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GEODETIC SURVEYS IN DETECTION OF GEOLOGICAL FEATURES: A CASE STUDY OF INOWROCŁAW AREA, CENTRAL POLAND

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Abstract: Remotely obtained geodetic survey data can be used to detect anomalies in the terrain surface over different geological structures, like faults or deposit boundaries. Some computer techniques are helpful to extract the influence of geological phenomena on typical distribution of the measured elevations. Certain disturbances in profile lines can be considered as additional, human-induced effects or caused by geological processes. The paper demonstrates such an analysis basing on geodetic data with some support of geophysical results. The examined morphological profiles and profiles of subsidence bowls caused by mining in the area of Inowroclaw (central Poland) illustrate the problem of an underestimated mechanism in non-geological disciplines. For geologists this is another example of environmental interaction between relief-forming processes and subsurface conditions. Furthermore, it brings additional information about processes of mining subsidence, which is the primary topic of this study.

Mutual relationships between vertical displacements induced by mining or other factors and morphological profiles point to the dominant role played by mobility of geological structures, as shown by correlation between geodetic and geophysical data.

Key words: recent geodynamics, salt geology, geodetic levelling, mining-induced subsidence, Inowrocław salt dome, central Poland.

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INTRODUCTION

Frequently carried out levelling surveys in the area of Inowrocław, central Poland, brought some unexpected data pertaining to the influence of geological structures on subsidence processes. The subsidence of the terrain surface, resulting mostly from mining excavation, used to be observed for decades. Closure of the "Solno" mine and backfilling of excavation halted significant ground displacements. Periodical subsidence bowls displayed specific characteristics, which have not yet been studied. Recent surveys conducted for civil engineering purposes have brought even more spectacular results. The aim of this paper is to combine data supplied by geodetic and geophysical surveys to estimate the effects of mobility of subsurface geological structures on the present-day relief and displacements of ground surface in a selected area of the city of Inowrocław. To achieve this goal, an integrated study of topographic profiles, levelling survey data, gravimetric and seismic profiling, as well as field examination of mining conditions was initiated. The presented geodetic and geophysical surveys were carried out to assess deformation induced by mining, and included those related to the former subsidence bowls as well as recent vertical displacements. The measurements were limited to the northern part of Inowroclaw.

LOCAL GEOLOGICAL SETTING AND MINING ACTIVITY IN INOWROCLAW AREA

Geological structure of the Inowrocław area is dominated by a Zechstein salt dome situated 120–190 m below the terrain surface. The salt body is more than 3 km thick. The existing elevated area is a visible effect of the rising dome. The city plan is directly controlled by topography: the central part (main market) is located above the centre of the salt dome, while streets tend to follow contour lines of a topographic high rising above the salt body.

Theories concerning the mechanism of mobilization and flow of the salt were discussed by Tarka (1991, 1992), while co-existing processes, such as: recent vertical move-

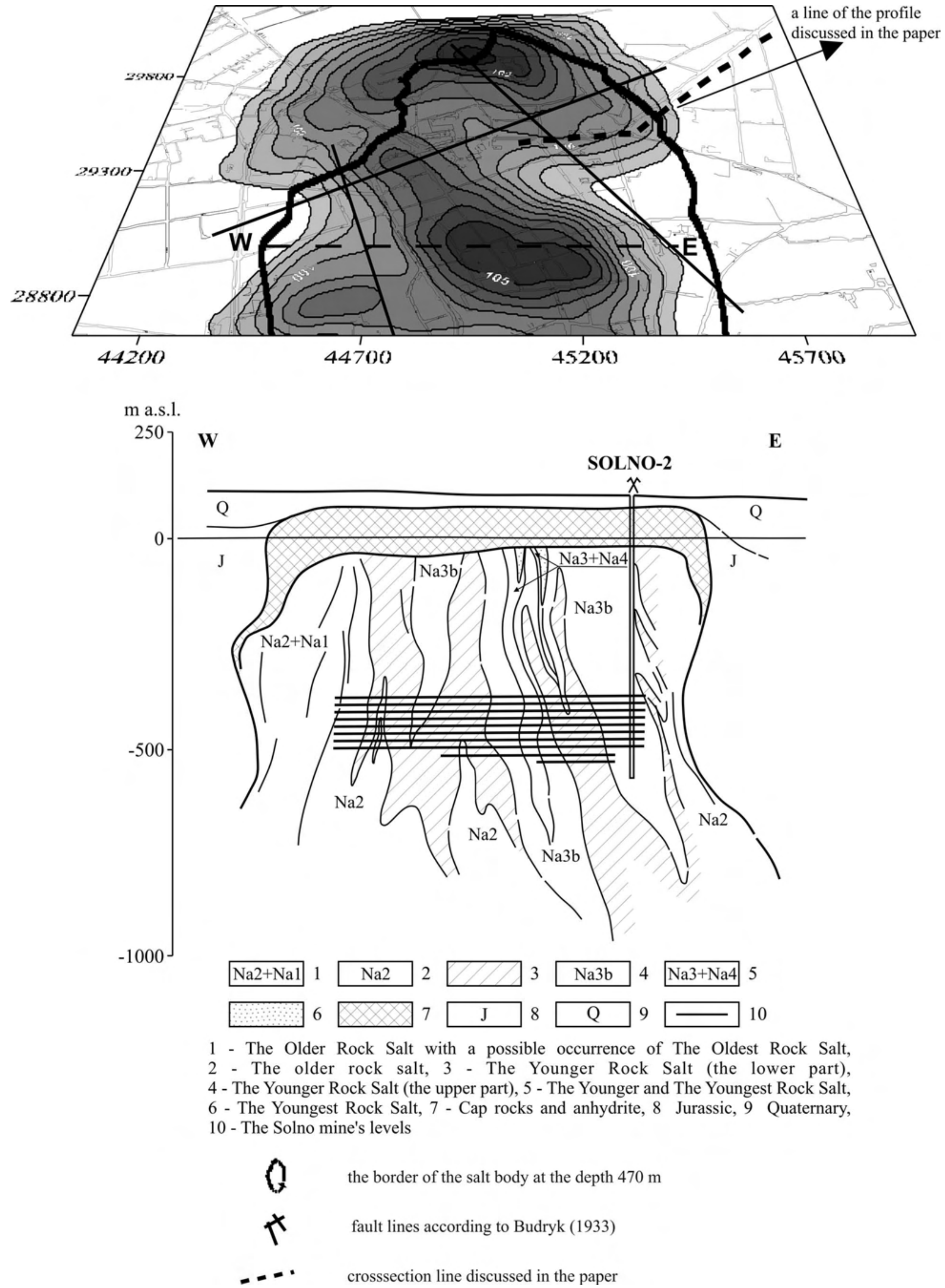

Fig. 1. Map view (data interpolated by triangulation method, contour interval 1 m, local coordinate system in metres; upper diagram) and geological cross-section based on Bujakowski (1986) (lower diagram), showing mining excavations and the Solno 2 shaft

ments, subrosion and karst phenomena were dealt with by Budryk (1933), Poborski (1957), Niewiarowski (1983), Poborska-Młynarska (1984), Tarka (1988), and recently by Molewski (2007, 2008). Another line of study concerned the internal structure of the deposit itself (Bujakowski, 1986; Tarka, 1992). This problem was examined owing to data gathered from numerous drillings and observations obtained from underground mining works. The overall geological structure of the dome is quite simple and typical. In plan view the deposit is elliptical. Both the eastern and western sides of the salt structure are steeply dipping or even upright (particularly in the eastern part).

The Permian salt is surrounded by the crushed Jurassic complex, which is divided into permeable sandy rocks in the west and carbonates (dolomites, limestones and marls) in the east. The reflection of this division is a difference in permeability of cap rocks, which are located at the contact between the Jurassic and Permian strata. The gypsum and gypsum-clayey cap rocks are typified by different permeability, which is the main cause of diversified intensity of karst phenomena (sinkholes, caves), most of them occurring in the western part of the city. Figure 1 shows the boundary of the permeable gypsum cap rock with location of sinkholes, which occurred in this zone in the past, as well as the position of faults interpreted by Budryk (1933) as fostering water migration from the north to the south, around the deposit. This migration led to underground karst processes, discovered at the end of the 19^{th} century during shallow mining works, and favoured formation of sinkholes scattered around the fault lines. The overlying sediments are composed of Pleistocene tills, few to 70 m thick, and thin Holocene sands.

MINING BACKGROUND

More than 100 years' long history of mining of the deposit in Inowrocław witnessed exploitation carried out in different periods with the use of different methods, such as: uncontrolled borehole mining in the roof part of the dome, mining in the roof part of the dome, brine intake and flooding the mine, unsustainable exploitation of the flooded mine, or exploitation with deep boreholes. The last method was involved in the 1920s, and this activity consisted in wet underground exploitation with pillar-chamber system carried by the Solno mine (Fig. 1). The mine was closed down and mining activity in this area was definitely terminated in 1991, when all underground excavations were flooded by saline wastes.

Continuous and discontinuous deformations (small sinkholes) resulting from the mining activity were occurring in the city up to the end of the 20th century. Depending on mining situation, different subsidence bowls were formed on the terrain surface: first extraction works caused deformation in the southern part of the city, while excavation works from the 1960s to the 1980s produced the northern subsidence bowl. During the salt mine operations collapses happened very rarely, and deep mining resulted in not very significant subsidence. The maximum total value of vertical displacements was less than 40 cm. Regular geodetic observations (levelling, GPS campaigns) were resumed in 2002. The aim of these measurements was determination of ground stability after mine liquidation, and detection of geodynamic processes and monitoring ground stability of the Church of the Annunciation of the Blessed Virgin Mary and its surroundings. The church construction was affected both by old mining and natural processes, and ongoing surveys are carried out for renovation purposes.

GEOPHYSICAL SURVEYS

Seismic and microgravimetric investigations aiming at determination of the rock mass state in the vicinity of the church were carried in 2002, in the framework of a research project (Szczerbowski, 2003). The results of seismic profiling enabled to construct a deep, 3D model of the rock mass of the test field. Conclusions related to the shallow part of the rock mass were obtained mostly with the use of microgravimetric network surveys.

On the basis of reflection and refraction profiling and special measurement geometry, some pieces of information about the location of zones of weakness and near-surface structure of the rock mass were extracted. The results provided some hints as to the causes of fracturing in the church wall (Pilecki *et al.*, 2003), resulting from the presence of a N–S oriented fault situated right below the church.

Microgravimetric measurements were carried out in the church area along lines making a grid with survey points spacing of 7.5 m. The obtained gravity anomalies were calculated with respect to gravimetric reductions. These anomalies (differences between the observed gravity and some theoretical gravity value predicted at the measurement point) mark, after removing the regional trend, the residual gravity areas. Such residuals are regarded as an effect of local features having a density contrast with the surrounding rocks. Figure 2 presents a distinctive anomaly passing through the church. Its geometry suggests the presence of a fault line, which was mentioned above. This agrees with the results of seismic surveys, and in both cases the detected anomaly confirms the location of the fault line already suggested by Budryk (1933).

Another gravimetric survey was carried out for the purpose of a regional study. Part of the survey included observations along an East–West trending profile that crossed the dome area in its northern part, with gravity stations spaced every 50 m. The significant anomaly observed along the profile line is the gravitational effect of the salt deposit representing a density change in the earth. The distribution of gravity values show the mass centre and boundaries of the deposit. The boundaries are much better visible on the chart showing the distribution of gradient values (dgB/dL – Bouguer gravity change per distance). Figure 3 presents the distribution of Bouguer gravity and calculated gradient values along the eastern part of the profile that passes through the test field area. A rapid change of these values marks the location of the eastern boundary of the salt deposit. This location has already been known from borehole data, but the results of gravimetric surveys brought another proof in this matter.

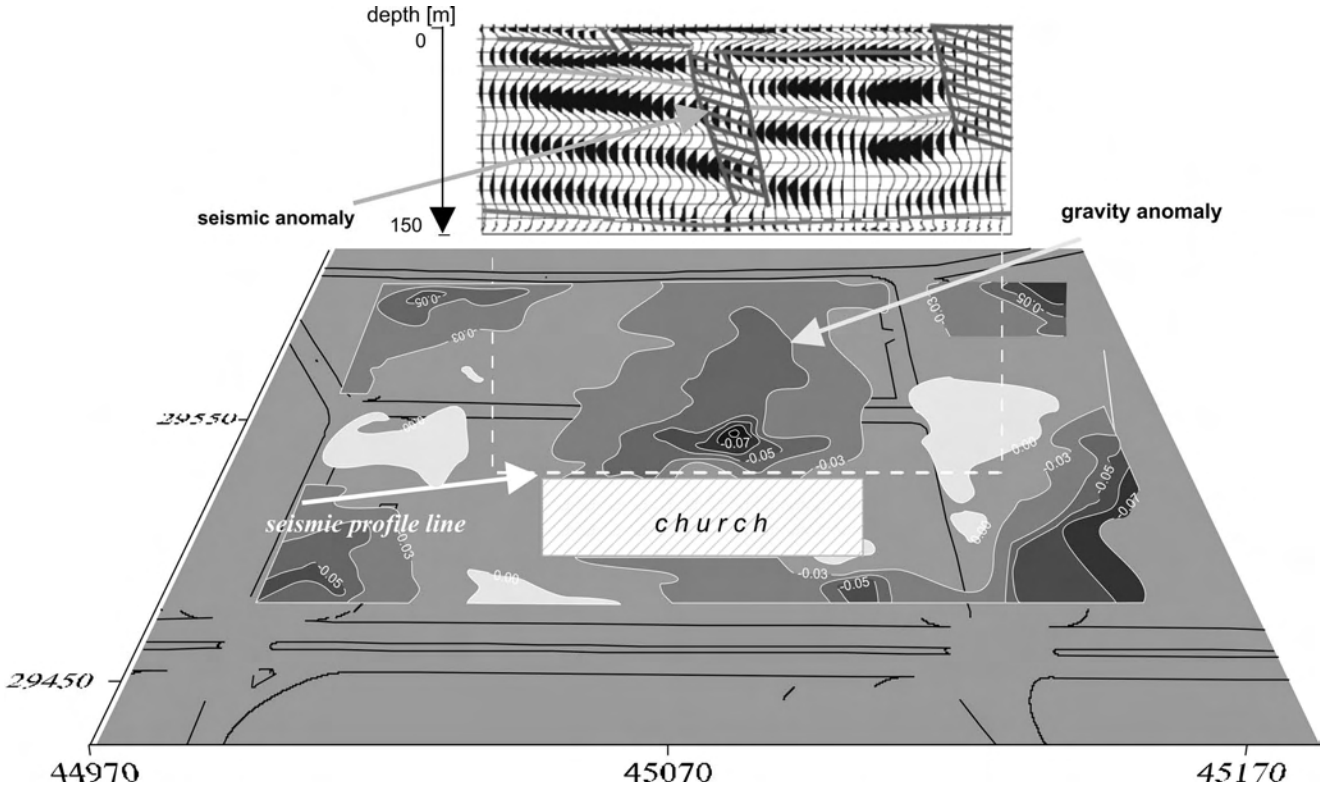

Fig. 2. Position of the gravity anomaly (after Szczerbowski, 2003) and seismic profile at the Church of the Annunciation of the Blessed Virgin Mary (after Pilecki *et al.*, 2003)

The main aim of presented geophysical data is to indicate the location of some tectonic features observed with the use of geodetic surveys as well. The next part of the study is devoted to the levelling results.

LEVELLING SURVEYS: MINING INDUCED SUBSIDENCE

All levelling surveys discussed in this paper were carried out for practical purposes. The results dealt with below document usefulness of such surveys in geomorphic analysis. The levelling data are considered as elevations or elevation changes. In both cases they reflect some geological features, like the location of fault zones and boundaries of salt deposit.

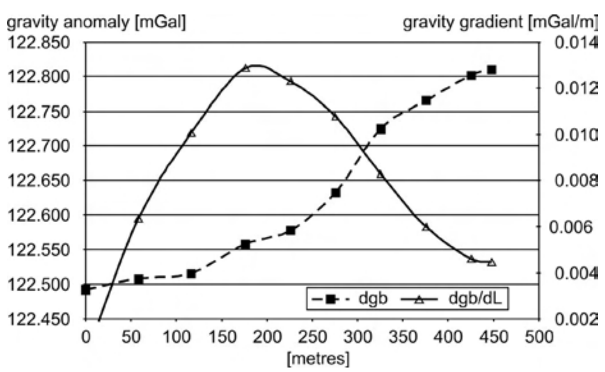

Fig. 3. Variations of Bouguer gravity values [dgb; mGal] and the calculated gravity gradient [dgb/dL; mGal/m] along the profile discussed in the paper. Local coordinate system in metres

Due to ongoing mining works and deformations induced by salt extraction, a number of benchmarks were placed to establish a network for monitoring surface deformations (mostly vertical displacements). The network was being extended until the Solno mine was closed down. The regular levelling observations carried out in the city area enabled to determine periodic subsidence of the terrain surface. From dozens of survey campaigns only some have been selected. The number of benchmarks involved in the surveys was greatest in the 1980s. Therefore, this period was analysed with respect to subsidence determination. The results of recent surveys carried out to estimate deformations induced by geological effects were analysed as well. Figure 4 portrays a map of total subsidence that was observed during the mining activity of the Solno mine, in the northern part of the area. Another figure (Fig. 5) demonstrates periodic height changes along the W–E trending line. The most interesting aspect of the analysis is qualitative characteristic of ground vertical displacements derived from levelling of a quite dense network of the observed benchmarks. Disturbances marked on the graph are distinctive. One of them is located nearly at the eastern boundary of the bottom of subsidence bowl, the others are placed between 200 m and 1200 m of the profile length that passes the subsidence bowl along the W–E line.

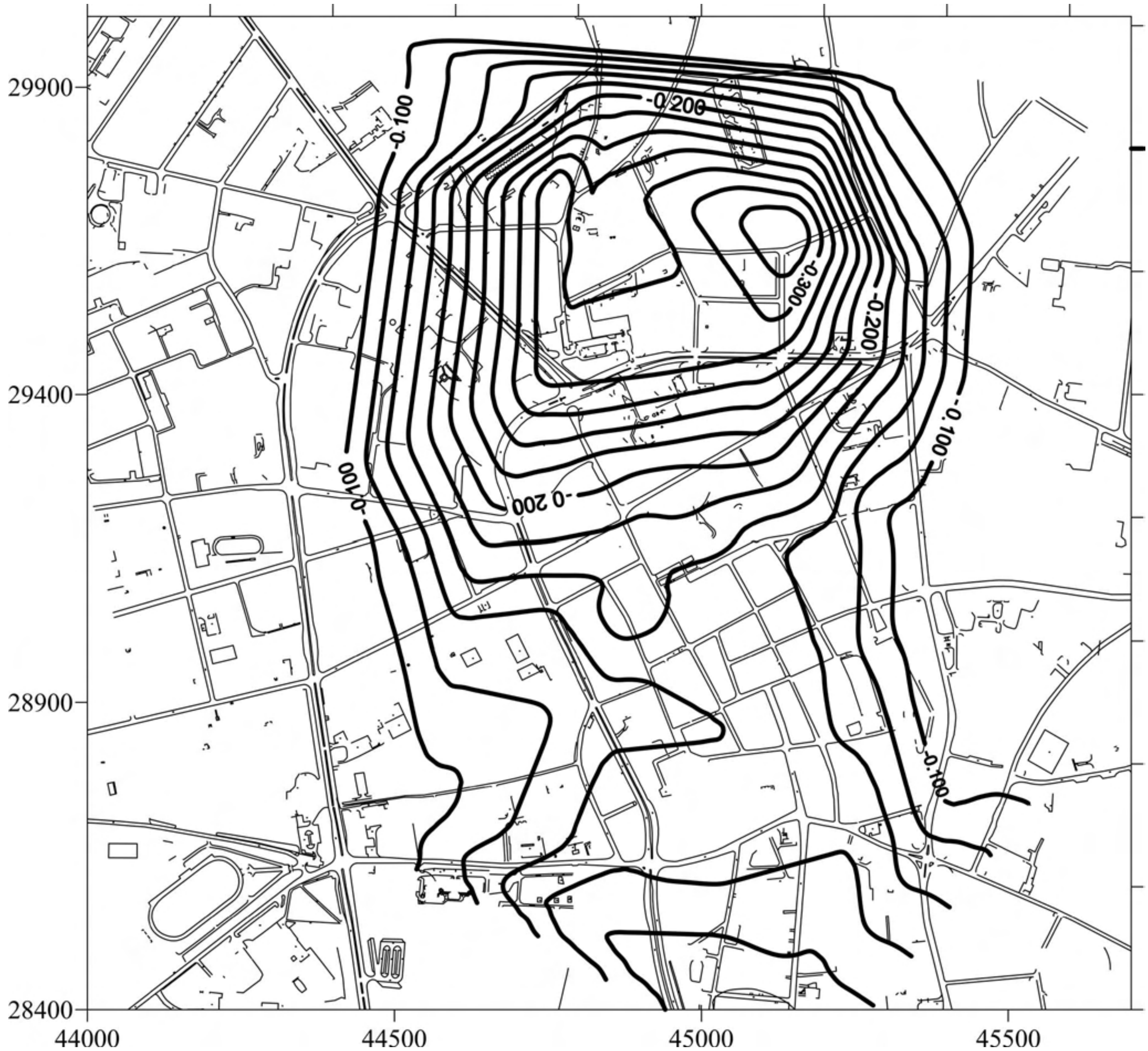

Fig. 4. Pattern of subsidence caused by the Solno mine in the area of Inowrocław in 1956–1991 (data interpolated by triangulation method, contour interval 0.02 m) and location of the W–E line. Local coordinate system in metres

LEVELLING AT THE CHURCH OF THE ANNUNCIATION OF THE BLESSED VIRGIN MARY

Specialized levelling surveys monitoring deformations of the church have been carried out every six months since 2005. One of these surveys relates to a grid of benchmark height changes. The benchmarks are placed in the church walls and other parts of its construction. During three years of observations they demonstrated small height changes, slightly exceeding the measurement error values. Minor differences in the measurement results provide a hint as to the technical condition of the building and its potential damage. The idea of establishing such a network originated during observations of three wall benchmarks that have demonstrated specific long-term deformations since the beginning of the 20th century (benchmarks 112, 731 and 732). The network was extended and currently it includes more points. The next group of benchmarks was established on the foundation pedestal in 2005.

Regularly conducted measurements show periodic seasonal displacements with distinct diversities in height changes that do not correspond to the construction conditions. The deformation processes proceed differently in the western and eastern parts of the church. Although vertical displacements are generally similar, the observed diversities are significant. Profiles of displacements of the northern (1964–2008) and southern (2005–2008) walls are available. The presented diversities occurred also in other periods, indicating different ground conditions or stress field causing the displacement. In both cases the diversities of the displacements are not accidental, and they do not relate to construction properties of the structure. The lowered values of the displacements shown in Fig. 6 are a kind of anomaly that

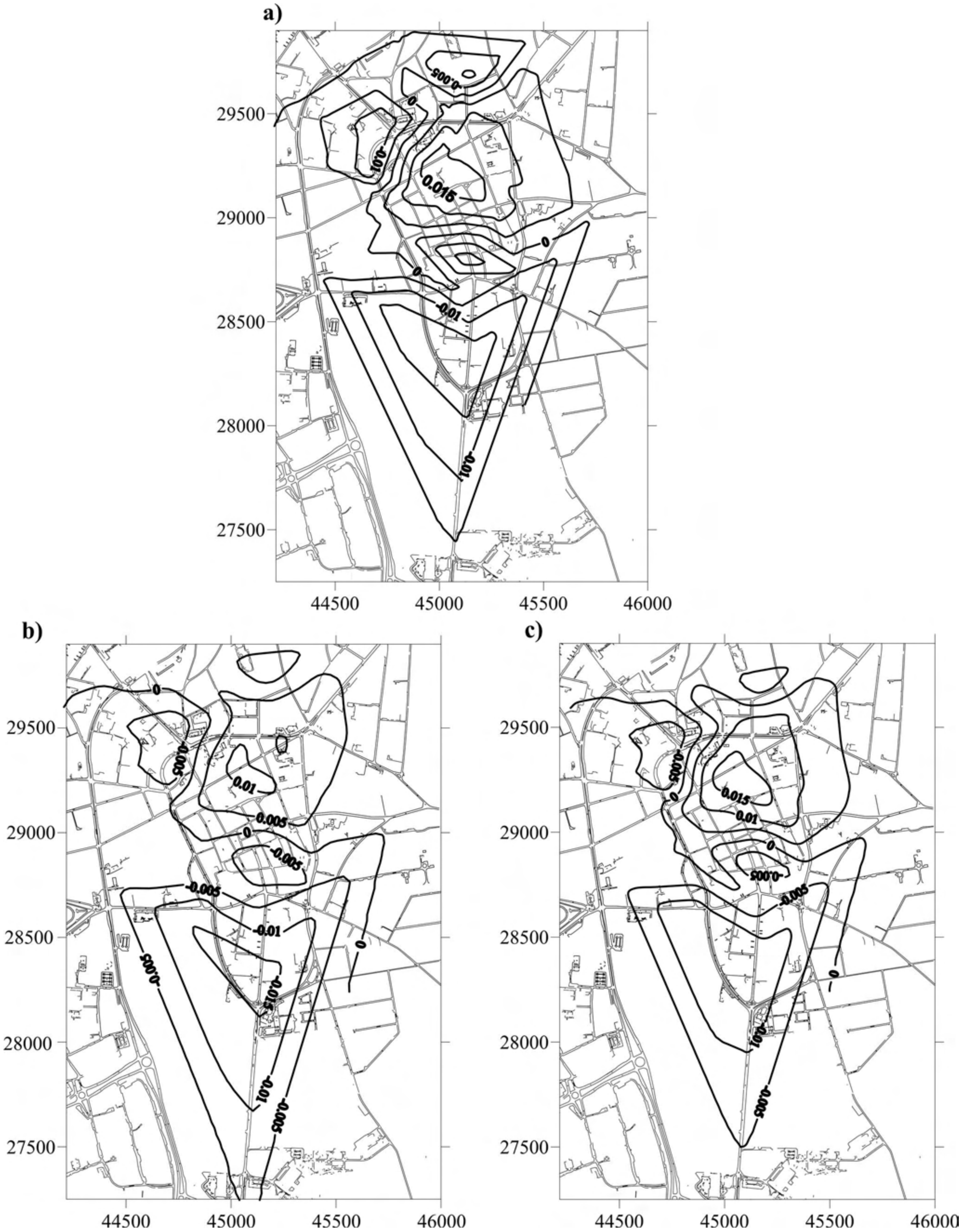

Fig. 5. Recent height changes in the area of Inowrocław in different time periods (data interpolated by triangulation method, contour interval – 0.005 m): A – 1991–2005; B – 1995–2005; C – 1992–2005. Local coordinate system in metres

corresponds to that determined by geophysical observations.

TOPOGRAPHIC PROFILE OF THE TEST FIELD

The elevation data were obtained thanks to tachymetric surveys carried out for microgravimetric profile surveys discussed before. The accuracy of the observation was less than in typical levelling measurements (error of determined heights was about 1 cm), but it was sufficient for quantitative analysis of elevation changes. The results are shown in Fig. 7. The morphological profile resembles that of gravity anomaly, although showing certain highs and lows, which are marked in Fig. 8. These do not correspond to man-made features of the terrain. It is clear that the boundary of the deposit is marked on the profile line, but quite remarkable is a peak in its middle part. This is the same location as that mentioned before with a reference to subsidence analysis, coinciding with the trace of a fault line passing along the dome.

DISCUSSION

The presented study involves survey data related to the static kinetic status of the terrain surface. The existing morphological profiles portray uplift of the ground surface due to halotectonic movement of the rock salt. The second category of data concerns vertical displacements of the terrain during previous mining activity, and recent movements caused mostly by geological processes. In both cases data distribution demonstrates some peaks, the location of which is related to the deposit boundary. The location of a fault that probably passes throughout the entire length of the salt deposit is probably marked in vertical displacements of the surface only. Higher values of displacement observed in previous years (due to mining influence) made it possible to

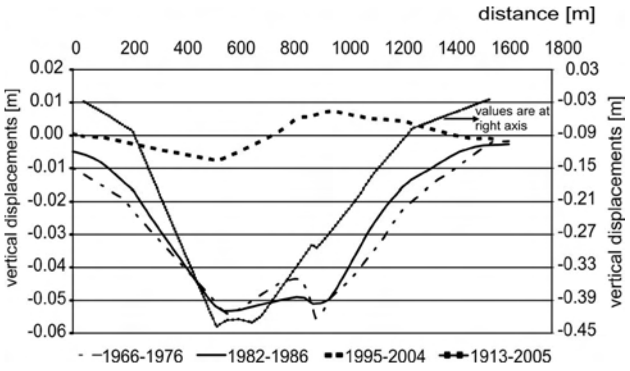

Fig. 6. The W–E profiles through the subsidence bowl in different time periods (subsidence in metres)

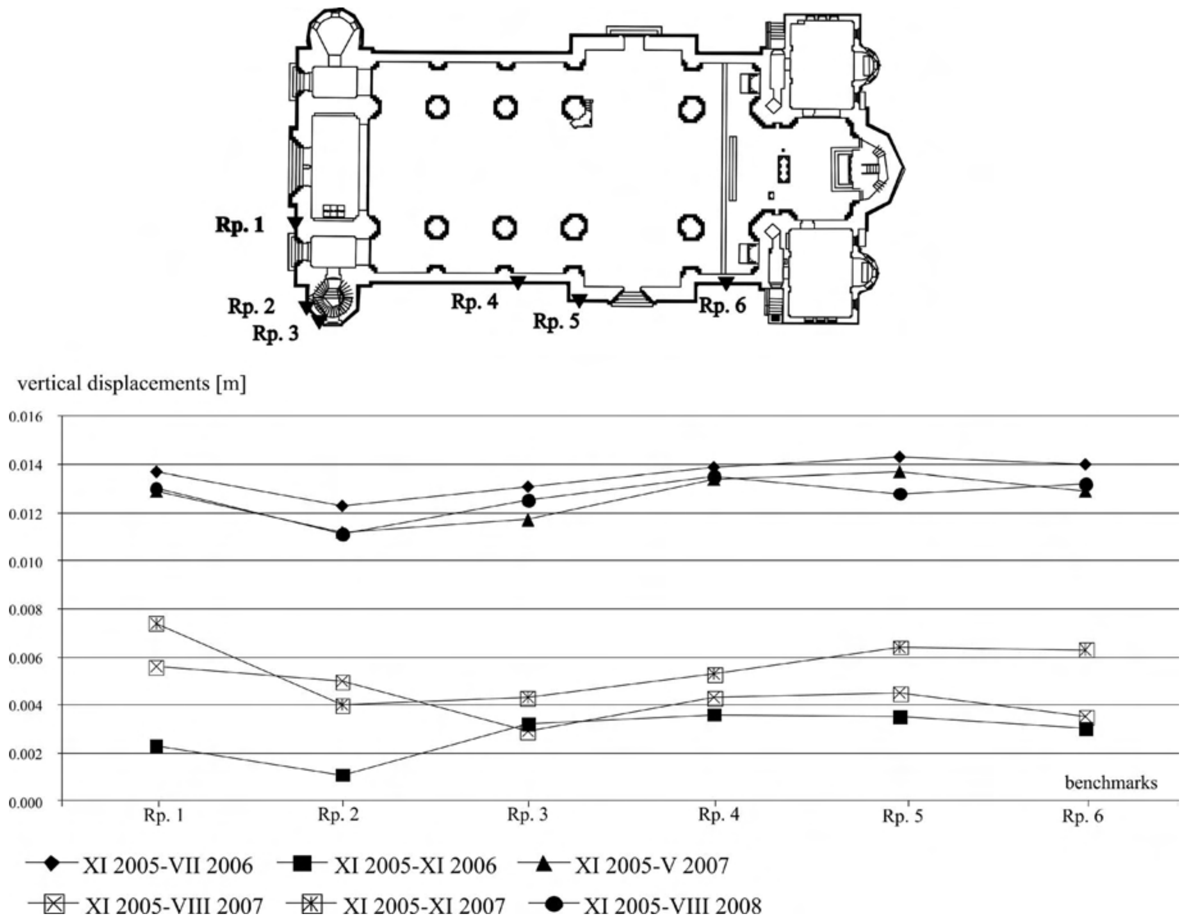

Fig. 7. The displacements of benchmarks placed in the southern basement of the church in different time periods

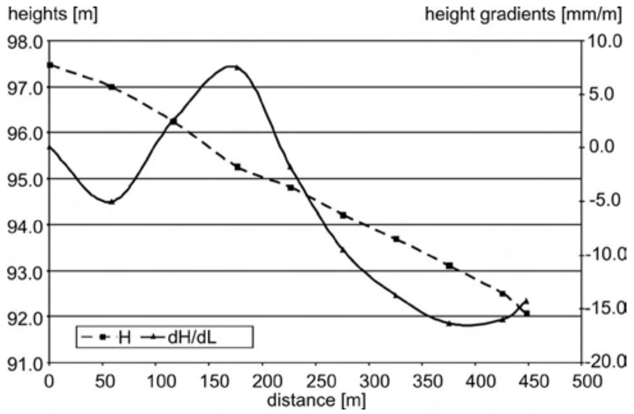

Fig. 8. Distributions of heights [H; m] and the calculated height gradients [dH/dL; mm/m] along the profile discussed in the paper

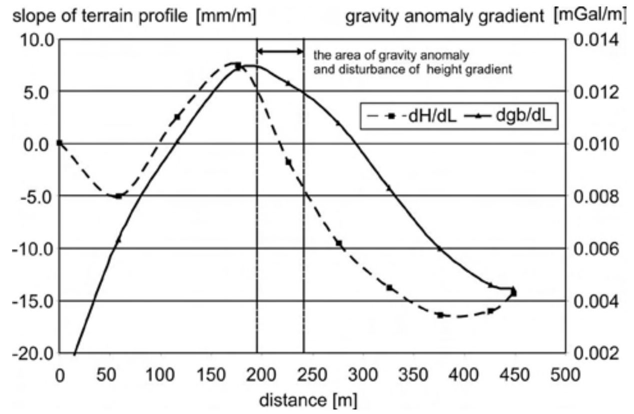

Fig. 9. Variations of height gradients [dH/dL; mm/m] and gravity gradients [dgb/dL; mGal/m] along the profile discussed in the paper

detect deformation differences between the eastern and western parts of the subsidence bowl that was formed in the northern part of the deposit. The line separating these parts is SE–NW oriented, like the tectonic line discussed in some papers. The location of the boundaries of the salt deposit is well known from geological and geophysical data; hence, geodetic surveys brought another contribution to detection of geological structures. Nevertheless, the relation between the latter and topography is not always clear. In the study area, the northern boundary of the salt body is placed below the topographic elevation. Data pertaining to the connection between displacements and location of geological structures is important in civil engineering problems, like that related to deformation detected in the Church of the Annunciation of the Blessed Virgin Mary. This functional aspect of the investigation is especially important in geologically active areas.

This study helped to identify the location of a fault, probably the main fault of the salt structure, and part of the western boundary of the deposit.

FINAL REMARKS

The presented example illustrates well the influence of mobility of geological structures on features of the terrain surface or observed displacement processes. Topographic profiling aided by repeated levelling and geophysical surveys proved very helpful in Inowrocław area, where rocks overlying the salt dome are relatively homogeneous. Spatial distribution of the detected local elevations and depressions reflects to a certain extent the amplitudes of uplift and subsidence, modified as well by proceeding erosion processes.

The reflection of geological structures in recent topography and surface displacements is an important element of an information system that should provide all data necessary for prediction of hazards related to geological and geotechnical environments (EN 1997 Eurocode 7, 2004).

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