lining. The recorded interval density values correspond to the lithological structure around the shaft and its variation [24,26]. The results obtained in this way can have three explanations. The first is the case in which the density values within each geological layer vary slightly and are related to facial changes. This indicates a solid rock mass behind the shaft lining. The second one is the occurrence of zones with significantly decreased density, indicating the existence of voids outside the shaft lining, which may pose a threat to it. The third one, an example of which is described in the article, is a situation where density changes correspond to lithological structure, however, there are small but visible zones of decreased density [26,42]. Additionally, taking measurements at opposing points relative to the center of the shaft, on one level, allowed us to identify on which side such a void was located [26]. Currently, the observed changes do not pose a threat to the mine shaft, however, their presence, especially in the running sand layers, requires monitoring. Linking density information from the measurements taken in the initial part of the shaft and those from the surface gives a more complete picture of the rock mass, which allows for better identification of possible threats to the shaft related to decreased density in the rock mass.

## 5. Conclusions

The safety problems related to mine shafts have three aspects, that is the safety while sinking the shaft, the safety of using the shaft, and the safety of the area after its liquidation. These are complex issues and they cannot be resolved with the use of a single method. Each method contributes to the safety of the mine shaft by providing new information. In the paper, the authors presented the application of one of the geophysical methods, that is the microgravity method to solve some problems related to all the three aspects. The advantage of this method is that it is non-invasive, not very susceptible to external interference, and it makes it possible to take measurements on the surface and inside the mine shaft. Additionally, what speaks in its favor is easy application. Microgravity method allows to trace the distribution of masses in the rock mass, which is the distribution of density. Voids and loosening zones pose a safety risk for the mine shaft and its surrounding infrastructure, so the method based on the detection of mass (density) lends itself for identification of a risk of this type.



The article presents examples of microgravity survey for each of the above-mentioned cases. Research has shown that the method can be applied not only in the areas of liquidated mine, but also in areas of acting mines, where the measurement conditions are difficult or very difficult.

The presented results of the surface survey showed how important the selection of the appropriate methodology for measurements and subsequent interpretation is. The correct separation of useful anomalies enabled a qualitative determination of the degree of threat of shaft and the surface around it from the voids and loosening zones in the rock mass.

The results of the microgravity survey inside the mining shaft confirmed the possibility of using the method to determine the density of rocks outside the shaft lining. The calculated density allowed to separate depth intervals with a decreased density, which proves the existence of voids or loosening zones. In addition, performing research in more than one vertical profile, their horizontal position can be specified.

It should be emphasized that the unquestionable advantage of the presented research method is the fact that a threat may be detected from the emergence of noticeable changes in infrastructure and on the surface of the area, as well as in the shaft lining. Thus, by performing the measuring in time intervals, it is possible to monitor density changes in the rock mass.

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## Abbreviations

$\rho$	bulk density, $\text{Mg}\cdot\text{m}^{-3}$
$g_M$	measurement value of gravity, $\text{nm}\cdot\text{s}^{-2}$
$\delta g_F$	free-air correction, $\text{nm}\cdot\text{s}^{-2}$
$\delta g_B$	Bouguer correction, $\text{nm}\cdot\text{s}^{-2}$
$g_N$	gravity normal value, $\text{nm}\cdot\text{s}^{-2}$
$\delta g_T$	terrain correction, $\text{nm}\cdot\text{s}^{-2}$
$\delta g_G$	mining correction, $\text{nm}\cdot\text{s}^{-2}$
$g$	gravity value with corrections, $\text{nm}\cdot\text{s}^{-2}$

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