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The comparison of different methods of determining the rock density from gravity data

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Abstract: We focus on two methods of determining the density of the rock environment based on gravimetric measurements. The first method, a combined underground-surface approach, relies on recent measurements made at pairs of points along the vertical. One point is located in accessible underground spaces, like tunnels, mine workings, or caves, while the other is on the Earth's surface. The second, surface method, is solely based on the analysis of the Gravimetric Database of the Slovak Republic. Both methods are based on the proportionality between free-air anomalies and the gravitational effect of topographic masses, calculated for unit density. We compare the respective outputs of both methods and attempt to understand the existing differences between them. We also confront the density estimates in question with one of the two existing density maps of Slovakia compiled from density measurements on rock samples. Across a total of 14 measured locations, we observe a relatively wide spectrum of values on the agreement-disagreement scale, ranging from close similarity to relatively significant differences.

Key words: underground and surface gravity measurements, near topographic effect, free-air anomaly, density estimates

1. Introduction

During the ground gravity survey boom in the 1930s, the question of estimating the appropriate correction density (as we call it now) or reduction density (as it was commonly called in the past) arose. This quantity is necessary for processing gravimetric measurements into the form of complete

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Bouguer anomalies. Traditional measurements on rock samples gradually turned out to be rather problematic, and so the gravimetric method was proposed (*Nettleton, 1939*). It is important to mention that other geophysical techniques exist that can provide rock density, either directly or indirectly, e.g., well-log methods or seismics. However, we consider these beyond the scope of this paper, which is concentrated on the application of gravity measurements.

Nettleton, considered the founder of the methodology of the correction density estimations from surface gravity data, wrote about density measurements on samples: "This, however, is not very satisfactory because the densities of individual samples usually vary over a wide range so that a large number of samples is required for a reliable average value" (*Nettleton, 1939, p. 177*). He then used the term "density of the surface material" (*Nettleton, 1939, p. 176*). But he also worked indirectly with the term "apparent density". Namely, in another place he wrote: "However, the density determined by the density profile method is that which reduces the apparent elevation effects" (*Nettleton, 1939, p. 179*). Nettleton then obviously noticed that his method could provide a density value that would, at the same time, correct also for both what was then called the anomalous vertical gradient and, in those times the relatively often occurring circumstance, namely erroneous constant of gravimeters (see also *Yamamoto, 1999, p. 583*).

Later on, practically up to the present day, other publications gradually appeared, either with modifications of the mentioned Nettleton density profiling method, or with independent methods. Among them, we are going to mention the well-known technique of *Parasnis and Cook (1952).* This author also pointed out the possible use of the estimated densities in the process of geological interpretation of gravity data. He used the term "density of the geological formation underlying a station" (*Parasnis and Cook, 1952, p. 253*) and realized that "the effective density determining the Bouguer anomaly will not simply be a mean of all such densities but will depend on the frequency of each band within the formation" (*l.c., p. 254*).

In connection with the Parasnis method, a rather unconventional and very successful application was undertaken by Fajklewicz and his colleagues in 1972 and 1973 at a big stockpile of mined-out sulphur in Iraq, as mentioned in *Fajklewicz (2007, pp. 285–287*). The sulphur density estimated by the mentioned method agreed as to the second decimal place with the value given by the laboratory.

An extensive overview of various techniques is provided by the already mentioned work of *Yamamoto (1999)*. Among the latest works of similar type should be mentioned that of *Zengerer et al. (2016)*.

From the point of view of terminology, there is considerable diversity in the field of density determinations (estimations) using surface gravity data. In addition to the terms we already mentioned here, the following ones can also be found in the literature: average, background, bulk, minimum or zero-correlation, near-surface mean, superficial, whole topographical volume or surface layer densities, respectively. And this does not seem to be a favourable situation. Trying to avoid deepening the existing terminological diversity, we will use here shortened form of one term which already has been in use, namely surface density. We realize, however, that this density should be considered not true but apparent. If we leave aside one of the Nettleton's reasons for considering the estimated surface density apparent, namely the erroneous gravimeter constant, we see the rationale rather in the wider analogy with the electrical methods of applied geophysics and with the concept (and term) of apparent resistivity in the framework of those methods. Mentions of this feature of the estimated surface density can also be found in other authors. For instance, *Zengerer et al. (2016)*, despite their different approach to the topographic effect, use the term "apparent density" throughout their contribution.

Except for the unspecified "depth penetration", there is one imperfection involved at least in some of the methods based on the surface gravity data only, namely the unwanted influence of regional or local gravity variations or trends, originating inside or outside the volume of topographical masses (*Bhaskar Rao and Satyanarayana Murty, 1973*). It is obvious that this drawback can be significantly suppressed by measuring at two or more gravity stations situated along the local vertical, preferably if at least one of those stations is located on the Earth's surface, while the rest of the stations are underground, e.g., in tunnels, mine workings or caves.

Hammer (1950, pp. 637–638) reported on the pioneering works of this type, mentioning *Airy (1856)*, *von Sterneck (1882, 1883)*, and the experiment of Hayford. But the quoted works of Airy and von Sterneck were, in fact, aimed at the estimation of the mean Earth density, while the densities of the rock volumes overlaying the underground gravity stations were introduced into the data processing in the form of an a-priori information obtained by measurements on rock samples. So that the measurements of Hayford conducted in the year 1902, carried out by two half-second pendulums, could represent the first attempt to estimate densities of the rock volume between the Earth surface and the underground station (stations). The unpublished report of Hayford, which is at the moment inaccessible to us, was dated 1904. Since then, a lot of measurements of this type have been carried out and reported about, including the one of *Hammer (1950)* which we just mentioned, and, later on, e.g., *Pick and Pícha (1971)*, *Madej (2017)*, and finally *Zahorec and Papčo (2018)* to which we refer to here.

If there are more underground points along the local vertical, the commonly used term for the output density estimates is the interval density between the respective underground measurement points (e.g., *Domzalski, 1955; Madej, 2017*). On the other hand, if there are only two measuring points along vertical, namely the underground one and the surface one, *Zahorec and Papčo (2018)* use exclusively the term correction density. Alternatively, the term underground-surface bulk density can be used as well.

In addition to correcting the raw gravity data, the estimated surface or underground-surface bulk densities we have written about so far can also be used as important parameters in the interpretation of gravity data and possibly in the characterization of geologic units or formations.

The main goal of this paper is to juxtapose density estimates resulting from underground-surface gravity measurements on one side with those coming from classical surface gravity data on the other side.

2. Recent underground-surface gravity measurements

The methodology for determining densities from underground gravity measurements has a relatively long history, rooted in works such as *Hammer (1950)*, *Domzalski (1955)* and others. Unlike these “classical” approaches employing approximations like the planar Bouguer slab, our method is simpler and more straightforward. The density value is directly obtained by dividing Δg (gravity difference between the surface and underground points, corrected for the normal gravity gradient, which in fact equals to the difference in the free-air anomalies) by ΔNTE (Near Topographic Effect) calculated for unit density, and including the tunnel/mine effect. The NTE is computed using the software Toposk (*Zahorec et al., 2017*), which accurately calculates the topographic effect at arbitrary point location, above or below the topographic surface, the latter being a special case of underground gravity stations. The NTE is considered up to the standard distance of 166.7 km, while the calculated area is divided into the following zones: inner zone up to 250 m from the calculation point, intermediate zone 250 – 5240 m and outer zones from 5.24 up to 166.7 km. Currently, the LiDAR technique is often used for the generation of high-resolution digital terrain models. The effects of underground objects (tunnels, mines, caves) were calculated using terrestrial laser scanning data. A more detailed description of the method is provided in *Zahorec and Papčo (2018)*.

The positions of surface gravity stations were determined using GNSS, while those in underground objects relied on terrestrial measurements using a total station. Surface gravity stations were set to be vertically aligned with the underground stations within a few centimetres in their horizontal positions. Gravity values at each station were measured using Scintrex CG-5 gravity meters.

To compare the two methods of determining densities, our efforts aimed to cover as many diverse geological units as possible within Slovakia, varying in their rock density (Fig. 1.). However, the site selection had to be adapted primarily to the existence of suitable underground objects. The most suitable were highway tunnels (Ovčiarsko, Považský Chlmec, Poľana, Višňové, Čebrať, Bôrik, Branisko, Bikoš, Prešov), where it was possible to move safely (during traffic shutdowns) and geodetic networks were available in them. Old mine corridors and tunnels were also suitable (Izabela, Slavošovce), functional drainage adits (Main hereditary adit near Kremnica – HDŠ, New adit for draining near Voznica – NOŠ) and we also used the measurements in the Dobšinská ice cave (DĽJ). At each site, several measurement points were selected inside the underground space (i.e. pairs of points underground-surface), either in the same geological unit for control purposes, or in different geological units to capture different densities.

The obtained density values range from approx. 2.1 to 2.8 g/cm^3 (Fig. 2). In the northwest of the territory, densities of approx. 2.4 to 2.6 g/cm^3 were measured in three tunnels excavated in Paleogene flysch rocks (tunnel Poľana in the Flysch belt, Ovčiarsko in the Peri-klippen zone and Chlmec in the Klippen belt). Densities of approx. 2.3 – 2.4 g/cm^3 were measured

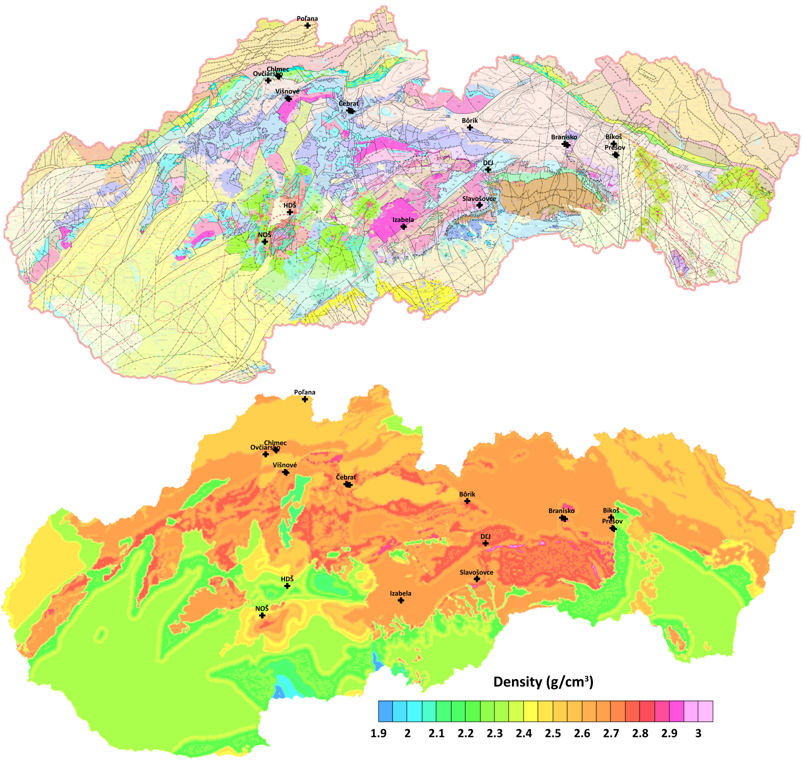

Fig. 1. Distribution of localities measured by the underground-surface method. The tectonic map of Slovakia (*Bezák et al., 2004*, above) and the density map (*Stránska et al., 1986*, gridded by *Paľáková, 2012*, below) are used as a background.

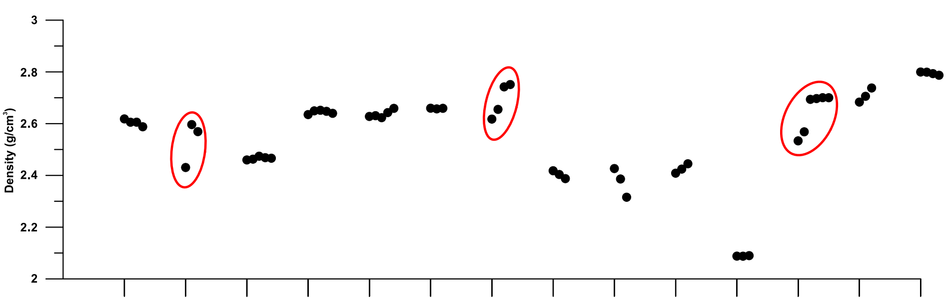

Fig. 2. Densities determined by the underground-surface method at individual sites. Several points were measured at each site. Sites with significantly different measured densities commented in the text are marked in red.

in the Inner Carpathian Paleogene in eastern Slovakia (Bikoš, Prešov). We measured the lowest densities in Central Slovakia Neovolcanics, specifically in the rhyolites of the Kremnické vrchy Mts., approx. 2.1 g/cm^3 (HDŠ), and in the andesites of the Štiavnické vrchy Mts. approx. 2.4 g/cm^3 (NOŠ). On the contrary, the highest densities were determined for the crystalline rocks of Veporic unit, reaching 2.8 g/cm^3 in Slavošovce tunnel (probably phyllites), 2.75 g/cm^3 in Branisko tunnel (gneisses, migmatites) and 2.7 g/cm^3 in Izabela adit (gneisses, migmatites).

At most sites, the results show relatively good agreement at all points within a site, indicating the approximate homogeneity of the rock environment. However, in some localities, there is a relatively large dispersion of densities within one locality (marked in red in Fig. 2), which we assume is mainly caused by the heterogeneity of the geological structure along the tunnel. For instance, in the case of the Branisko tunnel, we see in Fig. 3 that the two western points are located in a different tectonic unit (Permian, Mesozoic) than the two eastern points (Crystalline), which is also reflected in the differences in densities (Fig. 2). The situation is different in the case of the Izabela adit (Fig. 4), where the jump-like difference in

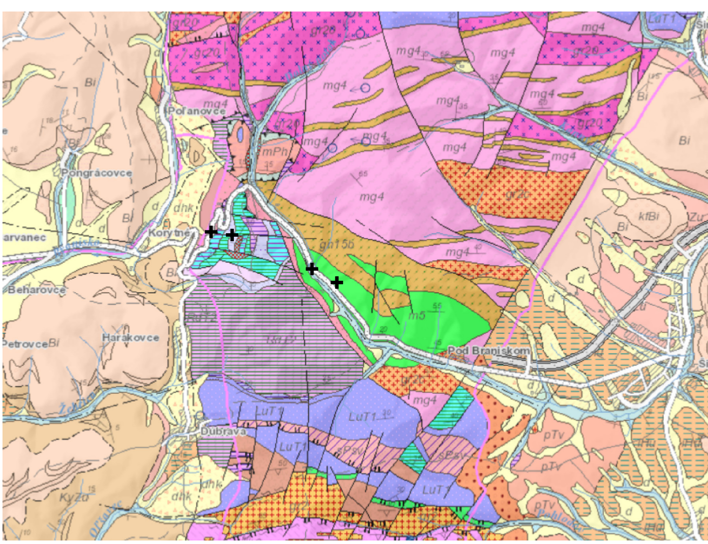

Fig. 3. Distribution of measurement points at the Branisko site. Geological background: Map server of the State Geological Institute of Dionýz Štúr (`https://www.geology.sk/geoinfoportal/mapovy-portal/`).

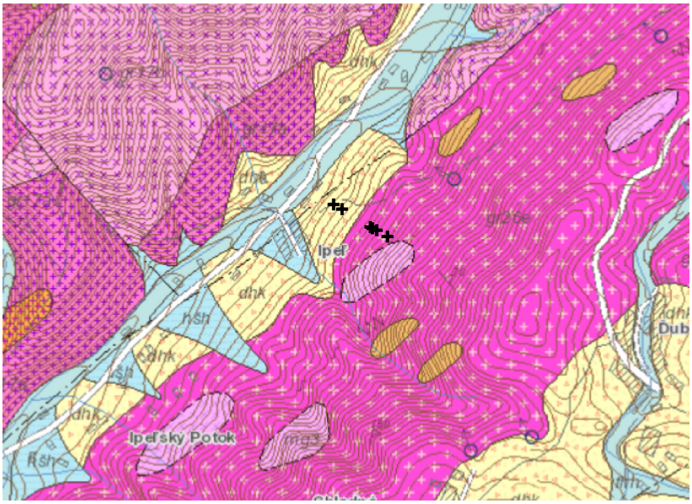

Fig. 4. Distribution of measurement points at the Izabela site. Geological background: Map server of the State Geological Institute of Dionýz Štúr (`https://www.geology.sk/geoinfoportal/mapovy-portal/`).

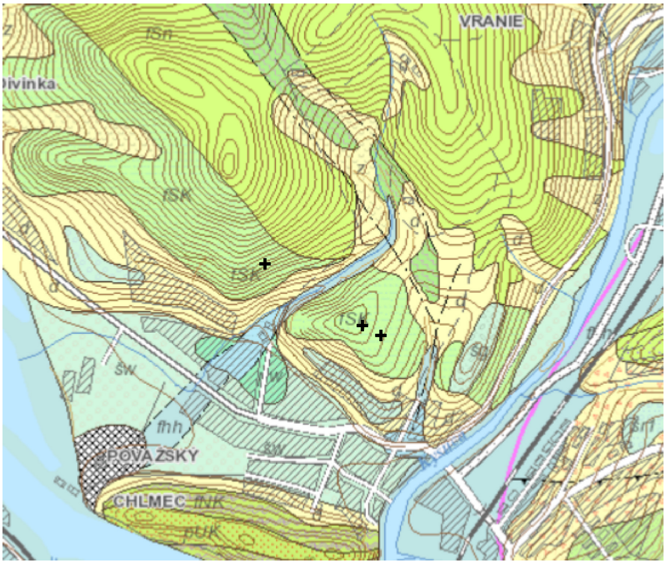

Fig. 5. Distribution of measurement points at the Chlmec site. Geological background: Map server of the State Geological Institute of Dionýz Štúr (`https://www.geology.sk/geoinfoportal/mapovy-portal/`).

densities between the first pair of points and the more distant four points (Fig. 2) is attributed to the presence of a fault/mylonitized zone. The mylonitized zone near the exit from the adit is documented e.g. in *Ondrášik et al. (1987)*. Another reason for the decrease in density may be the more significant representation of deluvial sediments in proportion to the lower rock overlay of the adit towards its exit. The thickness of the overlaying rocks there reached only 50 m.

The Považský Chlmec tunnel represents a different case. A sudden change in density is observed (Fig. 2) between the western point and a pair of more distant eastern points, though the geological map does not indicate a change in lithology between the mentioned sections of the tunnel (Fig. 5). Given the deviated density value is determined at only one point, we cannot rule out a measurement error either. The all mentioned situations document the fact that the underground-surface method is sensitive to changes in rock density in the horizontal direction.

3. Existing surface gravity data only

The gravitational effect of topographic masses calculated for a constant density on one side, and the free-air anomaly (FAA) on the other, are mutually proportional, at least at local scales. However, this proportionality is observed exclusively in mountainous areas. In lowlands, or generally flat regions, the situation is quite different. Here the gravitational effect of topographic masses usually represents either a slowly-varying or almost a constant (and mostly small) quantity, while FAA can vary extensively due to responses to the local subsurface geological structure. In other words, the above-mentioned proportionality cannot be observed when the topography is flat or nearly flat.

These facts have been recognized for a long time and were quite often mentioned in the literature. For instance, *de Graaff-Hunter (1958, p. 1)* wrote: "Topographic features ... will accordingly be more effective on gravity in regions of rugged topography than any underground (density) anomalies of same extent." Another example is *Woollard (1962, p. II-3)*: "In areas of marked surface relief, FAA are directly related to the topography and are positive on mountain peaks and negative in valleys."

It is important to note that, in the frame of the above-mentioned proportionality, considering gravitational effects of the topographic masses instead of topography or topographic features (i.e. heights), would be more correct. One (inferior) reason could be that gravitational effects of the topographic masses themselves are directly proportional to heights, although this represents a kind of statistical relation (e.g., *Mikuška et al., 2014*), and therefore the respective quantities can be considered approximately interchangeable. Moreover, especially near the summits of the highest mountains, proportionality of FAA and gravitational effects of the topographic masses is markedly better than that of FAA and heights, as we have proven earlier by unpublished numerical and graphical tests conducted on 885 gravity points within the Slovak part of the High Tatras.

Attempts to estimate the gravitational effect of topographic masses can be traced back even to *Bouguer (1749, the third term in his Eq. 3.1).* The quantity that well estimates the gravitational effect of the topographic masses we now call the Near Topographic Effect (NTE, *Mikuška et al., 2017, p. 47*). NTE is defined as the gravitational effect of all topographic masses up to the outer limit of the zone O (*Hayford and Bowie, 1912, p. 18*), calculated for a constant density.

In a hilly terrain, the existing proportionality between FAA and NTE (NTE calculated for unit density) can be used to estimate the value of surface density of the topographic features or geological units, commonly used as the gravimetric correction density. However, FAA often contain components or trends other than topographical ones that can cause disturbing effects on density estimates, as mentioned above. For this reason, residuals FAAres and NTEres can be introduced instead.

Calculating residuals (by definition, this must be performed simultaneously with evaluating regionals) always represents an equivocal process. “The problem is incapable of an exact solution because of the inherent ambiguity in defining the source of a potential field...” (*Nettleton, 1954, p. 2*). But, on the other hand, “...the proper application of a system appropriate to the particular problem encountered can give very useful results” (*Nettleton, 1954, p. 1*). In our case, based on several numerical experiments using both real and synthetic data, it became clear that we do not have to impose any strict requirements on the method of calculating the mentioned residuals. Paradoxically, even the ambition that these residuals should have some geological sense does not seem to be inevitable. On the other hand, it turned out to be essential that in both cases (i.e., FAAres and NTEres) they were calculated in an identical way. Additional requirements were that the calculation of the residuals was as simple as possible, that it did not require user intervention during the calculation (in other words, that it could be automatic), and that it could be applied also for an irregular network of gravity points as we have them included in the Gravimetric Database of the Slovak Republic (GDBSR).

Our calculation of FAAres and NTEres is based on the method of least squares and is very similar to that of *Agocs (1951).* The main difference is that we apply the method in a moving window around each calculation point. The size of the window is controlled either by its radius or by the number of gravity points inside. The (direct) proportionality between FAAres and NTEres is represented by the proportionality coefficient (PC), which is obtained by a simple regression analysis using commonly available tools as Grapher® from *Golden Software, LLC.* Based on many numerical tests, we have learned that PC value can be taken as the output apparent density. Here we were also inspired by *Parasnis and Cook (1952, p. 255).* Alternatively, our program for estimating linear tendencies within the data (X, Y and NTEres as the independent variables, and FAAres as the dependent variable; *Mikuška et al., 2012*) can be also used.

Here we do not present a wider methodological overview since, as we already wrote, this article is primarily focused on comparing density estimates based on underground-surface gravity measurements with those based only on the analysis of surface gravity data contained in the GDBSR. Actually, there exist a variety of density estimation methods based on the analysis of surface data. More on the topic can be found e.g., in *Yamamoto (1999).*

As an example of estimating surface densities, we present here some of the working materials from the location Ovčiarsko, vertical No. 1. In Fig. 6 are the estimates obtained by both used methods from the FAAres and NTEres residuals in the gravity points in the vicinity of the subject vertical, within circles with radii from 1000 to 10000 m. The residuals were formerly calculated for the smallest possible number of points around the calculation point ($n = 5$). We can see from the graph the clear decreasing trend of surface density estimates towards the vertical No. 1, as well as the overall difference compared to the underground-surface bulk density.

The estimates for the individual R look quite well as it is illustrated in

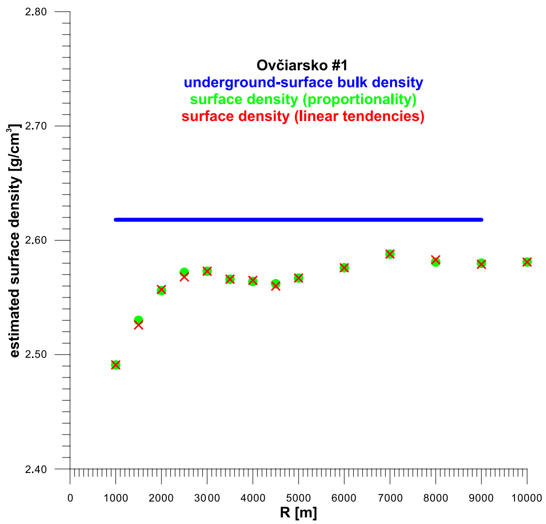

Fig. 6. Surface density estimates as a function of the radius R of the circle around the vertical No. 1 at the locality of Ovčiarsko. Underground-surface density in the same vertical is depicted schematically by the blue line.

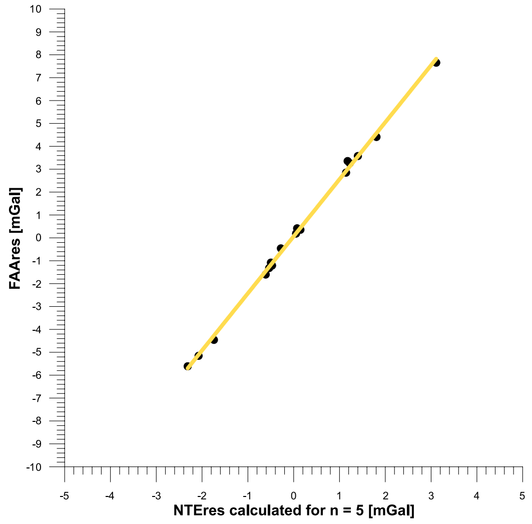

Fig. 7. Surface density estimate using the proportionality between FAAres and NTEres within circle around the vertical No. 1 with radius $R = 1000$ m at the locality of Ovčiarsko. The slope of the approximating line (or, the proportionality coefficient, PC) is equal to 2.491.

Fig. 7 by the cross-plot of FAAres versus NTEres values for $R = 1000$ m. It can be seen that the proportionality between the respective values is quite clear, even with a small number of pairs of FAAres and NTEres ($N = 17$ in this particular case).

4. Comparison of the two methods

In Fig. 8, a comparison of the densities determined by both methods is presented. Excluding the points mentioned in the previous chapter, where local changes in density are assumed (Branisko, Izabela, Chlmec), the largest differences (exceeding 0.10 g/cm^3) are observed at two locations: Ovčiarsko and Poľana. The differences at these sites have the opposite signs, so we do not assume the presence of a systematic effect caused by the methodology. Considering that the underground-surface method is more sensitive to lateral density changes than the surface method, in the case of Ovčiarsko the local geological situation seems to be a possible cause. In Fig. 9, it can be observed that the points are located at the junction of several geological units. The higher determined densities in the case of the underground-surface method (as well as their increasing trend from east to west, Fig. 8) can be attributed to the layers of Súľov conglomerates occurring in the rock overlay of the western part of the tunnel. According to *Stránska et al. (1986)* the density of Súľov conglomerates can be up to 2.73 g/cm^3.

In the case of the Poľana tunnel, the explanation for the density differences between the two methods is not clear. According to *Stránska et al. (1986)*, the differences in density between sandstones and claystones in this area of the Flysch belt correspond to the density interval found by us (2.60 vs 2.46 g/cm^3). Therefore, a partial explanation could be the location of our points in the area with the absolute predominance of claystones, which is documented by *Moravanský and Szabó (2018)*.

At the NOŠ site, the estimation of the related surface densities from graphs like that in Fig. 6 was more difficult than it was at the other sites. For instance, in the case of the most critical vertical No. 3 (the last red point from left to right in Fig. 8) the surface gravity point closest to the vertical was almost 380 m apart and, for $R = 1000$ m, in the circle there were only 11 gravity points of the GDBSR. Among the possible reasons of the discrepancies between the methods on this site, we assume to be the

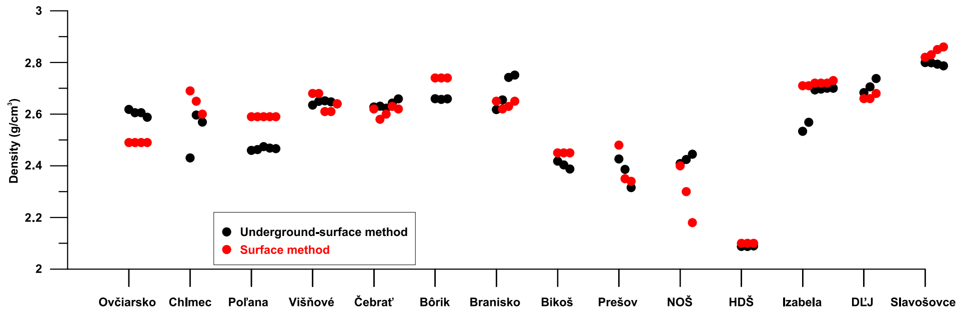

Fig. 8. Comparison of densities determined by the underground-surface (black) and surface (red) method.

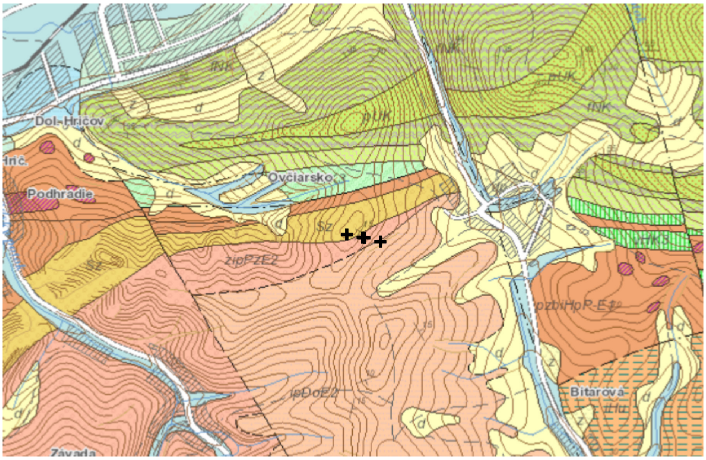

Fig. 9. Distribution of measurement points at the Ovčiarsko site. Geological background: Map server of the State Geological Institute of Dionýz Štúr (`https://www.geology.sk/geoinfoportal/mapovy-portal/`).

sparse and irregular coverage by the surface gravity points in the vicinity of the verticals. In other words, the reliability of the surface density estimates was at this site obviously worse than at the other sites.

5. Comparison of gravimetric methods with existing density map

In the previous chapter, we referred several times to the published density map *Stránska et al. (1986)*, Fig. 1. Therefore, it is interesting to compare all sites with the data from this map, or from its digital form by *Paľáková (2012)*, Fig. 10. Data from the density grid for most locations do not deviate significantly from the values determined from gravimetric measurements, with a few exceptions. More significant differences are observed for two tunnels (Bikoš, Prešov) located in the Paleogene of the Inner Carpathians, specifically in the Zuberec Formation (Fig. 1). Both the underground-surface and surface methods give values close to each other, averaging around 2.40 g/cm^3, while the density map gives 2.65 g/cm^3. In our opinion this difference could be attributed to some overgeneralization that may have occurred during the final phases of the quoted density map preparation. Some other sites with larger differences in densities are discussed in the following chapter.

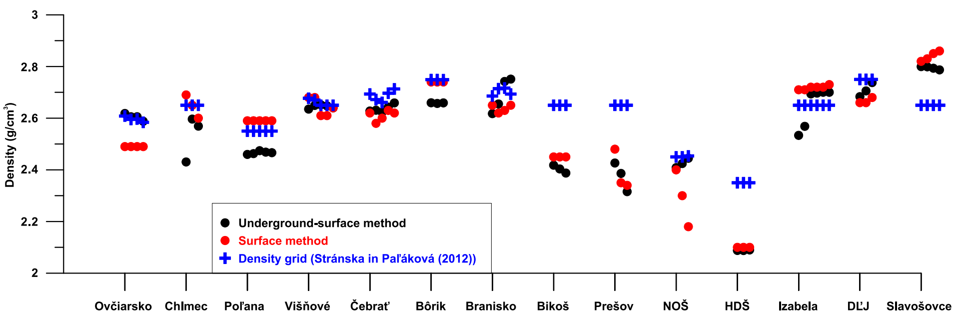

Fig. 10. Comparison of densities determined by the gravimetric methods (black and red) and those interpolated from density grid *Paľáková (2012)*.

6. Discussion

A natural question arises as to how all the mentioned methods of determining densities are related to each other, or how and why they agree or disagree with each other. In general, it must be stated that it is not possible to expect complete agreement among these methods, neither between surface and underground-surface methods nor between "gravimetric" methods and the density map. Obviously, the primary reason for the differences in the determination of densities is the inhomogeneity of the rock environment in both the horizontal and the vertical directions. As demonstrated, the underground-surface method is highly sensitive to local density changes in the horizontal direction. We can consider this fact as an advantage, if our goal is to estimate the density as accurately as possible at a given place, if we consider density changes only in the horizontal direction. In this way, for example, it would be possible to "map" the density changes along the tunnel in detail. On the other hand, it can be a disadvantage if our goal is some average density of a broader area (e.g. correction density). In that case, the result of the underground-surface method may be too "local". On the contrary, the surface method provides an image of the densities over a wider area. However, the reliability of this method is significantly dependent on the coverage of the territory by the database points and on how far from the analysed location these points are considered. For example, at the Bôrik site, the tunnel is situated in an isolated massif of Triassic dolomites (Fig. 11). The points of the GDBSR in the immediate vicinity of the measured points are also displayed. There are very few database points in the massif itself, which obviously must complicate the analysis of the surface data. The solution could be an approach in which we would analyse only those database points for which we know a priori (according to geological data) that they cover the given geological unit. We have also studied such an approach, but it is rather beyond the scope of this paper.

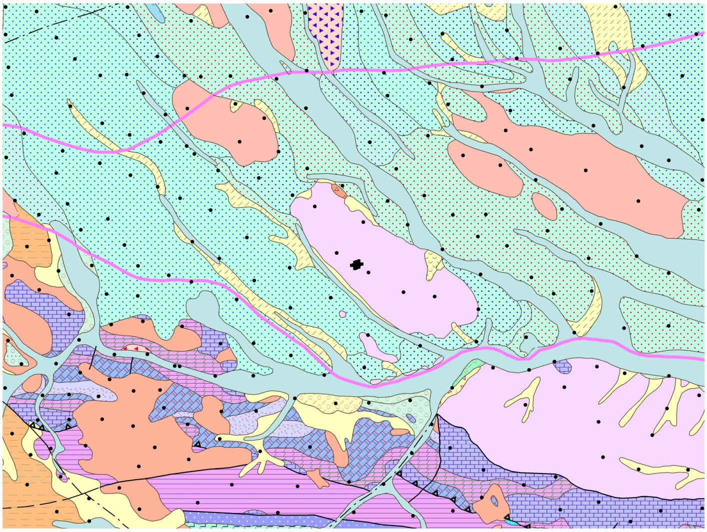

Fig. 11. Distribution of measurement points using the underground-surface method (larger crosses) and gravimetric database points (smaller dots) at the Bôrik site. The tunnel is located in an isolated massif of dolomites (pink colour).

The inhomogeneity of the rock environment in the vertical direction is another factor that is not easy to evaluate quantitatively. In the case of the Izabela site, it was previously mentioned that we can assume that the strongly reduced density in the first pair of points could be influenced by the thickness of the Quaternary sediments, especially given the low rock overlay towards the exit of the adit. We can attempt to simulate this situation using simple elementary models. Let us consider a layer of planar topography (in the form of a vertical cylinder) with a thickness of 50 m and a density of 2.70 g/cm^3 in one case. In the second case, we replace the upper part with a layer with a thickness of 10 m and a density of 2.00 g/cm^3. When we compare these two situations, we find that the presence of a “deluvial” layer will reduce the density estimate from 2.70 to 2.56 g/cm^3, which is quite a significant decrease. If we consider the same layer of “deluvium” for the rock overlay with a thickness of 150 m (instead of 50 m), we get a decrease from 2.70 to 2.65 g/cm^3.

Another example of how a heterogeneous rock environment near the measurement points can influence the estimation of density is the DĽJ site. The cave is known for its ice filling, which in some places reaches a thickness of 25 m. Based on measurements of the ice thickness by ground penetrating radar (GPR), we constructed an approximate three-dimensional model of the ice fill and used it to correct the NTE calculation. Density estimates, including correction for ice (used in graphs in Fig. 2 etc.), and without this correction are compared in Table 1. The influence of the ice filling on the gravity measurements conducted in the cave and the subsequent estimation of densities by the underground-surface method is evidently significant.

In addition to the surface geological structure, the deeper geological background also plays a role in both methods. Since the vertical gradient of the

Table 1. Densities determined by the underground-surface method at the DĽJ site. The density values show the significance of the introduced corrections for the gravitational effect of the ice filling of the cave.

Point No.	Density (no ice correction)	Density (with ice correction)
1	2.65	2.68
2	2.74	2.71
3	2.95	2.74

Earth's normal gravity field is involved in the FAA calculation, we are aware of that if the change in the gravity acceleration in the vertical direction is more significantly affected by deeper geological sources, this may also affect the calculated densities. This fact has been pointed out by several authors (e.g. *Hammer, 1950*). We attempted to evaluate this effect using the example of the Slavošovce site. At this site, we determined the highest density of all sites, namely 2.8 g/cm^3. According to the report of *Klinec et al., (1979)* the tunnel is located in the formation of Hladomorná dolina. For the rocks of this formation, specifically for biotitic phyllites, *Stránska et al. (1986)* report a density of 2.69 – 2.73 g/cm^3, which is not as high value as the value we determined from the gravity measurements. Although these rocks obviously have a higher density compared to their surroundings, in the Bouguer anomaly map this area belongs to the local gravity minimum (Fig. 12). This fact is interpreted by the presence of the Rochovce granite captured by the KV-3 well at a depth of approx. 700 m (*Klinec et al., 1979*). Based on a quantitative estimate of the influence of such a granite body on our mea-

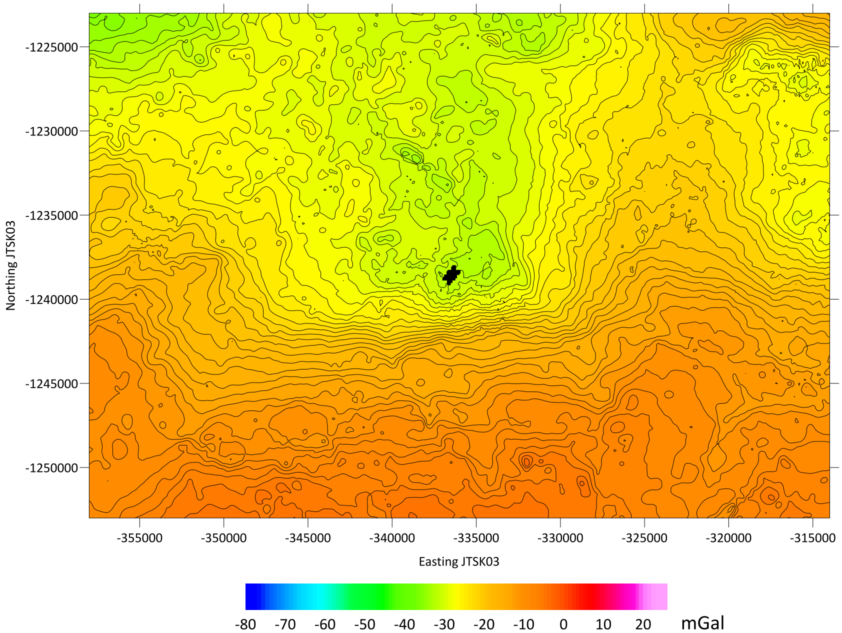

Fig. 12. Section from the Bouguer anomaly map of Slovakia in the vicinity of the Slavošovce site. Crosses indicate measurement points used in the underground-surface method.

surements using the underground-surface method, we concluded that the presence of such a body can increase our density estimate at the level of a few hundredth of g/cm^3.

Using the example of the Slavošovce site, we can also document the characteristics of the third source of density information that we use for a comparison in this article, namely the Density map of the Western Carpathians (*Stránska et al., 1986*), Fig. 1. When compiling the map, the authors considered not only the specific places of rock sampling, but also the geological division of the Western Carpathians, indicating that the generalization of the map plays an important role. In the case of Slavošovce, we get a value of 2.65 g/cm^3 from the map (used in Fig. 10), although the mentioned table values for biotite phyllites are higher (2.69 – 2.73 g/cm^3). Therefore, it is essential to distinguish between tabular data according to *Stránska et al. (1986)* and map values interpolated from the grid *Paľáková (2012)*, Fig. 13. In some localities we will thus get significant differences. For example, at the HDŠ site, the map/grid value is 2.35 g/cm^3, which should correspond to rhyolite/rhyodacite, but in the tables we also find values around 2.00 g/cm^3 assigned to rhyolite pyroclastics/tuffs. The latter corresponds more closely to the densities found by gravimetric methods and agree with the geological background (`https://www.geology.sk/geoinfoportal/mapovy-portal`).

The mentioned facts lead us to conclude that, despite all the discussed problems, gravimetric methods can provide more consistent density estimates than the existing density map. If we attempt to quantify these relations, we can statistically evaluate the differences between the underground-

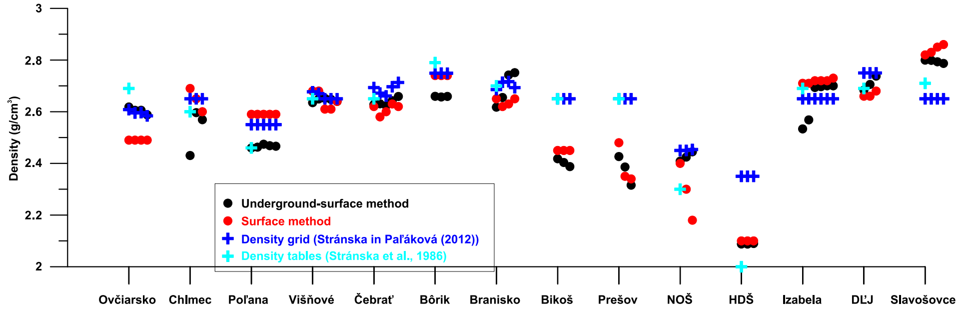

Fig. 13. Comparison of densities determined by the gravimetric methods (black and red dots) and densities derived in two ways from the density map: interpolation from grid (blue crosses) and table values (cyan crosses).

surface and the surface method (shown in Fig. 8). The standard deviation of the differences between these two methods is at the level of 0.09 g/cm^3. If we exclude some problematic points from the comparison, we obtain a standard deviation below 0.07 g/cm^3.

7. Conclusions

To summarize, we compared two different methods for estimating the rock density based on gravimetric measurements: the underground-surface method based on measurements in selected underground spaces (and above them on the surface), and the surface method based on the analysis of the surface gravity points included in the GDBSR. Both methods are based on the same theoretical principle of proportionality of FAA and NTE, but their spatial implementation and sensitivity is different. The inhomogeneity of the rock environment in the horizontal as well as the vertical directions means that these methods are not completely comparable to each other. The underground-surface method is more sensitive to local density inhomogeneities/interfaces, while it can be implemented relatively quickly if suitable underground spaces (i.e. tunnels, mine works, caves) are available. On the other hand, the surface method yields density estimates with a wider scope, but it is significantly dependent on the available surface gravity measurements, i.e. the existing gravimetric database, and on the ruggedness of the topography. However, if certain assumptions are met, we can speak about the mutual agreement of these methods in determining the density better than 0.1 g/cm^3.

Additionaly, we compared these gravimetric methods with the existing rock density map in Slovakia, revealing more significant differences in some locations, probably mainly caused by (over)generalization during the creation of the density map.

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