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Knowledge is a value.
Implementation of knowledge is power.
[anonymous]

Application of generalized function of time in preventive measures undertaken in mining on account of the protection of civil structures

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Abstract

The article presents the application of the Knothe-Budryk theory as a tool for the prediction of surface deformation and as a preventive measure in mining, using the example of the exploitation of longwall no. 6 in seam 503 and as measurement verification of the estimation of subsidence formation speed. In particular, the generalized function of time was utilised, which is an expansion of the Knothe function of time and which is analogous to the drift function of rheological models. The relation of subsidence speed determined a posteriori, which confirmed the connection between the speed of subsidence formation and the rate of longwall face advance and the *k* coefficient, which is equal to the maximum slope of an unsteady trough.

Keywords: underground mining exploatation, surface deformations, time function, method, prediction, geodetic measurements

1. Introduction

The Knothe-Budryk theory is a physical theory, which consists in adequately interpreted mathematical structures. The conformity of the obtained theoretical predictions with experimental results is a consequence of the fact that the mathematical structures enable the calculation of some of the coefficients, based on the proper interpretation of the given structure, and the comparison of them with the results of the measurements.

This article refers to mathematical structure, which is the Knothe function of time (Knothe, 1953b) which provided inspiration for the authors to describe unsteady (time-dependent) surface deformations over an advancing longwall face (Gruchlik, 2003; Kowalski, 2007).

The formulas of the Knothe-Budryk theory and of the generalized function of time have been utilized for designing preventive measures in mining, covering the determination of the speed of longwall face no. 6 in seam 503, advancing under the church building in Bytom-Miechowice. This article presents the effects of the applied mining preventive measures, i.e. the results of deformation measurements and the speed of subsidence formation.

A number of expert surveys conducted by the consortium of the Central Mining Institute (GIG) with the Building Research Institute (ITB), Silesian Branch, in the years 2016-2017 (Kawulok et al., 2017) have formed the basis for this article.

The objective of this article is to present the application of a theory as a tool for predicting surface deformation and taking mining preventive measures using the example of longwall no. 6 exploitation in seam 503 and the measurement verification of the estimation of subsidence formation speed.

2. Theoretical background

2.1. Knothe-Budryk theory

The original model of the Knothe-Budryk theory concerns *asymptotic* deformations[1] and assumes the existence of the so called impact function, determining the distribution of subsidence caused by *elementary*[2] exploitation versus the horizontal distance of the point object from the subsidence (Knothe, 1953a, 1984). Subsidence resulting from the exploitation of a mining panel with finite dimensions is a sum (integral) of all subsidences caused by all elementary exploitation works in the panel (Kowalski, 2015). Horizontal displacements are described based on additional assumptions denoting their mutual relations with subsidence (Budryk, 1953). The form of the impact function, as given by S. Knothe, has been assumed after analysing numerous profiles of real subsidence troughs (Knothe, 1953a). Normal distribution, Gaussian curve is the form of this function. The form of this function is also a particular solution of the Litwiniszyn general theory (Knothe, 1993).

2.2. Generalized function of time

The unsteady deformations are arrived at based on the following equation determining the speed of subsidence (Knothe, 1953b):

$$\frac{dw(t)}{dt} = c\left[w_k(t) - w(t)\right] \tag{1}$$

where:

- c – constant coefficient of proportionality called the time coefficient, independent of time, describes the speed of deformations' transition through rock masses,
- $w_k(t)$ – steady subsidence (asymptotic) caused by the exploitation of a panel with a shape at moment t,
- $w(t)$ – depression of the point in moment t,
- t – time measured from the commencement of the exploitation.

In a theoretical case, the immediate exploitation of a part of a seam, i.e. when $w_k(t) = w_k$ = const, the solution of equation (1) for the initial value $w(0) = 0$ takes the form:

$$w(t) = w_k\left(1 - e^{-ct}\right) \tag{2}$$

The other factor in formula (2) is the Knothe function of time, which takes the form:

$$T(t) = 1 - e^{-ct} \tag{3}$$

Function (3) was devised when mining production was carried out by means of slowly advancing longwall faces, up to 2.5 m/day, most often in rock masses which had never been mined before (virgin rock masses), and when deformation measurements which were performed in time intervals much longer than one day, every three or six months, were available, which was of prior importance.

The surface subsidence measurements carried out over the last twenty five years, with one day or even a few hour intervals, enabled the generalization of function (3) (Kowalski, 2007, 2015):

$$T(t) = \Theta(t) \cdot q(t) \tag{4}$$

where the principal function of time Θ takes the form:

$$\Theta(t) = 1 - \sum_{i=1}^{n} A_i \exp\left[-c_i t\right] \tag{5}$$

[1] determined after sufficiently long time, called also steady or ultimate.
[2] of infinitesimal volume.

and the adjunctive function q is denoted by the formula:

$$q(t) = \begin{cases} 0 & \text{for } t < 0 \\ 1 & \text{for } t \leq 0 \end{cases} \tag{6}$$

where:

- t – time from the moment of mining of an element of the seam,
- A_i, c_i – parameters of equation,
- c_i – time coefficient of i-th exponential component,
- n – number of exponential components,
- $0 < A_i \leq 1$ – participation of i-th component A_i of elementary exploitation with the time coefficient c_i.

So that the function $\Theta(t)$ does not have a minus value, the A_i factors must satisfy the following restriction:

$$A = \sum_{i=1}^{n} A_i \leq 1 \tag{7}$$

The generalized function of time (4) is an expansion of the Knothe function of time and is analogous to the drift function of rheological models (Gruchlik, 2003; Kwiatek, 2007), when:

- $A_1 = 1$, $A_2 = 0$, $c_1 = c$, then parameter c is the only parameter; this is the Knothe function (3)-(Kelvin model),
- $A_1 = A$, $A_2 = 0$, $c_1 = c$, then there are two parameters A and c (Zener model),
- $n = 2$, parameters are $A = A_2 < 1$, c_1 and c_2, where $A_1 = 1 - A_2$;
  in this model's case the principal function of time Θ has the form (two-element, serial Kelvin model):

$$\Theta(t) = 1 - A_1 \exp(-c_1 t) - A_2 \exp(-c_2 t) \tag{8}$$

- $A_i = 0$ or $c_i = \infty$, $T(t) = 1$, function of immediate interactions.

The shape of the generalized function of time (growth of standardised subsidence) for two types of rock mass is shown in Figure 1.

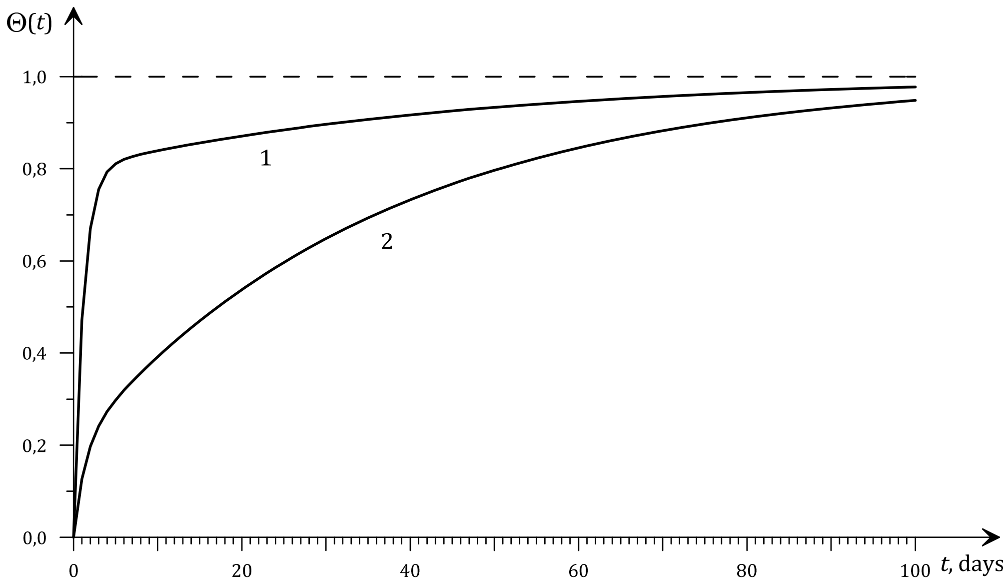

Fig. 1. Diagram of the two-element function of time (8) for two types of Carboniferous rockmasses
1 – weak, 2 – solid (Kowalski, 2007)

It is evident that in the case of weak rock masses, a substantial part of deformations (approximately 80%) appears within a few days of the commencement of mining work, in solid rock masses around 30%

of final deformations develop in the same time, Figure 1. The classification of Carboniferous rock masses into two types was carried out according to the following scheme:

- solid rock masses are rock masses which contain more sandstones than siltstones or where thick sandstone benches occur,
- weak rock masses are rock masses which contain more siltstones than sandstones or where multi-layered siltstones occur as well as rock masses which have already been mined multiple times.

3. Mining and geological conditions

One of the regions, where the Knothe-Budryk theory formulas and the generalized function of time (8) have been applied for the purpose of the design of coal exploitation and the undertaking of preventive measures in mining in the years 2016-2017 is the protecting pillar in the Miechowice district in Bytom. Within this area the monumental building of the Church of the Holy Cross is located (Picture 1).

Pic. 1. View of the portal and tower of the Church of the Holy Cross in Bytom-Miechowice from the Western side (*pic. P. Gruchlik*)

The protecting pillar of the district has been delimited for category III mining area indices, where several hard coal seams are deposited in Ruda layers as well as in anticline layers, beneath the strata of ore-bearing dolomites in the Triassic. Before 1965 coal mining was carried out in this district mainly in upper Ruda seams, whereas after 1965 lower Ruda seams as well as anticline seams were also mined. In total, 11 layers were mined with roof caving.

The subject of the article is the mining of another layer in seam 503 by means of longwall panel no. 5 and 6 with roof caving; longwall no. 6 advanced under the church building, in figure 2 on the left.

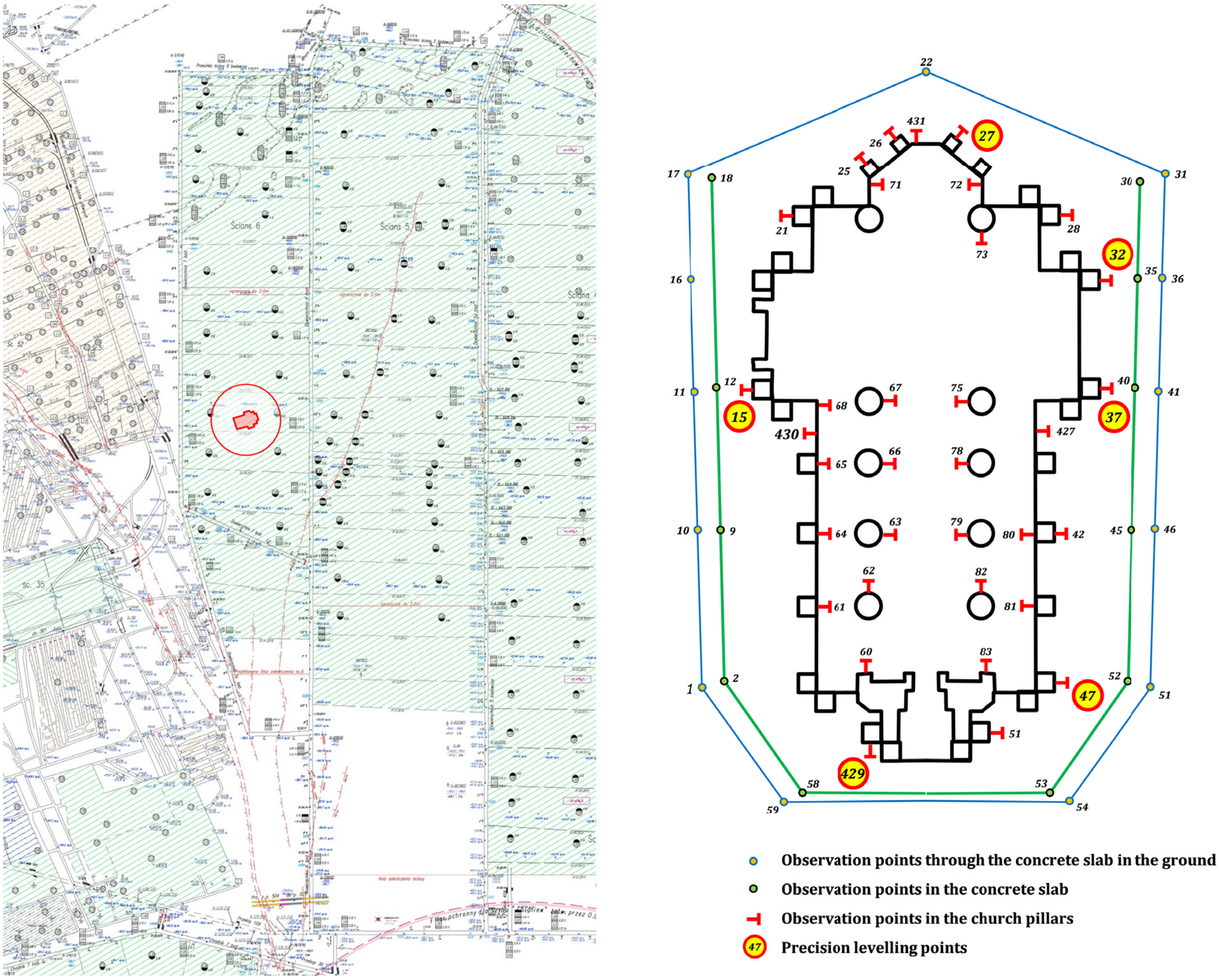

Fig. 2. Left: longwall mining –longwall faces 5 and 6 in seam 503 in the area of the church at the end of 2017, right: mining survey grid for deformation study

Longwall no. 5 was put in to operation in March, and longwall no. 6 in August 2016. In order to minimize the deformation of the surface in the area of the church, the height of the seam layer in longwalls 5 and 6 was limited to 2.0 m. The depth of mining was $H = 680$ m.

The original mining plans assumed a restraint, halting the operation of longwall no. 6 100 m before the church building in order to protect it. Earlier the church was repeatedly subjected to the effects of mining, through the impact of vertical concave curvatures and horizontal deformations of a compressive nature.

Taking into consideration the repair work and the reinforcement of the church building, as well as the existing protective measures (the so called Ledwoń band – a rigid plate strengthening the foundations, visible in Figure 2, as well as steel beams at the level of the foundations and skewbacks (Kawulok et al., 2017) the range of longwall 6 exploitation was adjusted to increase the length of its run.

The basic restriction of longwall 6 operation, in light of the protection of the church, was the reduction of the speed of longwall panel advance to 2.0 m/day and its operation in a quasi-continuous manner in its run from 10 0 m before the church to approximately 100 m beyond the church contour, wherein the latter boundary was to be confirmed by measuring the subsidence speed. The quasi-continuous longwall advance was attained by operating the longwall during shifts 1 and 3 or 2 and 4 for every day of the week, by dividing daily face advance into 4 shifts.

The speed of the advance of longwall 6 was determined by means of successive trials, considering the varying daily longwall face advances and the assumption that the effects are manifested almost immediately (8) as well as the criterion that the maximum speed of subsidence formation does not exceed 7.5 mm/day, which corresponds to the daily subsidence of category II mining areas (Knothe and team, 1997). The determined maximum speed of daily subsidence in the case of longwall 6 amounted to 7.2 mm/day, figure 3. In case of category III mining areas, the daily subsidence is 15 mm/day.

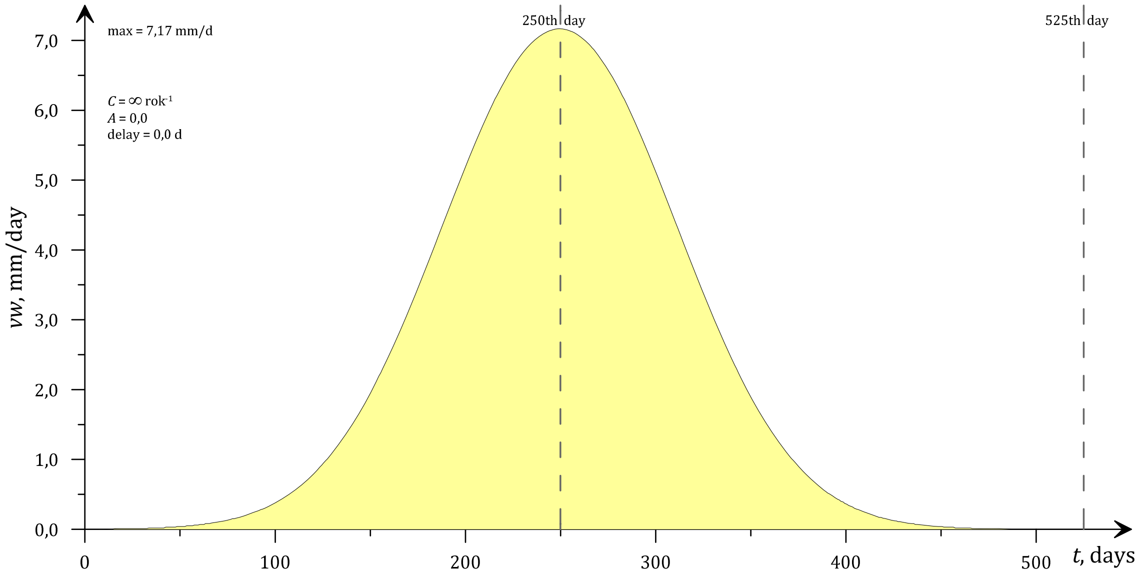

Fig. 3. Daily growth of subsidence, determined on the assumption of the immediate manifestation of effects

Considering fire and bump hazards, the limitation of the speed of advance of longwall 6 was not favourable. Due to the rock burst hazard it was recommended that longwall 6 should follow closely the face of longwall 5, both of which in their final run would reach the bottom of the Bytom Basin. Thus, research was done in order to define the boundary (date or distance from the church) from where the speed of the face advance could be increased to 3.0 m/day. The mine survey measurement of the speed of the church building's subsidence growth was carried to determine the speed of advance.

4. Results of subsidence measurement against the function of time and analysis

Beside scheduled measurements of surface deformations within the district area as well as of the church building's deformations since April 2017, the church was additionally monitored, initially through daily observation. The technical levelling of changes to the height of the benchmarks on the church building was carried out (Fig. 2, right). In addition weekly inspections of the building took place.

Results of the measurements of the speed of subsidence for points 27 and 15 are presented in Figure 4 and they show results with the application of technical levelling at one-day intervals and precise levelling at one week intervals on average.

On 25.07.2017 when longwall 6 face was under the centre of the church, the total subsidence caused by longwalls 5 and 6 amounted from 0.455 m to 0.672 m, which constituted an average of 33% of the final subsidence (1.55 m), the speed of subsidence amounted to 4 mm per day on average.

Due to mining being carried out in a steady manner, i.e. with a quasi-constant speed, the demonstrated surge of daily subsidence with the application of technical levelling was questionable. This was probably the result of measurement error due to distant reference, as the estimated mean error of technical levelling was 9.6 mm. The estimated mean deviation of fluctuation against the speed of subsidence growth, determined by means of precise levelling, amounted to 3.7 mm/day.

Taking the above into consideration, successive measurements were done entirely using the precise levelling method in 3-4 day intervals. The measured subsidence of all 6 points on the church building, as well as the average value, is shown in figure 5, and figure 6 presents the speed of their growth and the mean value.

At the end of 2017, the total measured church building subsidence amounted to 1.110 m to 1.719 m, which on average constituted 92% of the predicted final subsidence, visible in Figure 5. The graphs of the speed of the subsidence of points presented in Figure 6 prove that the maximum speed of subsidence varied between 7.5 and 13.0 mm/day with an average of 10.5 mm/day. Maximum speed values occurred on the 58th day, when the longwall face was beyond the centre of the church building, which corresponds to the distance of 116 m (0.17 *H*). After this date the speed of longwall 6 face advance increased.

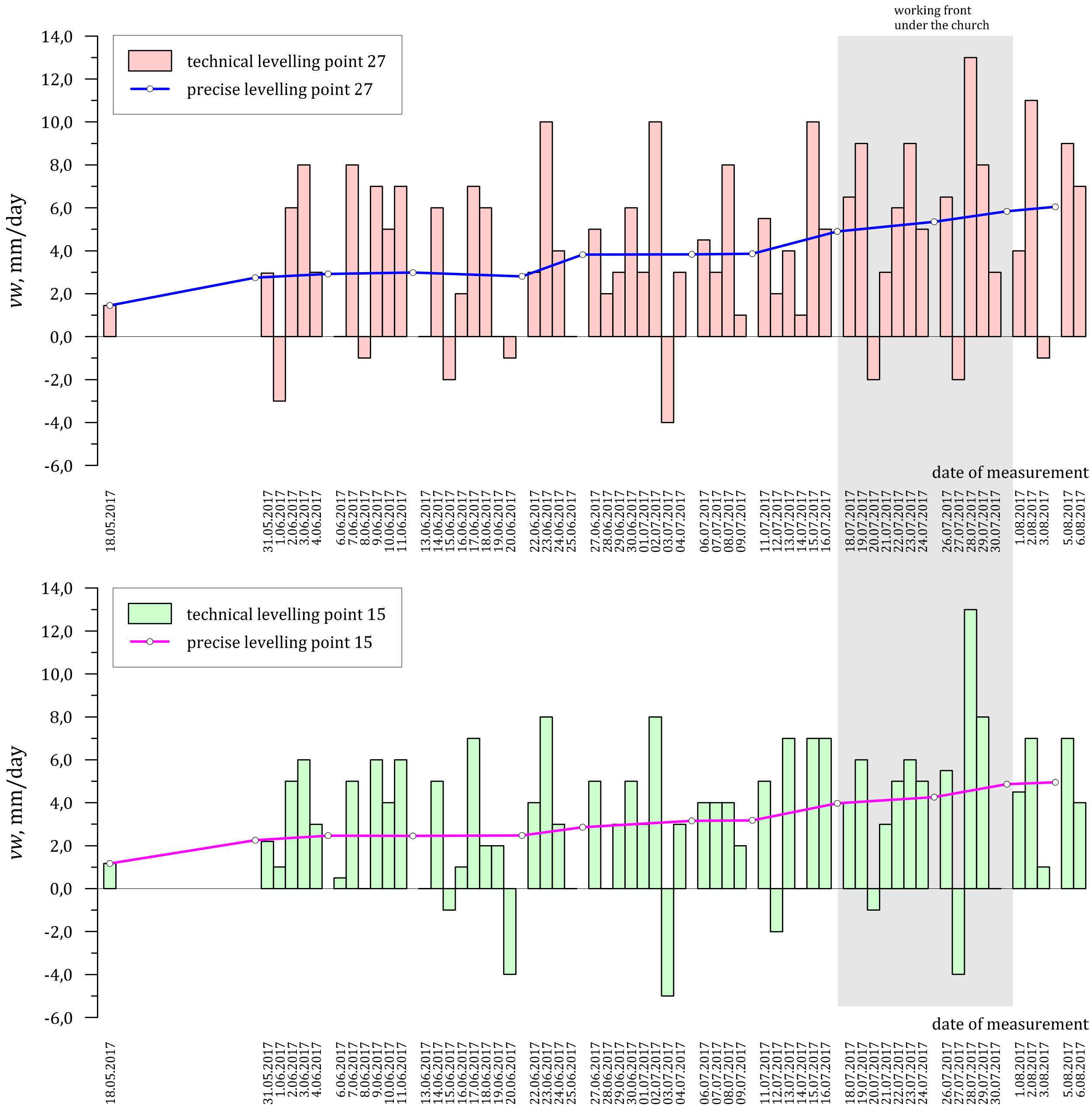

Fig. 4. Speed of the subsidence at points 15 and 27 on the church determined by means of technical levelling and precise levelling

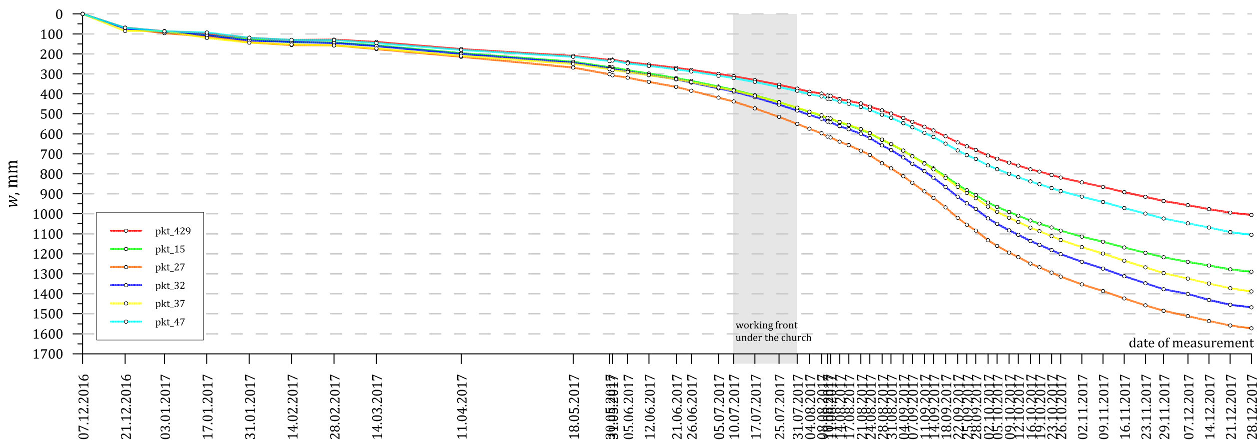

Fig. 5. Subsidence of points on the church over time

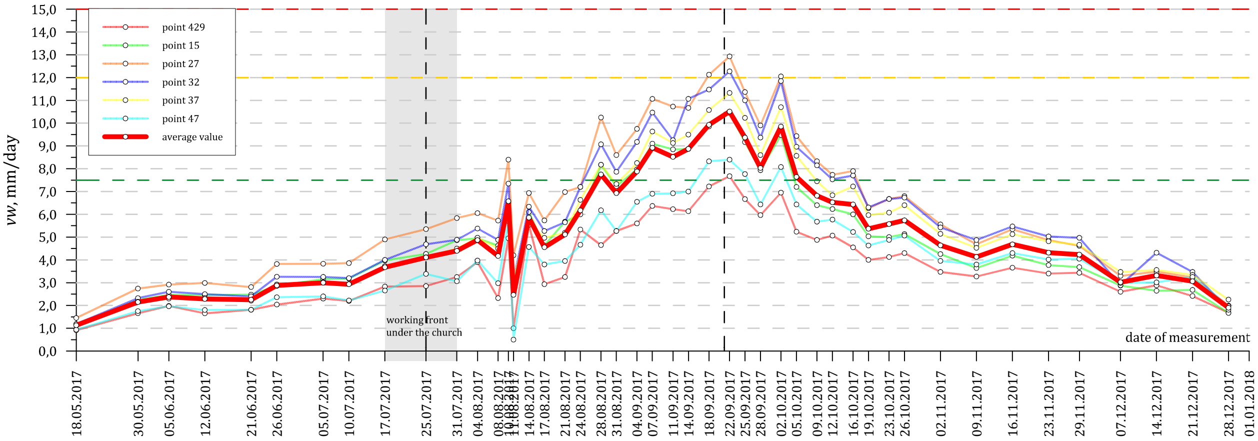

Fig. 6. Speed of subsidence of points on the church over time, determined by means of precise levelling

In Figure 6, the horizontal broken lines marked in green correspond with the predicted maximum speed of subsidence (7.5 mm/day), the lines marked in orange correspond with the tolerated 12 mm/day subsidence, and those in red correspond with the dangerous speed of subsidence (15 mm/day) which is equivalent to the boundary value for a category III mining area. In comparison to the predictions, the maximum speed of subsidence was greater by 30%, but within the speed limits tolerated by the authors of the expertise.

The evaluated factor of proportionality (9) amounts to $k = 5.0$ [mm/m], between the maximum speed of subsidence and the speed of longwall face advance, which approximately corresponds to the maximum slope of unsteady subsidence trough, amounting to 4.6 mm/m.

$$\frac{dw}{dt} = k \cdot v \tag{9}$$

where:

k – the factor of proportionality, corresponding to maximum unsettled subsidence,
v – the speed of longwall face advance.

5. Conclusions

1. The formulas of the Knothe-Budryk theory meant for predicting unsteady deformations and computational computer programmes elaborated for them are utilized not only for predicting, but also for determining the restrictions of mining prevention in order to minimize the mining damages in objects on the surface. They have been applied in the case of longwall 6 in seam 503 of the "Bobrek-Piekary" mine, in the "Bobrek" area, which has been in operation since 2016 under the Miechowice district of Bytom. The termination of longwall operation is planned for the end of January 2018.
2. Making use of mining and construction preventive measures, resulted in insignificant damage to the structure and furnishings of the church, which served as a place of worship throughout the entire time mining was carried out by longwalls 5 and 6. The principal negative impact of the mining work on the church building was an increase of its deflection in the Eastern direction. Levelling is planned to rectify this issue.
3. The applied and strictly observed limitation of the speed of the longwall face advance and quasi continuous mining led to the growth of deformations being regular, though fluctuation around mean values could not be avoided.
4. The daily growth of subsidence approximately corresponds to the almost immediate appearance of deformation, predicted to be (undervalued) 7.2 mm/m, but was measured to be an average of 10.5 mm/day. The relation of subsidence speed determined *a posteriori* confirmed the relationship between the speed of subsidence and the speed of longwall face advance and the factor of proportionality k, the value of which corresponds to the maximum slope of an unsteady trough.
5. The demonstrated example was a big challenge, because mining under the city of Bytom and its districts is also used for non-scientific purposes.

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