A R C H I T E C T U R E C I V I L E N G I N E E R I N G E N V I R O N M E N T
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ANALYSIS OF THE IMPACT OF LONGWALL MINING ON SACRED HISTORIC BUILDING

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A b s t r a c t

This paper presents an analysis of the impact of longwall mining on the Saint Wawrzyniec and Antoni's church, located in the area of Upper Silesia (Wirek - Ruda Śląska). That century old historical monument has been exposed to mining influences since it was erected. For 40 years the structure, its protective slab and nearby area have all been under geodetic observations. Based on data obtained over the course of those observations, an analysis was carried out of how mining the 133 longwall of the 413/2 seam did influence the church building, which was located above the mining panel's corner.

This paper explores how the body of the church behaved during mining exploitation, based on theoretical computations and analysis of geodetic observations data. The subsidence process and linear strain over time were studied. Registered subsidence and deformations were plotted against individual measuring points attached to structural members inside the building. Significance of identified influences for the building's supporting structure was discussed.

S t r e s z c z e n i e

Praca poświęcona jest analizie wpływu podziemnej eksploatacji górniczej, prowadzonej system ścianowym, na budynek kościoła pw. św. Wawrzyńca i Antoniego w Wirku (Ruda Śląska). Ten stuletni, zabytkowy obiekt narażony był na oddziaływania górnicze niemal od początku swojego istnienia. Od 40 lat prowadzone są obserwacje geodezyjne budynku, płyty zabezpieczającej oraz terenu wokół kościoła. Na podstawie wyników tych pomiarów przeprowadzono analizę oddziaływania eksploatacji ściany 133 w pokładzie 413/2 na budynek kościoła, który zlokalizowany był nad narożem pola eksploatacyjnego. Praca zawiera studium zachowania się bryły kościoła w trakcie prowadzenia eksploatacji przeprowadzone w oparciu o obliczenia teoretyczne oraz analizę rezultatów obserwacji geodezyjnych. Rozważono przebieg procesu osiadania oraz zmiany odkształceń liniowych zachodzące w czasie. Przedstawiono wykresy zarejestrowanych wartości osiadań i odkształceń dla poszczególnych punktów i baz pomiarowych umieszczonych na elementach konstrukcyjnych wewnątrz budynku oraz omówiono znaczenie stwierdzonych oddziaływań dla ustroju nośnego obiektu.

K e y w o r d s: **Mining damage; Building deformation; Influence of mining on buildings.**

1. INTRODUCTION

Over the years, antique buildings located in areas affected by underground coal mining have been exposed numerous times to mining induced surface deformation. In the area of Upper Silesia, where the coal mining industry has existed for over a century, historical land development sustains damage on a regular basis primarily due to mining influences. Additionally, increasing the potential threat are bad technical condition and lack of adequate protection against mining induced deformation of the base. In majority of cases, even put in place structure protection suitable against mining influences might prove insufficient due to repeated exposure, which consequently causes surface deformation to progress [1].

In order to expand the knowledge on structure responses to time-varying deformation of the base and subsequently devise preventative measures, scientific research is being conducted. Measurements taken of base deformation and the buildings themselves give grounds for analyses. Measurements of surface deformations lie in the scope of responsibilities with which a mining company's measurement office is charged. Measurements of building deformation are rarely taken. Moreover, small number of measuring points usually renders impossible to carry out an in-depth analysis of structural behaviour. Hence, data provided, to the broad extent specified by measurement programmes is a particularly valuable scientific and utilitarian source of information.

Saint Wawrzyniec and Antoni's church is among buildings, which are enlisted for geodetic observations programme monitoring both the groundwork and the structure. Measurements are taken by the measurement department of "Pokój" Black Coal Mine. Because the building has been under extensive observation since 1972, 40 years worth of research material has been gathered. This paper presents an analysis of influences generated by mining the 133 longwall of the 413/2 seam from 2009 to 2010.

2. DESCRIPTION OF THE BUILDING

Saint Wawrzyniec and Antoni's church (Fig. 1) is located in Nowary St. in the Wirek district of Ruda Śląska. Its origins clock back to the beginning of the XX century. It was completed by 1909. The church is a typical for that period Neo-Gothic structure. It has three large-bodied naves, whose dimensions are approx. 66×60 m.

Frame construction of the church is given by pillars and buttresses, between which cross-rib vaults span. Sexpartite lierne vault is spanning over the presbytery. The main building material is brick, which almost entirely composes the supporting structure: pillars, vaults, buttresses and walls and the 50 metre high tower. The churches underpinning brickwork is made of sandstone. The building is a historical monument and remains on the register of the Historic Building Conservation Office for Ruda Śląska. The structure holds a so called *white paper*, which gives identification to architectural and building historical monuments [2].

In the seventies of the previous century the church's structure was fitted with protection to safeguard it from mining damage. It involved embracing the floor level with a reinforced concrete slab – so called Ledwon slab – and strengthening the floor with reinforced concrete tie-beams [3],[4]. Unfortunately, as the time passed the protective slab became perforated with considerable cracks (Fig. 2). Cracks provide a path of least resistance for transport of moisture, chlorides, and various other deleterious substances,

Figure 1.
Saint Wawrzyniec and Antoni's church in Ruda Slaska – Wirek. South-east view

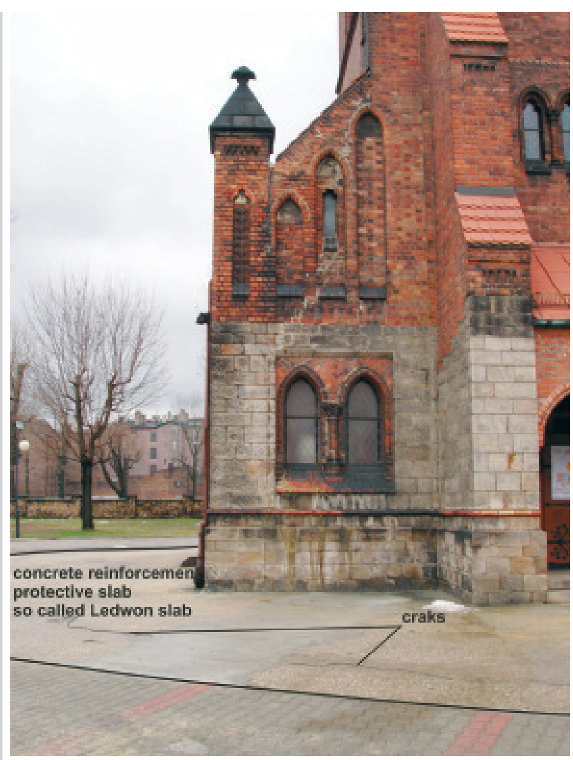

Figure 2.
Protective Ledwon slab attached the church

which may affect durability and structural performance. Cracks, reaching the depth of the steel reinforcement in reinforced concrete structures, allow rapid depassivation of reinforcement and corrosion initiation in some cases. [5]. Consequently the slab's reinforcement corroded and became damaged [6].

3. MINING HISTORY OF THE CHURCH'S AREA

According to the documents provided by Kompania Węglowa S.A., mining in the area of the 133 longwall has been going on since 1814. That year, coal extraction commenced 20-30 m deep at the 402 seam using the caving exploitation technique. Until 1966, coal was also extracted from 5 seams. The total combined thickness of the removed strata is approx. 17 m. Because surface deformation was not monitored at that time, there is no information how deep the subsidence was. In 1966 subsidence measurements started to be taken on a regular basis. From 1966 to 2010, coal was also extracted from 8 seams. Over that period a combined total of 19 m in removed strata was extracted, and confirmed subsidence reaches 14.5 m. Based on that information, the coefficient of excavation (subsidence factor) found in Budryk-Knothe theory equations [7], [8], [9] is $a = 0.76$ m. Having produced the a parameter, one can estimate the total mining induced subsidence in the Church's area. The total strata excavated since 1814 translates into an estimated 27 m plus subsidence.

4. MINING DESCRIPTION

Location of the 133 longwall of the 413/2 seam in relation to the Wirek district is illustrated in Fig. 3. The church building is situated above the corner of that longwall panel. The longitudinal axis of church's horizontal projection is sloping in relation to the extraction direction by approx. 52°. The 413/2 seam is located approx. H=450-460 m deep. The longwall is almost perfectly horizontal. Thickness of removed coal stratum g=2.1 m.

Extraction from the 133 longwall commenced in May 2009 and achieved an average extraction rate of approx. 5 m/day. Forecasted maximum subsidence according to the deformation forecast in "Mining activity plans for the period 2009-2011" [10] was w_{max}= 1.6 m. It is worth pointing out, that the 133 longwall is located above the 173 longwall of the 416 seam, which was excavated from 2004 to 2008. During the 173 longwall mining beneath the church, a protective pillar was left behind (see Fig. 3).

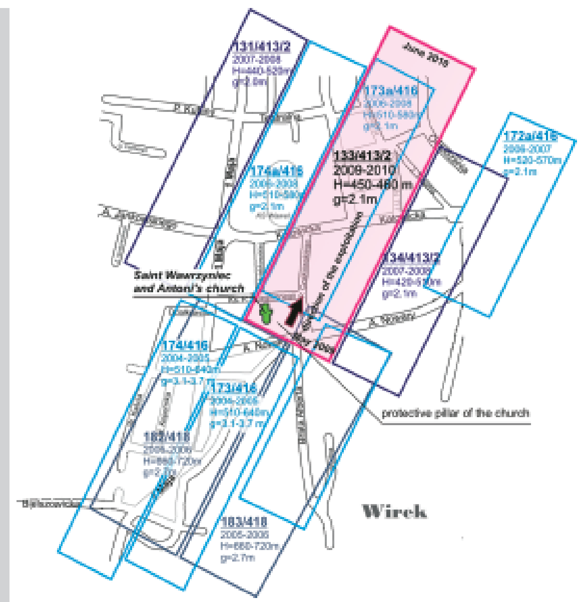

Figure 3.
The 133 longwall in relation to the saint Wawrzyniec and Antoni's church

5. IMPACT OF MINING ON THE CHURCH BUILDING

Mining influences buildings through extraction induced surface deformation. The saint Wawrzyniec and Antoni's church – as aforementioned – in 2009 became situated above the corner of the 133 longwall panel. Unfortunately, such location means permanent undulation and surface deformation, which are characteristic for mining basin's slope above the corner of a mining panel.

Using the Budryk-Knothe theory equations [8], which describe steady-state subsidence above a worked out panel of ds=dx·dy surface area as:

$$w(x,y) = \frac{w_{\max}}{R}\iint_{s}\exp\left(\frac{-\pi}{R^2}(x^2+y^2)\right)dxdy \qquad (1)$$

where:

w – subsidence of a surface point P (Fig. 4),

w_{max} – maximum final subsidence:

$$w_{max} = a \cdot g,$$

a – subsidence factor, its value depends on an established system of exploitation and from a method of filling the void,

g – thickness of excavated seam,

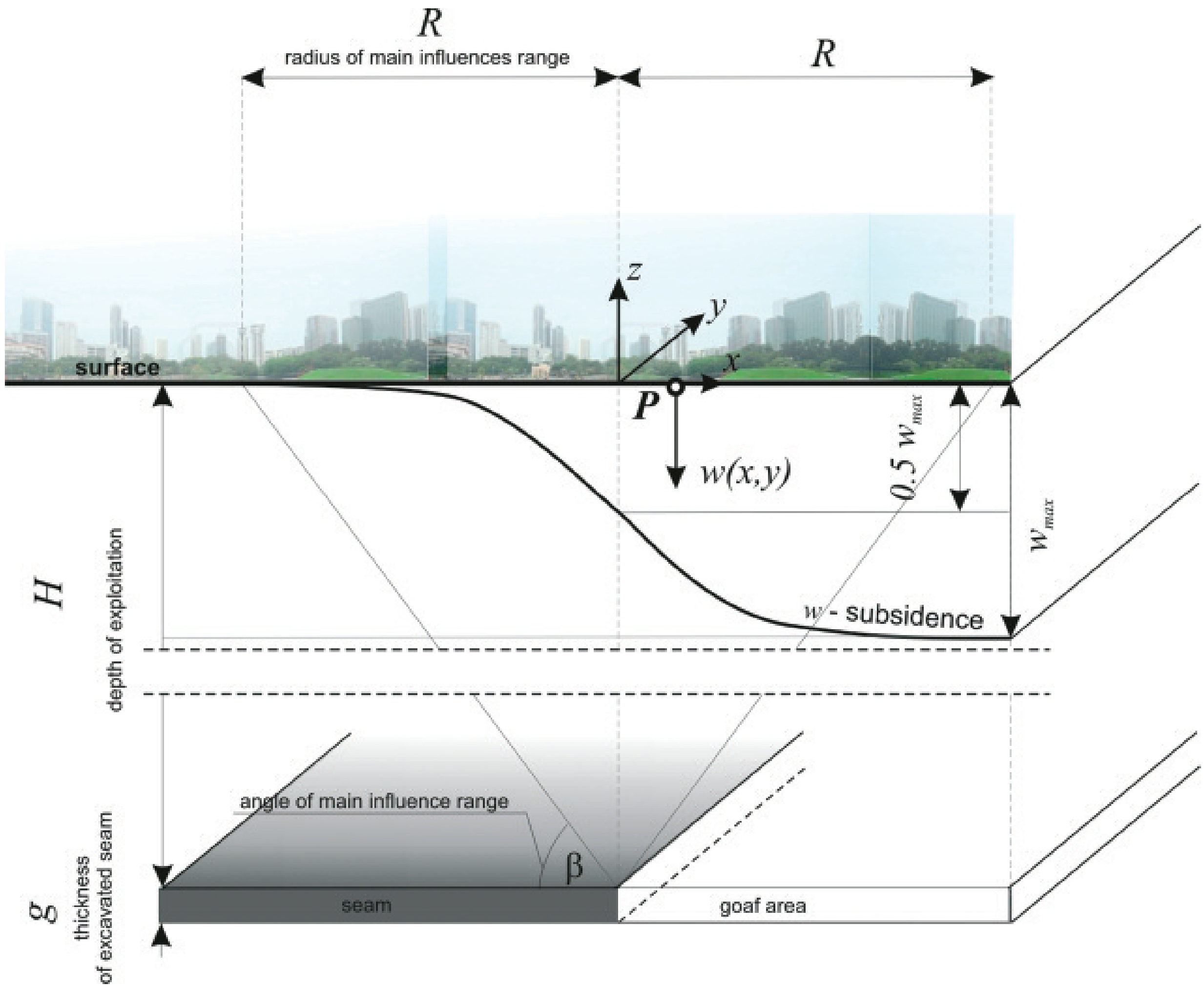

Figure 4.
Subsidence profile parameters above a single longwall panel according to Budryk-Knothe theory

R – radius of main influences range on the surface:

$$R = H \cdot tg\beta,$$

H – depth of exploitation,

β – angle of main influences range on the surface.

Shape of subsidence's surface was computed for the corner of the 133 longwall, which has been illustrated in Fig. 5. The theoretical linear surface strains across the longitudinal axis of the church building has been illustrated in Fig. 6. Fig. 7 shows how the subsidence evolved over time. It was computed using the rate determined in accordance with the Budryk-Knothe theory [7], [8], [9].

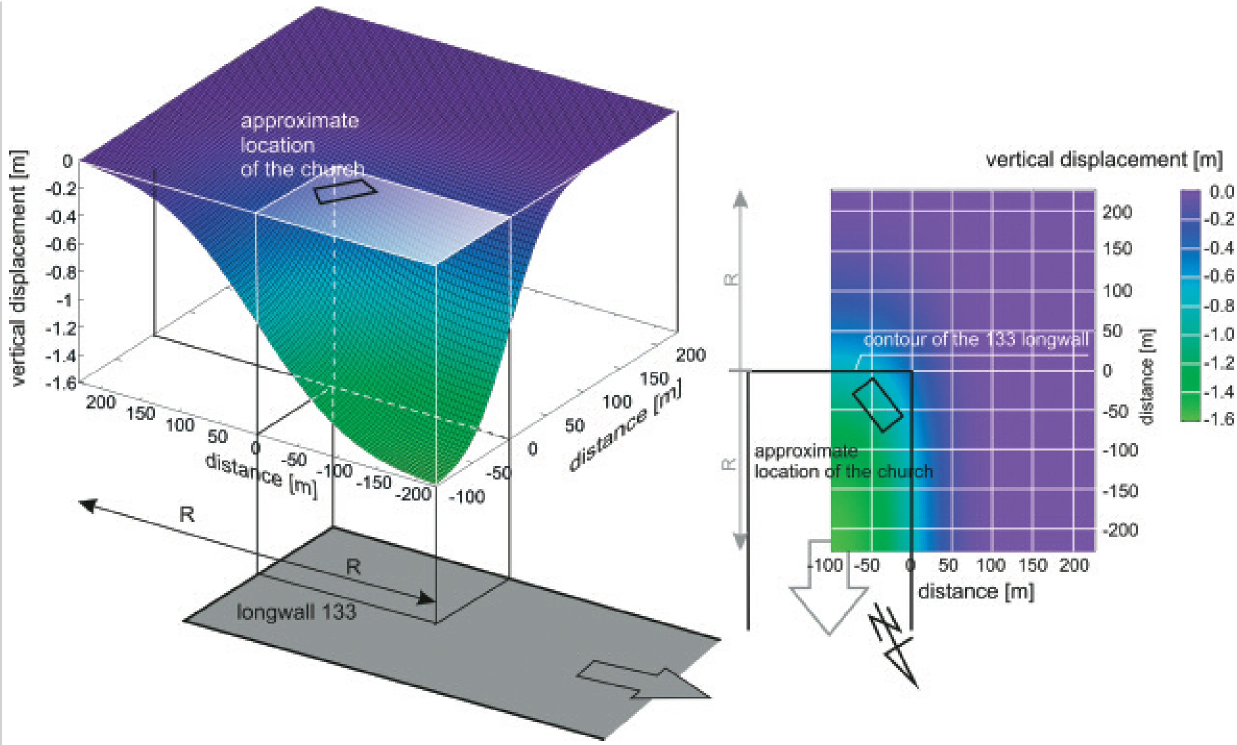

Figure 5.
Theoretical surface area of steady-state subsidence above the corner of the 133 longwall

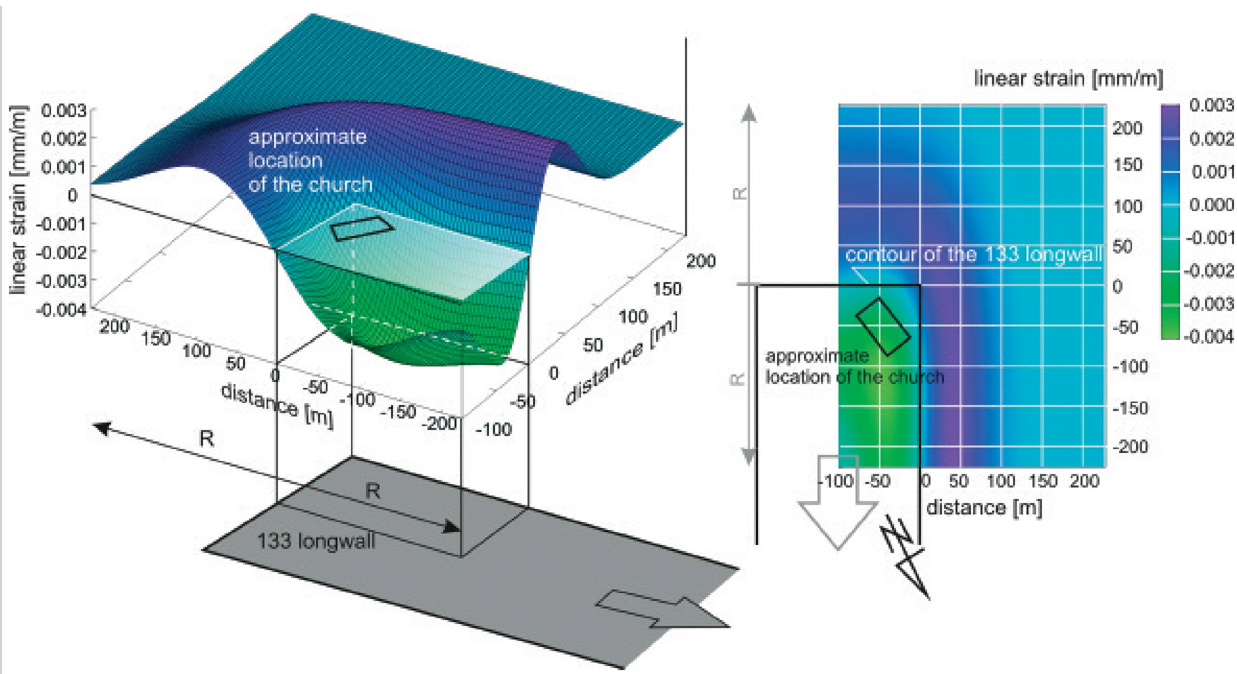

Figure 6.
Theoretical surface area of steady-state linear strain across the church's longitudinal axis

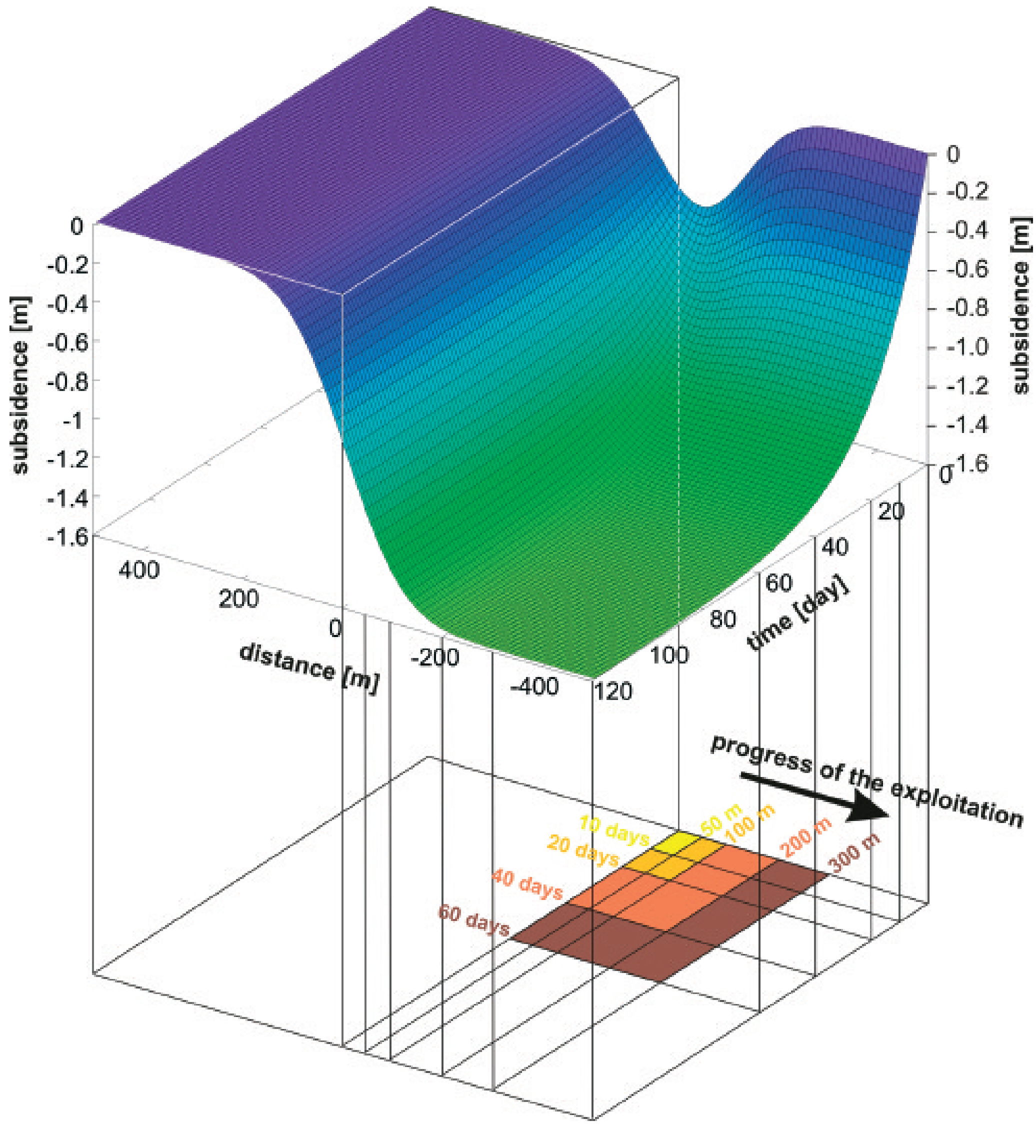

Figure 7.
The time course of subsidence

6. MEASUREMENTS

The real building's reaction to longwall mining is possible to be investigated by analysing geodetic measurements, relying on a system of measuring points. Benchmarks were fitted to the church's structure (inside of the church in the pillars and outside of the church in the walls), the protective slab (on the inner contour and on the outer contour) and the groundwork beyond the slab. Distribution of benchmarks has been illustrated in Fig. 8. In order to determine linear strains between selected points, distance measuring equipment was fitted. The measurement base lines used for the church's inside has been illustrated in Fig. 9. The strains are measured as a change of the distance between the measuring points (benchmarks).

Figures 10, 11 and 12 illustrate measurements taken of subsiding, computed with respect to reference elevations dating back to January of 2009 – before mining begun.

Fig. 10 shows charts of subsiding registered by benchmarks near the longitudinal axis of church's projection. The variable subsidence rate is clearly visible on the chart depicting the subsidence process over the time.

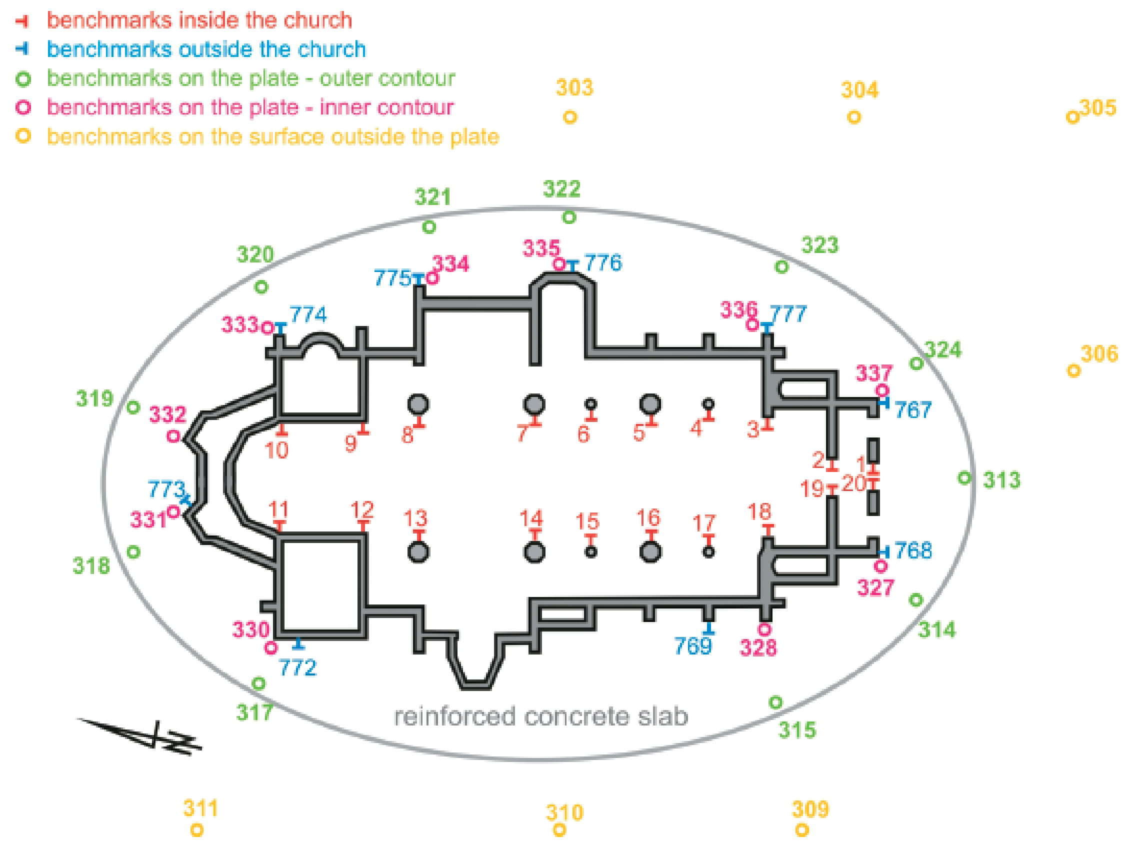

Figure 8.
Distribution of measuring points

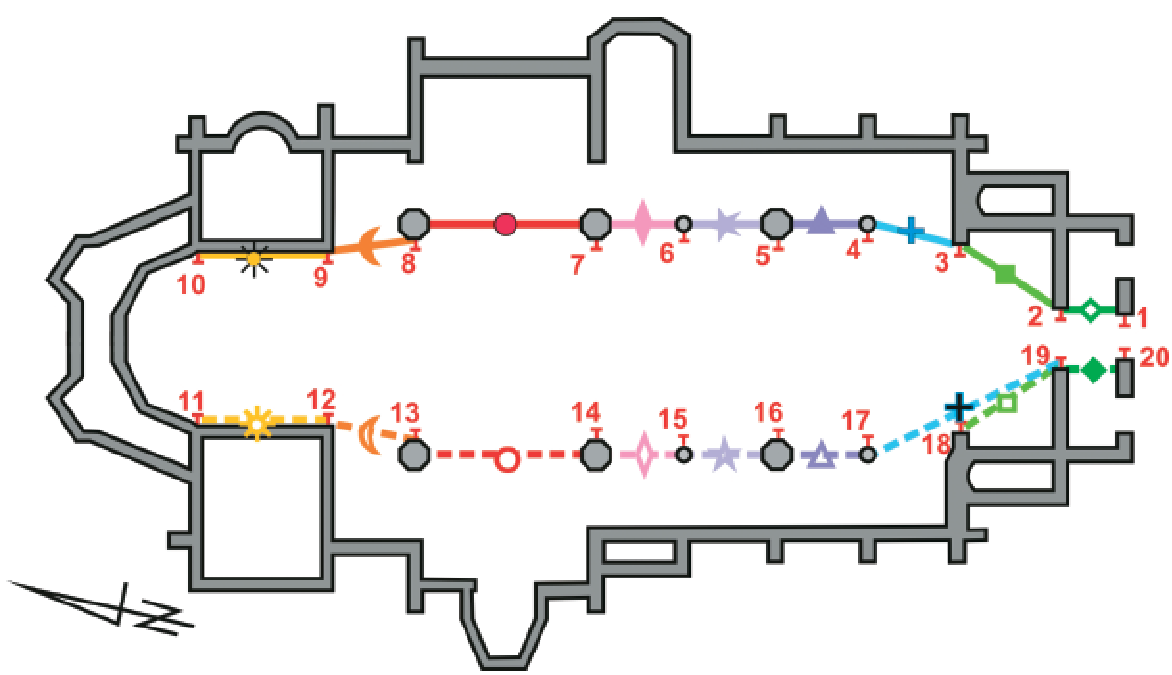

Figure 9.
Baselines for geodetic measurements of distance, fitted to the church's inside structure

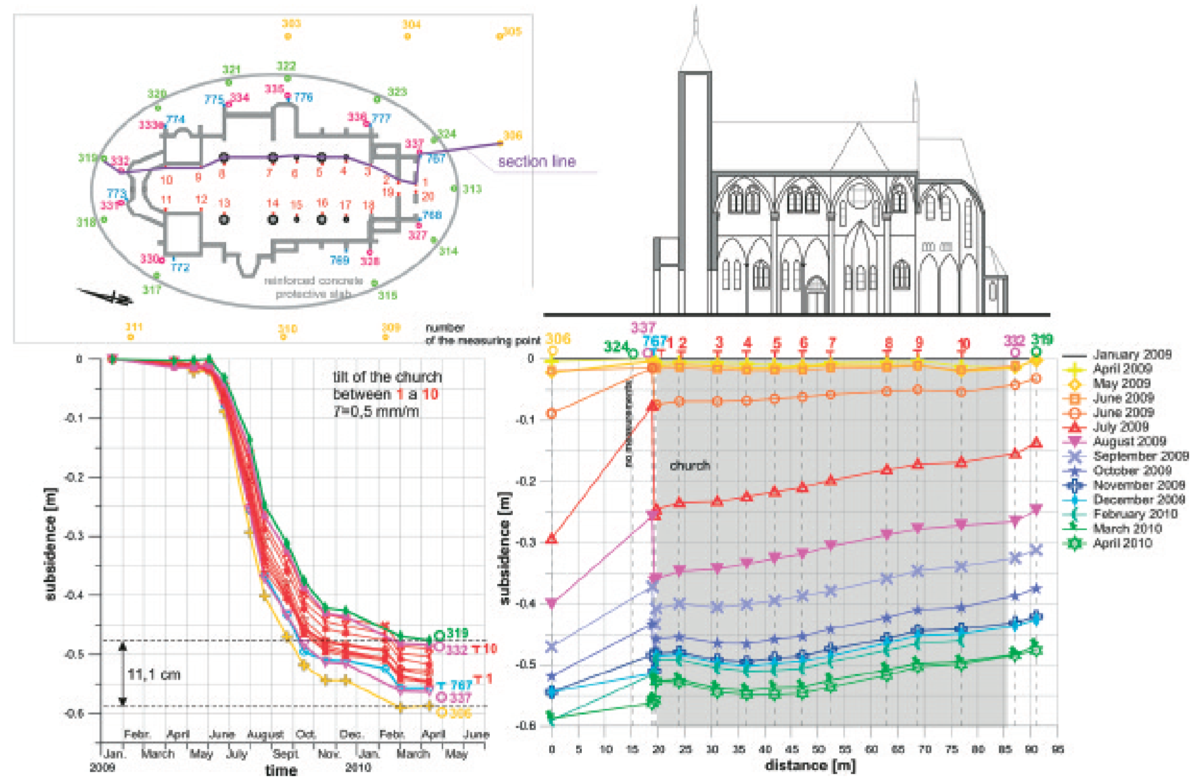

Figure 10.
Subsidence measurements for the 306-319 cross-section

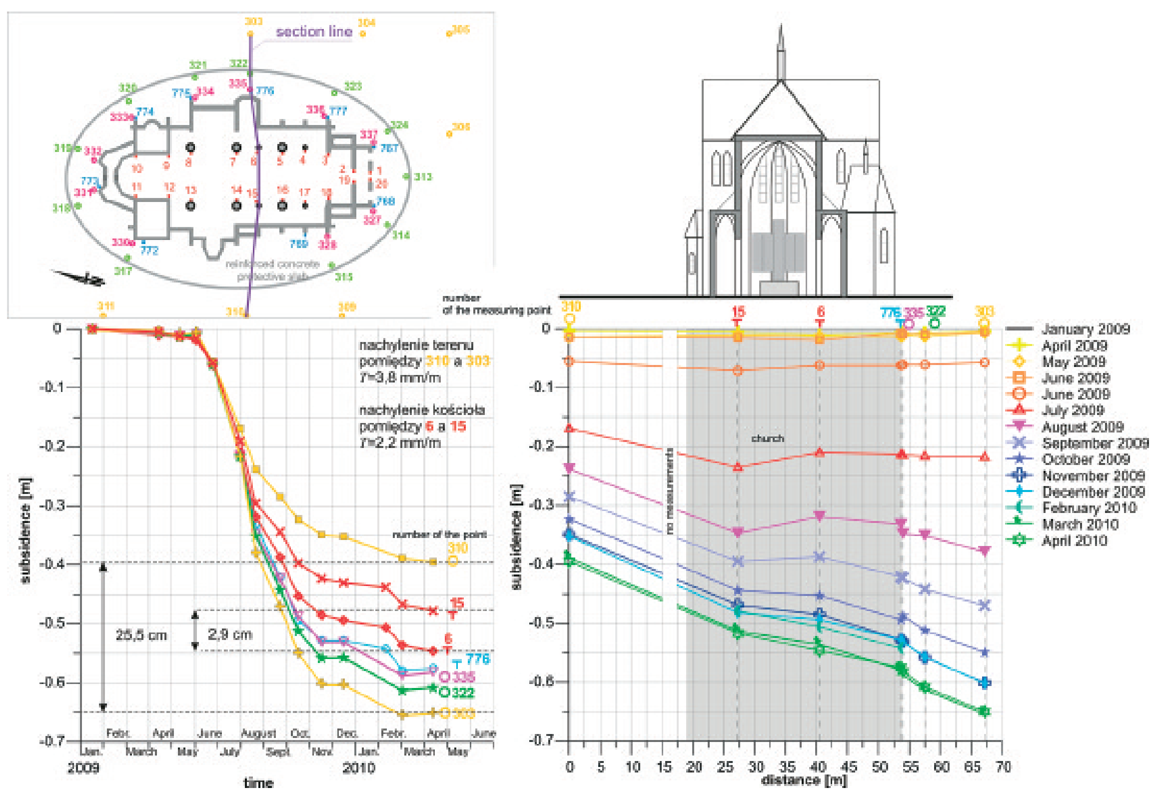

Figure 11.
Subsidence measurements for the 310-303 cross-section

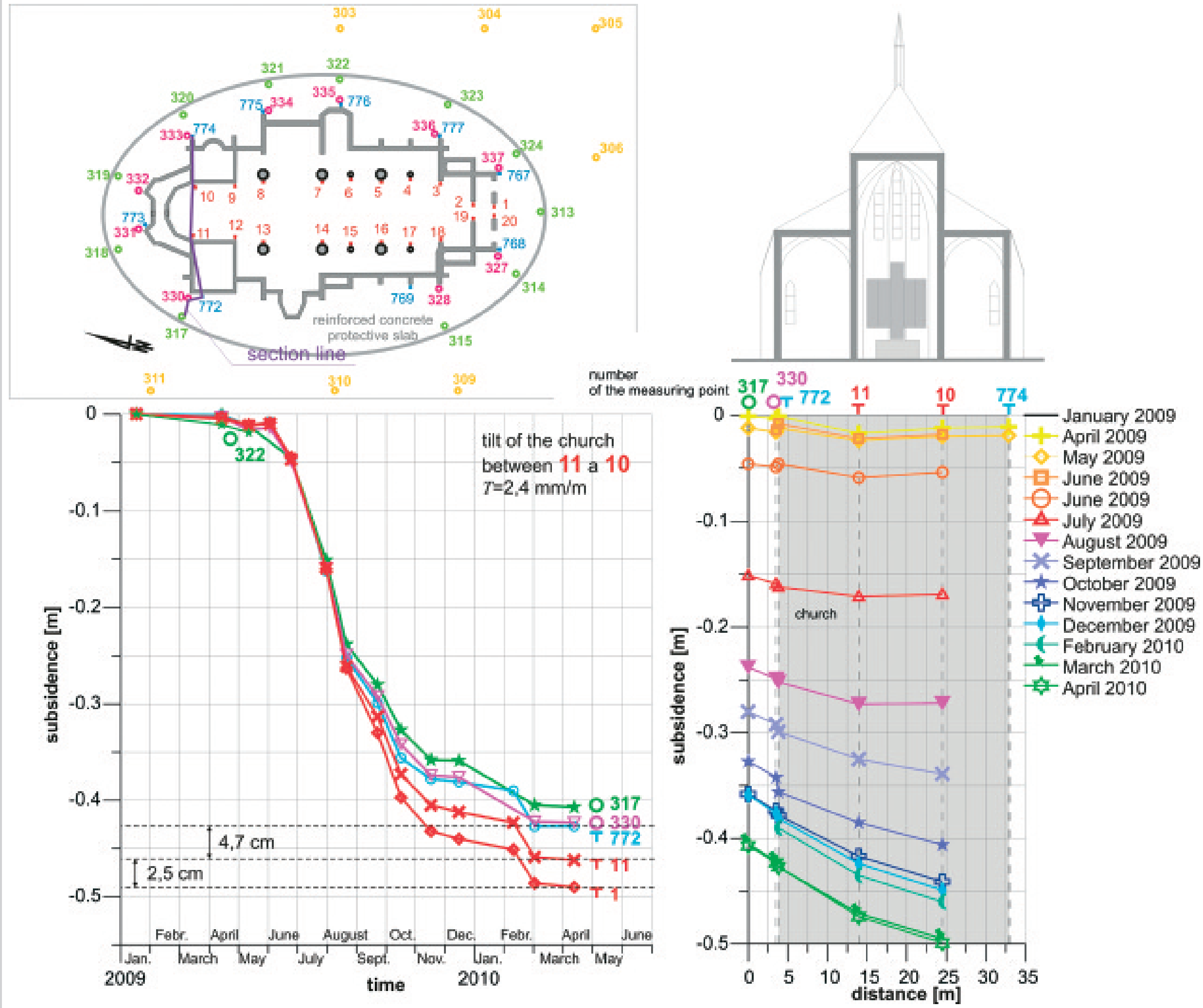

Figure 12.
Subsidence measurements for the 317-774 cross-section

It is an effect of progressing coal exploitation and advancing longwall face. The aforementioned mining of the 133 longwall started in May 2009. Because the building is situated in close proximity to the longwall's edge, mining influences were registered shortly after it had begun. June 2009 was marked by the highest increase in subsidence on record, and exceeded 0.20 m/month and 0.17 m/month for the surface and the church respectively. By then the longwall had already advanced 188 m (June 2009). Starting from September a significant slowdown of increase in subsidence is visible. At that time, the longwall face was within 200 m of the church, thus the reach of main mining influences was already shifting outside the area in question. Measurement taken in March and April of 2010 showed the subsidence process stabilising. On average, the subsidence was determined to be 0.50 m.

Subsidence over time illustrated in Fig. 10 also carries data on increasing differences in subsidence at individual measuring points. It is indicative of the building's longitudinal axis leaning south. The final tilt of the church between the 1-10 benchmarks is 0.5 mm/m (The tilt is expressed as a ratio. It is the vertical distance between two benchmarks divided by the horizontal distance between these two points). The plot of subsidence against distance also reveals, that the body of the church is not uniformly tilted. A certain curvature has appeared – downwards convex – in the church's main nave. Structural behaviour of the tower and the presbytery differ from how the main nave behaves.

Fig. 11 illustrates the subsiding process of benchmarks arranged perpendicularly to the building's lon-

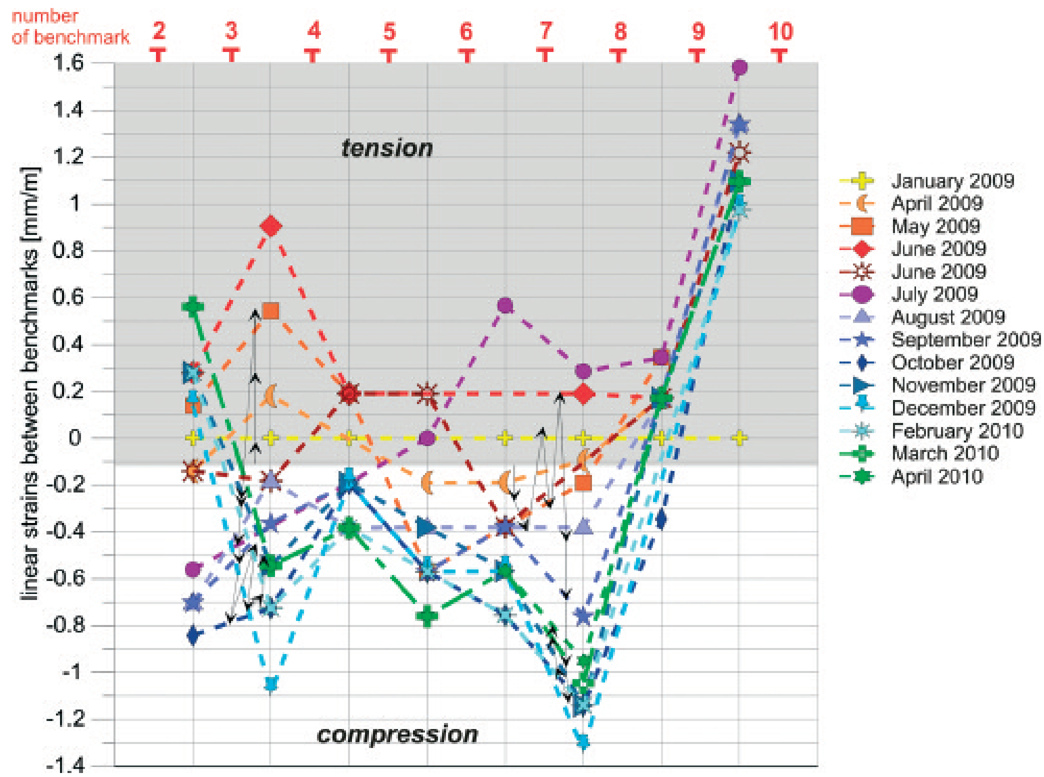

Figure 13.
Linear strain between measuring points over time

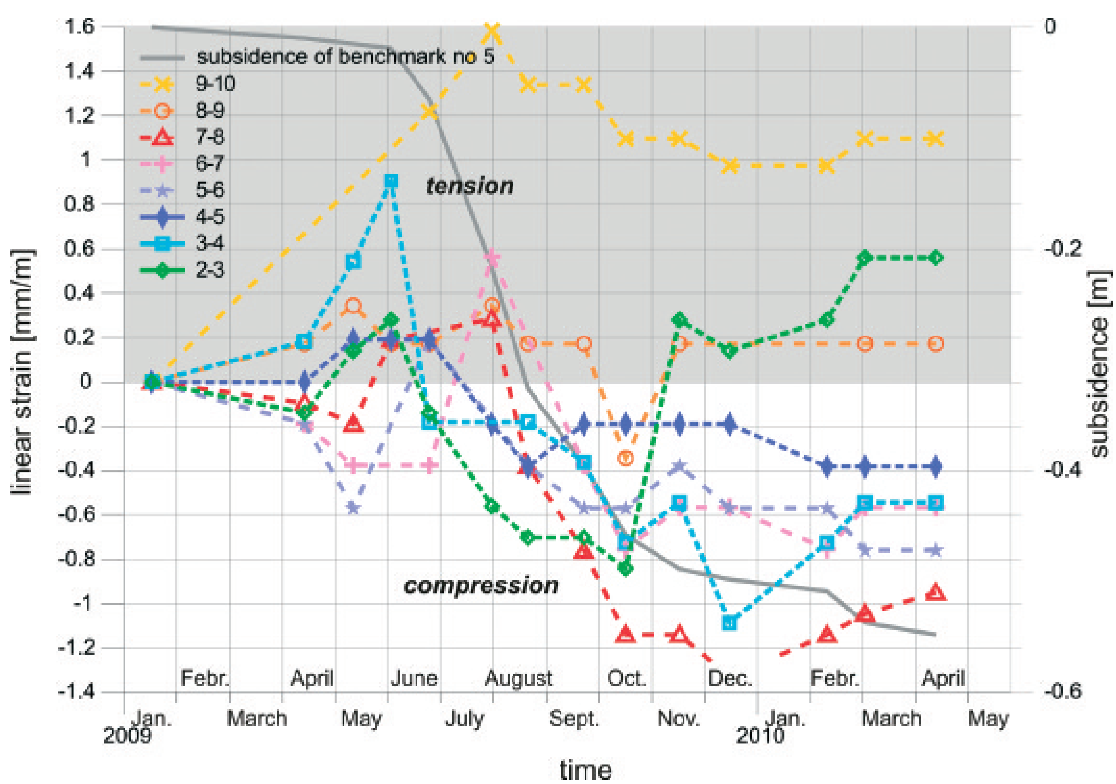

Figure 14.
Linear strain over time between measuring points located along the building's longitudinal axis

Figure 15.
Cracked protective plate and church's exterior wall

gitudinal axis. Consequently those points created a cross-section. Within it, the highest subsidence differences were measured. They were:

- surface (between points 303-310) – 0.25 m,
- church (between points 15-6) – 0.03 cm.

Thus, the surface gradient between point 303-310 was 3.8 mm/m, whereas the body of the church has permanently tilted east between points 6-15 by 2.2 mm/m. Plot of the "subsidence – distance" relation illustrates how the body of the building leaned concurrently with advancing longwall face. Initially, the body tilted slightly west (July, August and September 2009). Then the building straightened up and once the longwall face came past it, started to lean east. The highest subsidence of 65 cm was registered at the 303 point.

Fig. 12 presents corresponding subsidence charts for the points creating the cross-section passing through the presbytery. Similar tilt of the body of the church was registered in that cross-section. Between points 10-11 it was 2.5 mm/m.

Figures 13 and 14 illustrate strains measurements taken from baselines located between benchmarks inside the church (see Fig. 9). Figure 12 reveals how

Figure 16.
Damage to church's exterior walls

strains between main nave pillars shifted from small positive reactions towards the negative reactions. By comparing it with chart No. 10 it is evident, that negative strains appearing within the main nave is related to the curvature which has appeared in that area and started to generate compressive stress. Positive strains between benchmarks 9-10 confirm, the sector where the presbytery is behaves differently. Strains over time illustrated in Fig. 13 indicate that 9-10 strains line differs from measurements taken at other baselines.

7. SUMMARY

Discussed results of geodetic observations enable to study thoroughly how the building reacted to mining of the 133 longwall and to compare measured subsiding and linear strain to theoretical steady-state surface deformation. Location of the body of the building is – as mentioned before – disadvantageous due to the nature of permanent deformations related to the shape of surface above the corner of the longwall panel. Theoretically determined steady-state subsidence and strains illustrate the distributions and the values of these quantities. Charts in figures 5 and 6 show that subsidence near the church is theoretically 70-90 cm, whereas linear strain across the church's longitudinal axis is between 1÷2 mm/m.

Geodetic observations revealed lower than theoretically forecasted surface subsidence. The deepest subsidence of 65 cm was recorded at point 303 (on the surface). Generally speaking, uniformly distributed subsidence poses no threat to the structure. In case of the church, however, subsidence was recognised as uneven. In the longitudinal axis of the church the curvature appeared, which could induce a negative strain (Fig. 10) generally. Whereas in the transverse axis a curvature was observed, which could cause the positive strain (Fig. 11). Positive strain reached the value of 1.6 mm/m in the presbytery – between points 9-10 (Fig. 13-14). As commonly known, the concept of static behaviour of brick cross-rib vaults is based on assumption, that an entire given structure is loaded with compression only [11]. Hence, any tensile stress is highly dangerous and poses a serious threat to the entire structure.

Moreover, permanent surface gradient related to the shape of subsiding trough in the corner of the longwall panel is another negative factor [12]. By analysing charts in figures 10-12 a conclusion can be drawn, that permanent tilt of the building alone is less than surface gradient (e.g. between points 303-310). This has probably to do with the protection provided by the reinforced concrete slab surrounding the church.

Despite protection against mining damage, due to mining influences the building sustained damage and became deformed. Already before mining of the 133 longwall commenced, the church's protective slab became damaged to a certain extent. Fig. 15 i 16 shows damage in the church's exterior walls.

To summarise, the discussed and analysed computational results and measurements prove, that in spite of relatively insignificant deformation caused by mining the 133 longwall on its own, its influences have taken their toll on the building in question. There are seemingly two reasons to justify such state of affairs. On the one hand this is a result of multiple mining influences, the building has been subject to over its entire history. Moreover, the building has remained within the permanent deformations zone, related to its location relative to the mining panel.

In 2010, after finishing of excavation of 133 longwall, the building underwent a heavy repair, which involved fixing all damage and renovation. There are no mining plans in the foreseeable future for the area.

ACKNOWLEDGMENTS

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