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CONTENTS

APPLICATION OF KNOTHE-BUDRYK THEORY AND RIGID BODY CONDITION FOR ASSESSMENT OF SUBSIDENCE

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The objective of this study is to assess the surface subsidence due to mining activities at a study site in Upper Silesia Region (Poland). For this purpose, the geodetic time-series monitoring data was used from the period of 3 years (2009–2012). Knothe-Budryk theory was adopted for the influence of underground mining on the subsidence and inclination whereas the rigid body condition method was used to evaluate the stable of buildings. The final inclination values, computed from the rigid body method, are few times bigger than the prediction of the Knothe-Budryk theory. Therefore, we conclude that computation of rigid body condition would be a proper tool to verify the predicted inclinations from deformation models like Knothe-Budryk theory.

KEYWORDS:
Knothe-Budryk theory, Rigid body condition, subsidence, tensions, reservoirs, Poland

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1. Introduction

Mining influences on the surface depend on many factors, like depth and thickness of seams, types of bedrocks and soil, excavation method and soil, the load of constructions [1]. In open pit mines the damages are clearly visible – the soil is removed from the wide areas, the landscape is changed by tonnes of exploitation wastes, the ground water level is lowered, the ground vibrations appear and the pollution of water, ground, and air (dust, noise) around the excavation area [2–5]. In underground mining where some of these problems do not occur, mining dust can be filtered out from the air, the noise level is lower due to the depth, and the damages on the surface are smaller. On the other hand, the area influenced by subsidence is larger due to the depth of excavation, the underground water may be polluted and its level lowered. Also, there appear different types of deformations [1; 6–8].

Proper assessment of mining influences and monitoring surface's subsidence is mine surveyors' task. The main goal is to prevent damaging buildings and constructions on the surface, measuring of and restraint upon the inevitable influences of exploitation [9; 10] and eliminating existing damages. For many years, scientists have been trying to describe deformation processes with mathematical and empirical models [11–14].

In the beginning, the data was received from classic survey techniques like leveling. Nowadays, more common become the use of state-of-the-art tools like GIS [15], GNSS [16; 17], satellite interferometry [18–20], prediction by artificial neural networks [21] and many others.

The Knothe-Budryk model [11; 12; 22], with further developments, is one of the most important prediction models in polish mine industry. It describes horizontal and vertical displacements, inclinations and deformations. The Knothe's generalized differential equation for description of subsidence of a point over time was compared with two-parameter Sroka-Schober's model [23] leading to the conclusion that both models have some imperfections. Knothe's model is easier to applied, while the Sroka-Schober's model is better for a description of deformations for pillar-chamber extraction.

The Knothe-Budryk model was applied in numerous case studies. The theory was successfully applied to assess the deformation of the urban area of Bytom city in Poland [24] and horizontal displacements of coal mine BW Prosper Haniel in Germany [25]. Niedojadło, Jura [26] applied the model with fixed parameters for pillar-chamber extraction in LGOM area (Poland). Authors proved the need of changing theory's parameters describing rock mass for a wider observation area.

The constructions, or their isolated parts, are considered as a rigid body after the end of a construction process. However, due to different factors, they may be cracked or bent, and may not be longer considered as a rigid body [27]. Mattern, Blankenhorn [28] have presented the results and the comparisons of building collapse simulation from finite element and rigid body models. Kuras [29] used rigid

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body method to evaluate deformations of retaining walls due to the weather conditions and the natural use of the object. The rotation of the rigid body is one of the parameters used in the evaluation of damages and the danger to the constructions placed on the mining influence areas [30; 31].

The paper's authors present assessment of mining influences on the water reservoirs supplying water to the cities of Upper Silesian Coal Basin (Poland). In this area, the underground coal mining has a long history. For a few centuries, the area of around 5000 km^2 has been used to develop coal and metal industry. The industry growth was accompanied by the growth of population and urbanization of those lands [32]. Due to the essential role in the water supply system, the installation cannot be turned off during the excavation process underneath. Despite the mining activity, the reservoirs were still in use during the excavation and subsidence process. Each one of them was emptied and filled up with water few times. In order to assess the mining influence and evaluate the risk the structural health monitoring network was established.

The main objective of this study is to assess the influence of exploitation on the water tanks and evaluate the health of the reservoirs. The computation of rigid body condition was used to determine the stability of concrete monolith construction and to make a conclusion about its further working. In contrast to the aforementioned literature, in this study, the results of rigid body method are used for the verification of the predicted values from Knothe-Budryk theory. The authors point no-mining factors, not included in the models, which could negatively be influenced on the object during the deformation process.

2. Methodology

Knothe-Burdyk theory

Land subsidence is a vertical movement (downward) relatively to a datum. In mining areas, it is usually caused by post-excavation voids and abandoned workings. The changes of pressure equilibrium in the rock mass causing the collapse of rocks into the empty spaces. As the result, the deformations appear on the surface [33]. The surface damages caused by excavation of underground coal seams can be divided into the discontinuous and continuous deformations. The phenomena from the first group appear mostly randomly and they are difficult to predict. The phenomena from the second group are easier to predict due to their clear correlation with mining activity. Scientists have been researching the problem of mathematical description of continuous deformations.

In Upper Silesia Coal Basin, excavation was conducted with longwall mining system. The *longwall* is the working face advancing laterally towards the mine boundary. The excavation takes place in the narrow open strip (*face working*) between mined-out seam (*goaf*) and the coal-face. Space is protected against roof falls by an array of vertical props capped with horizontal bars, or by composite supports having broader roof canopies [1].

Budryk and Knothe [22] created the subsidence theory, especially for the Upper Silesia region. In order to compute the maximal predicted subsidence W_{max}, one has to know the thickness of excavating seam *g*, and exploitation parameter *a (values* between 0 and 1).

$$W_{max} = a*g. \quad (1)$$

The maximal area of exploitation influences contains mining area and area in the influence range of exploitation *r* (Figure 1). To compute the range *r* (Eq. 2), one has to know the depth of seam *h*, and the rock mass parameter *tan(β)* (where *β* is the angle of main influences). With known values of maximal subsidence W_{max} and range *r*, one can compute the inclination *T* (Eq. 3) in the distance *x* from the edge of exploited seam.

$$r = \frac{h}{tg\beta}, \quad (2)$$

$$T = \frac{W_{max}}{r} e^{-\pi \frac{x^2}{r^2}}. \quad (3)$$

For standard geological conditions of Upper Silesia Coal Basin, the assumption of tan(β) = 2 is usually made. With known parameters of exploitation and empirical values of subsidence, one can determine, if exploitation is the only cause of displacements. If the real values of subsidence are bigger than theoretical ones, then one can assume there is more than one cause of deformations. This theory assumes that above the sidewall of longwalls, subsidence

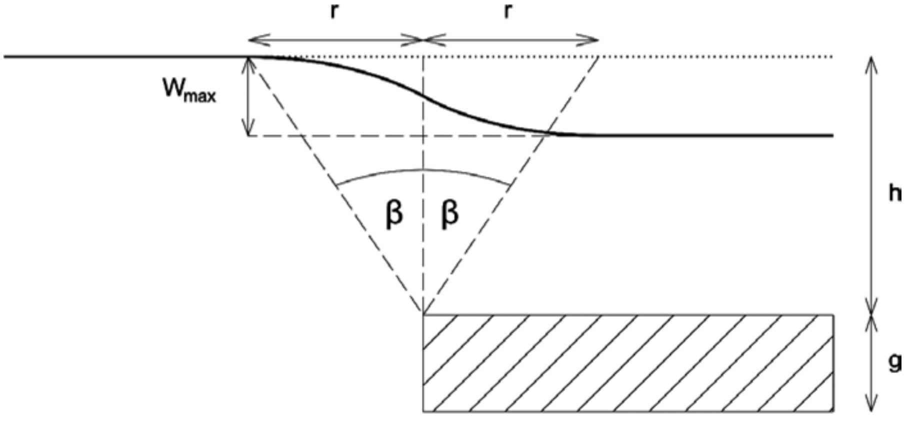

Fig.1. *Parameters of the Knothe-Budryk Theory /* ***Рис.*** **1.** Параметры теории Кнота-Будрика

occurs only the half of maximal predicted descending. In addition, in this area, maximal inclination appears. In the neighborhood, maximal tensions also occur (extending and compressing forces). Thus, to protect the constructions on the surface in the proper way, they should be located outside the area of the range of exploitation. Buildings inside the range of exploitation area are endangered by tensions and uneven subsidence causes inclination.

Rigid body condition method

Buildings in the mining areas are endangered with damages caused by uneven subsidence of ground under them. Despite vertical movements, there are also horizontal movements causing tensions in the ground (extension and compression). As the result, the construction can change its shape. To prevent from cracking, different building techniques are applied, like expansion joints and separated foundations. The goal is to raise construction from smaller objects considered as rigid bodies. The rigid body's shape remains unchanged in time, and its elements cannot move against each other.

External tensions can violate the stability of the rigid body. In order to check the rigid body condition, surveyors conduct different kinds of measurements. As the result, the geometrical features of the measured object are established. With a few series of observations, one can compute the changes in shape with time. If the changes are smaller than boundary value (tolerance), then the rigid body condition is met. Otherwise, the object cannot be considered as a rigid body.

Before deformation process, the building can be considered as the rigid body. If the surface is lowering uniformly, all points of the object are lowering in the same way and one is able to calculate the mathematical plane for them. It can be described using the least square method. In the matrix *A*, each row contains control point's *X* and *Y* coordinates. The matrix *L* contains deformation values for each control point correspondingly to matrix *A* [27].

$$A = \begin{vmatrix} X_1 & Y_1 & 1 \\ X_2 & Y_2 & 1 \\ X_3 & Y_3 & 1 \\ \ldots & \ldots & \ldots \\ X_n & Y_n & 1 \end{vmatrix} \quad L = \begin{vmatrix} \Delta L_1 \\ \Delta L_2 \\ \Delta L_3 \\ \ldots \\ \Delta L_n \end{vmatrix} \quad X = \begin{vmatrix} E_X \\ E_Y \\ W_C \end{vmatrix}$$

$$X = \left(A^{\mathbf{T}}A\right)^{-1} * A^{\mathbf{T}}L \tag{4}$$

The least mean square method (Eq. 4) is used to compute the result matrix *X*. The matrix *X* contains values of plane inclination in directions *X* (E_X) and *Y* (E_Y), and the coordinates system origin point's subsidence (W_C). Therefore, all computations should be conducted in the local coordinate system. The computed values are relative to the beginning plane before the deformation process. The first two values can also be assumed as the rotation *R* around axes *X* and *Y* (Eq. 5). Using those two values one can calculate maximal inclination E_{max} (Eq. 6) and its azimuth Az_{Emax} (Eq. 7).

$$\begin{cases} R_X = -E_X \\ R_Y = -E_Y \end{cases} \tag{5}$$

$$E_{max} = \sqrt{E_X^2 + E_Y^2}. \tag{6}$$

$$Az_{Emax} = \tan^{-1}\left(\frac{E_Y}{E_X}\right). \tag{7}$$

Statistical measure

Using equation 8 the differences between real values of displacement and theoretical ones are computed. The accuracy of the models is measured using the standard deviation (Eq. 9) of the least square method and the variance-covariance matrix (Eq. 10), where *n* is the number of observations and *u* is the number of the computed parameters. The variances of the observations are along the covariance matrix diagonal.

$$V = AX - L. \tag{8}$$

$$m_0 = \sqrt{\frac{\sum V^2}{n-u}}. \tag{9}$$

$$\mathrm{Cov}(X) = m_0^2 \cdot \left(A^{\mathbf{T}}A\right)^{-1}. \tag{10}$$

The value m_o is compared with the boundary value multiplied by the statistical significance value *k* ($k = 2$ for P=95.5%, $k = 3$ for P=99,7%). If the value m_0 is bigger, the object cannot be considered as a rigid body anymore. The different points of object do not behave in a linear way and move against each other.

3. Description of the study site and the data used

The coal exploitation before reservoirs' construction

Coal seams under reservoirs were excavated several times during the years. From the middle of XIX century shallow seams were exploited (depths around 60m). Some years before constructing works, there were also excavated seams on depth around 90m, 150m, and 370m in the longwall system. Before putting reservoirs into operation, the deformation process has already ended. Thus, one can assume that the construction was not influenced by the previous mining activities. For the next decades, water tanks had not been monitored due to the lack of mining works underneath.

The coal exploitation after reservoirs' construction

After the year 2000, a new exploitation in the longwall system (lwA) was designed on the depth up to 400m. The distance to the reservoirs from the closest point was not smaller than 200m. Thus, the object was placed on the borderline of excavation's mining influences area and the influences are negligible.

The exploitation of the two next seams was planned as follows: the sidewall of the next longwall (lwB) was placed exactly under one of the reservoirs, and close to the others. The third longwall (lwC) was planned to run under the whole object. As the result, the influence on the object was unambiguous and inevitable.

Object and the health monitoring network

Each of six reservoirs is based on the concrete monolith foundation. The constructions' walls are made out of a reinforced concrete and according to the project could be considered as a monolith.

In order to assess the water tanks' stability, a monitoring network was established. It contained control network points, ground benchmarks, benchmarks on the buildings, inclinometers and control points on the pillars of buildings. Measurements were conducted with 1mm accuracy. The measurements were taken every two weeks, and during the period of biggest deformations, even more often. 24 benchmarks were used to monitor water tanks (four on each of buildings).

4. Results

Mining influence assessment using the Knothe-Budryk Theory

The excavation parameters used in Knothe-Budryk theory were presented in Table 1 (with rock mass parameter tan(β) = *2*). The distances to the furthest water tank were almost 200m. According to the predictions of Knothe-Budryk theory (Table 1), all water tanks were in the influence range of exploitation lwB. The exploitation of lwB was conducted around 300th day after the beginning of survey observations.

The longwall lwC was designed under reservoirs and parallel to the lwB. During the mining works on lwC, the influences of lwB had appeared on the surface and damaged unequally the construction. The damages and further danger to the water tanks resulted in a decision to stop exploitation lwC around 1100 day of observations. Its parameters in the moment of abandon are presented in table 1.

The described object was in the influence area of two longwalls (lwB and lwC). Figure 2 depicts localization of object and exploitation fields. For both excavations, the water tanks were placed in the incline and tensions occurring area.

The displacements and tensions were revealed on all elements of the structural health monitoring network. Figure 3 depicts subsidence of benchmark on the wall of one of the reservoirs. Dotted line presents the moment of exploitation lwB under the water tanks, and dashed line denotes the moment of stopping lwC. The displacements of the benchmark are distributed randomly before the mining works. After mining excavation, the points lowered up to around 0.5m. In the end, the distribution once again is random. The first subsidence caused damages on the construction. Due to these damages, the decision to stop lwc was made to prevent from escalating the danger. Thus, the influence of lwc have not revealed on all the control points of the monitoring network.

For each water tank, the maximal subsidence W_{max} and distance to excavated seam x were found and used to compute the inclination T_x (Eq. 3). The results are presented in Table 2. The maximal theoretical inclination $T_{\max}$ was computed to compare with the results of rigid body method. All computations were conducted in local coordinate space, separate for each water tank. The center point (0,0,0) was placed in the middle point of the construction (Fig. 2 – black dots), and axes were directed to benchmarks n-2 (north) and n-3 (east), where n is the number of a water tank.

Result of Health of buildings evaluation using the rigid body condition method

The rigid body condition was calculated in the local coordinate system with the beginning at the center of each water tank. The boundary error m_u was assumed as the mean error of accuracy of measurements. The parameters of space orientation (rotation, inclination, inclination's azimuth) were computed for each water tank in succeed-

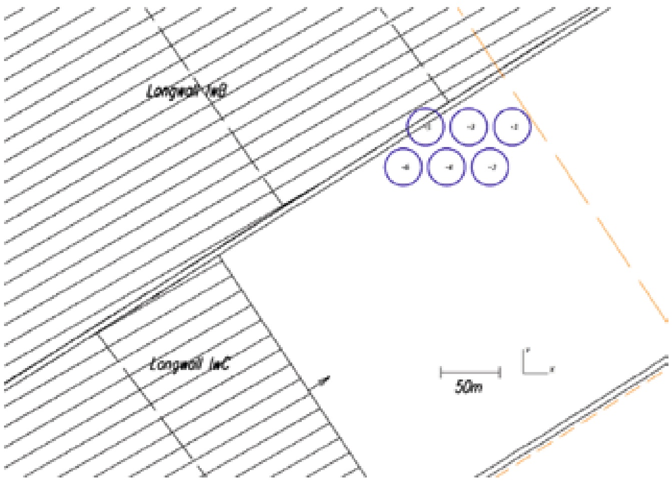

Fig. 2. *Localization of reservoirs (blue) on the plan of coal exploitation and influence range (lwB – short dashed line, lwC – long dashed line)*

Рис. 2. *Локализация коллекторов (синий) по плану эксплуатации угля и диапазон воздействия (lwB – короткая пунктирная линия, lwC – длинная пунктирная линия)*

Table 1 */ Таблица 1*

The parameters of excavation and the results of Knothe-Budryk Theory

Параметры раскопок и результаты теории Кноте-Будрика

ID	**Depth, m** *Глубина, м*	**Influence range, m** *Диапазон влияния, м*	**Distances to reservoirs, m** *Расстояние до резервуаров, м*
lwA	~400	~200	>200
lwB	~570	~285	0 – 200
lwC	~570	~285	>150

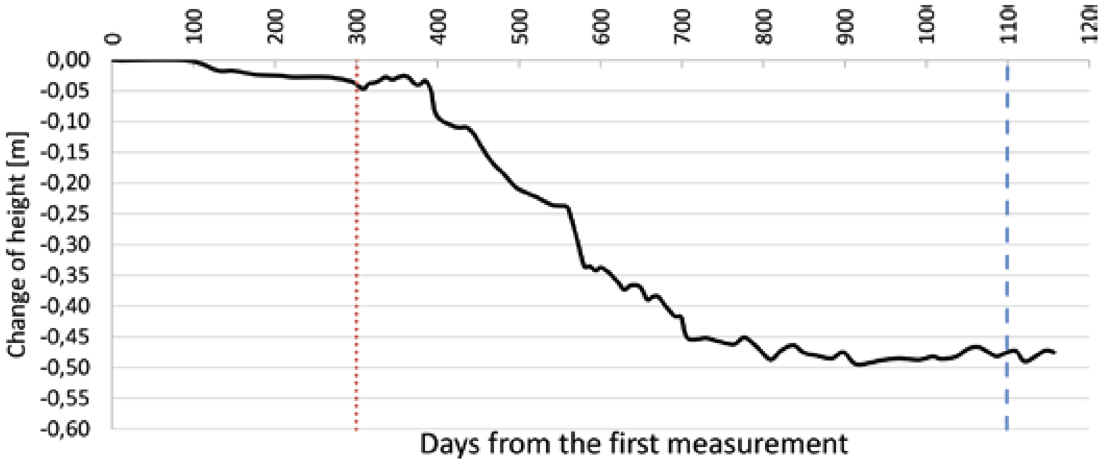

Fig. 3. *Subsidence of benchmark 1-1 /* ***Рис. 3.*** *Оседание уровня 1-1*

Table 2 */ Таблица 2*

Maximal inclinations of each water tank for lwB and lwC

Максимальные наклоны каждого резервуара для воды для lwB и lwC

Tank num. *№ резервуара*	W_{max} **[m]**	T_{max} **[mm/m]**	**lw*B***		**lw*C***	
			x **[m]**	T_x **[mm/m]**	*x* **[m]**	T_x **[mm/m]**
1	-0.41	-1.45	46.3	-1.33	267.5	-0.09
2	-0.37	-1.30	65.0	-1.10	233.0	-0.16
3	-0.57	-2.00	26.6	-1.94	237.0	-0.23
4	-0.52	-1.83	45.4	-1.69	202.4	-0.37
5	-0.73	-2.57	7.0	-2.56	206.4	-0.49
6	-0.67	-2.35	25.7	-2.29	171.8	-0.75

Table 3 */ Таблица 3*

Parameters of space orientation for reservoirs (series 77)

Параметры пространственной ориентации водохранилищ (серия 77)

Series 77 / *Серия 77*	**Tank 1** *Резервуар 1*		**Tank 2** *Резервуар 2*		**Tank 3** *Резервуар 3*		**Tank 4** *Резервуар 4*		**Tank 5** *Резервуар 5*		**Tank 6** *Резервуар 6*	
	Value *величина*	**Dev.** *погрешн.*	**Value** *величина*	**Dev.** *погрешн.*	**Value** *величина*	**Dev.** *погрешн.*	**Value** *величина*	**Dev.** *погрешн.*	**Value** *величина*	**Dev.** *погрешн.*	**Value** *величина*	**Dev.** *погрешн.*
Center point subsidence, mm / *Понижение центральной точки, мм*	-403.7	0.7	-333.3	13.3	-539.3	3.7	-489.0	5.0	-690.5	12.5	-639.5	0.5
Rotation around axis *X*, mm/m / *Вращение вокруг оси X, мм/м*	2.54	0.06	2.02	1.096	2.310	0.31	3.45	0.41	5.146	1.034	1.696	0.04
Rotation around axis *Y*, mm/m / *Вращение вокруг оси Y, мм/м*	-4.44	0.06	-4.33	1.09	2	0.31	-4.91	0.41	-4.56	1.03	-4.56	0.04
Inclination in axis *X*, mm/m / *Склонность в оси X, мм/м*	-2.54	0.06	-2.02	1.09	-2.31	0.31	-3.45	0.41	-5.15	1.03	-1.69	0.04
Inclination in axis *Y*, mm/m / *Склонность в оси Y, мм/м*	4.44	0.06	4.33	1.09	3.22	0.31	4.91	0.41	4.56	1.03	4.56	0.04
Overall inclination, mm/m / *Полная склонность, мм/м*	5.12	0.01	4.78	0.23	3.96	0.08	6.00	0.07	6.88	0.15	4.87	0.01
Inclination azimuth, grads / *Азимут склонности, градиент*	366.90	0.74	372.23	14.61	360.35	4.99	361.02	4.39	346.17	9.57	377.34	0.54

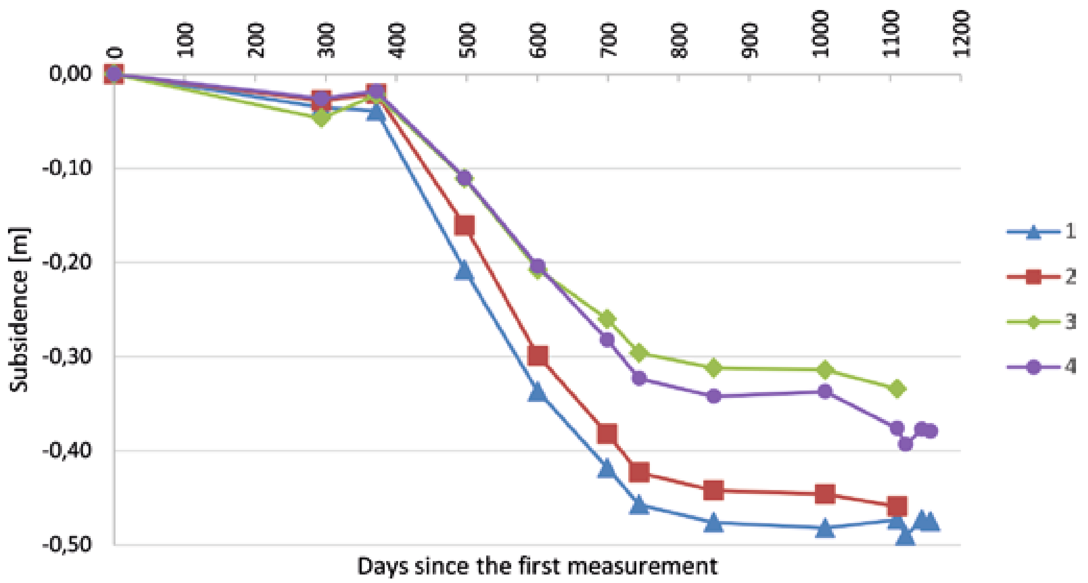

Fig. 4. *Averaged subsidence of benchmarks on the 1st water tank*

Рис. 4. *Усредненная просадочность уровней на 1 резервуаре для воды*

ing series. The example for the series 77 is presented in Table 3.

For comparison, three measurement series were picked up. The series 7 was made on 179 days after the beginning of observation, but still before the start of exploitation lwB. Series 42 was made on 613 days, during the period of the fastest subsidence, and series 77 on 1085 day, when the process of lowering was almost over.

The parameters of planes for each water tank were used in the computation of the differences between theoretical and real values of vertical displacements, and the mean errors m_0. The results for the series 7, 42 and 77 are presented in Table 4. The fulfilled rigid body conditions are marked in gray.

5. Discussions

The trend for all benchmarks is the same – pairs of point 1-2 and 3-4 are lowering with different speed, but with similar to each other. In the other words – points 1 and 2 are lowering faster than 3 and 4. Figure 4 presents these phenomena. As a result, all constructions inclined in direction of line 4-1 (north-east), the 1st water tank in about 0˚ 21.3'. Figure 5 presents localization of benchmarks on the reservoirs, the final subsidence of them presented with Kriging interpolation.

The direction of contour lines is approximately parallel to the sidewalls of longwalls lwB and lwC. The computed parameters of mathematical planes for each reservoir confirm these observations. Table 2 presents the maximal values of inclination of objects computed using the Knothe-Budryk theory.

This inclination and subsidence are clearly caused by exploitation of lwB. The influences of lwC could elimi-

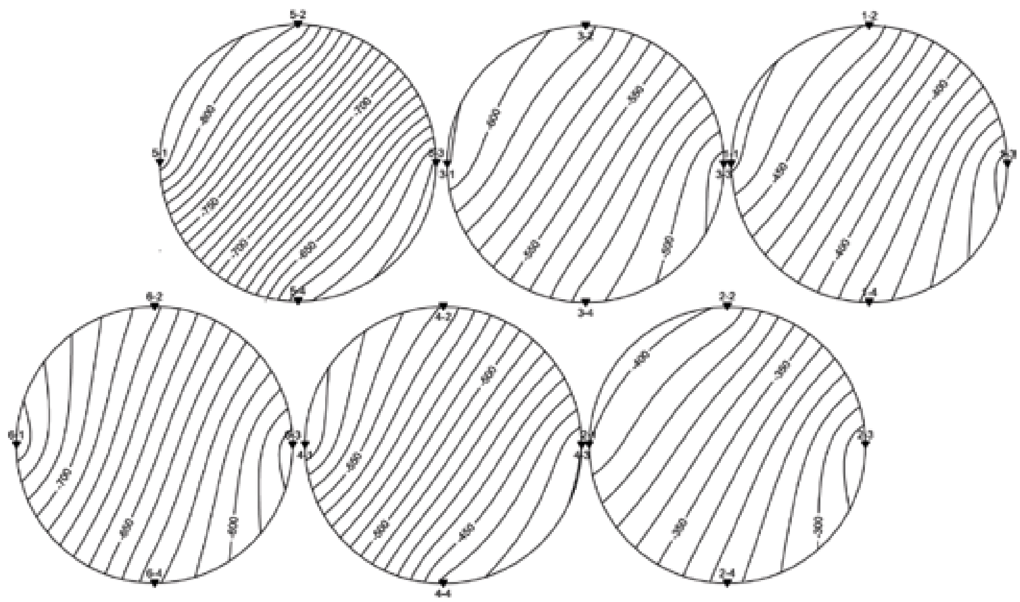

Fig. 5. *Final subsidence contours (Kriging method) with localization of benchmarks (values in millimeters)*

Рис. 5*. Контуры окончательного оседания (метод Кригинга) с локализацией уровней (в миллиметрах)*

Table 4 / *Таблица 4*

The rigid body condition (parameter *k*=2 and *k*=3) with m_0 error for series 7, 42 and 77

Состояние твердого тела (параметр k=2 и k=3) с ошибкой m_0 для рядов 7, 42 и 77

Series 7 ***Серия 7***	**Tank 1** ***Резервуар1***	**Tank 2** ***Резервуар 2***	**Tank 3** ***Резервуар3***	**Tank 4** ***Резервуар 4***	**Tank 5** ***Резервуар 5***	**Tank 6** ***Резервуар 6***
m_0	2.31	1.00	9.00	2.00	0.50	2.50
$2m_u$	2.83	2.83	2.83	2.83	2.83	2.83
$3m_u$	4.24	4.24	4.24	4.24	4.24	4.24
Series 42 ***Серия 42***	**Tank 1** ***Резервуар 1***	**Tank 2** ***Резервуар 2***	**Tank 3** ***Резервуар 3***	**Tank 4** ***Резервуар 4***	**Tank 5** ***Резервуар 5***	**Tank 6** ***Резервуар 6***
m_0	12.12	2.00	2.50	17.50	2.50	2.00
$2m_u$	2.83	2.83	2.83	2.83	2.83	2.83
$3m_u$	4.24	4.24	4.24	4.24	4.24	4.24
Series 77 **Серия 77**	**Tank 1** ***Резервуар 1***	**Tank 2** ***Резервуар 2***	**Tank 3** ***Резервуар 3***	**Tank 4** ***Резервуар 4***	**Tank 5** ***Резервуар 5***	**Tank 6** ***Резервуар 6***
m_0	1.44	26.50	7.50	10.00	25.00	1.00
$2m_u$	2.83	2.83	2.83	2.83	2.83	2.83
$3m_u$	4.24	4.24	4.24	4.24	4.24	4.24

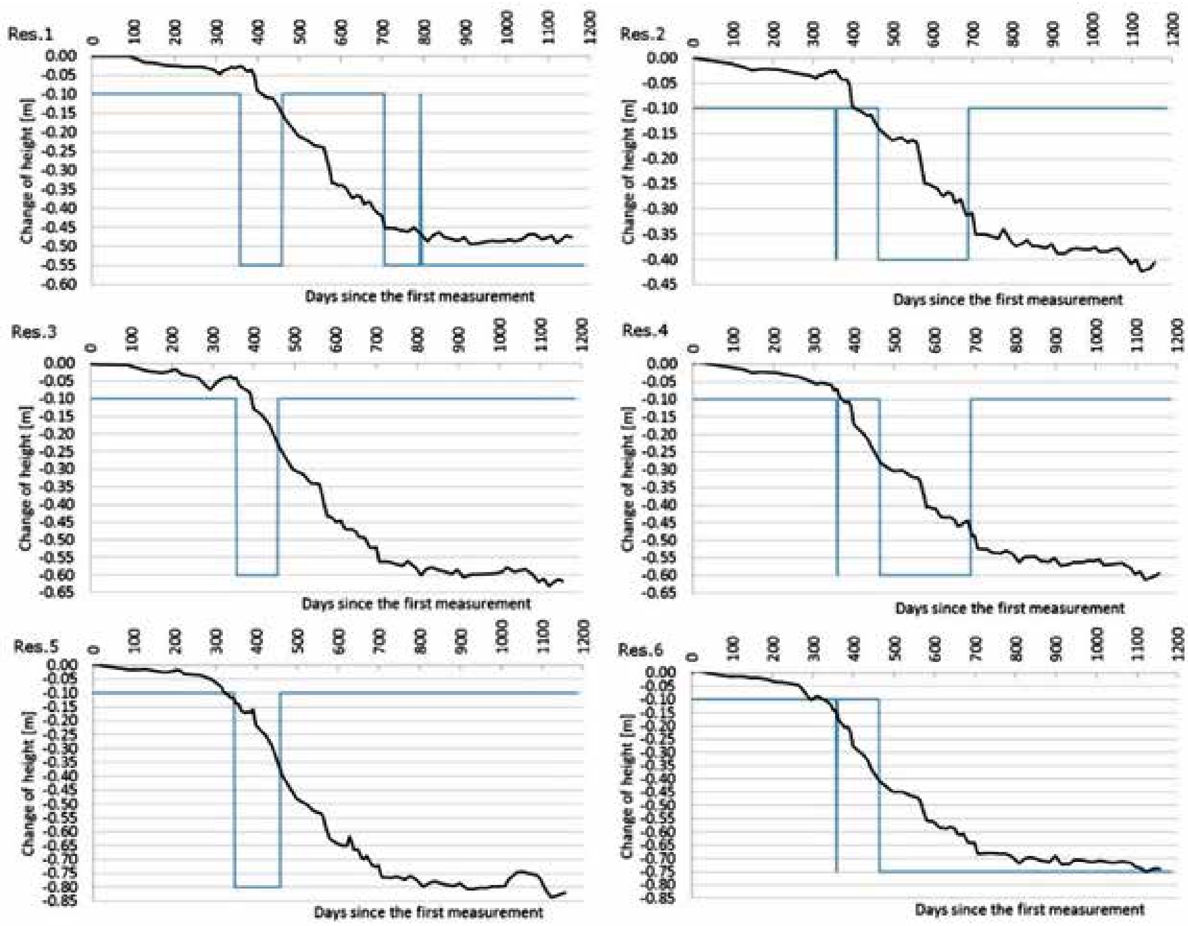

Fig. 6. *Periods of filling up (blue line) water tanks with subsidence of benchmarks on each reservoir*

Рис. 6. *Периоды заполнения (голубая линия) резервуаров для воды с просадкой уровней на каждом резервуаре* nate them if the works did not stop before going underneath the buildings. However, due to the abandoning of lwC, constructions remained inclined. In addition, some of the lwC's influences occurred on the water tanks, are closest to the lwC. The 6th water tank started to incline in direction of line 3-4 (south-west).

The theoretical inclination values from the Knothe-Budryk theory are a few times smaller than the overall inclination values computed from the rigid body method (e.g. for the series 77 in Table 3). Even the maximal theoretical values still do not present the observed scale of the phenomena. Thus, this theory cannot be applied to all objects and conditions to predict inclinations. This can be also a clue, that the mining factor is not the only one influencing the object, and the observations of subsidence are not enough.

The results between the series may differ due to the different speed of lowering as well as the errors made during the measurements. Thus, to establish the rigid body condition, the computations were conducted for the different series. The final values for three example series, 7, 42 and 77, are presented in Table 4.

The series 7 was conducted before the excavation under the reservoirs. Almost all results are positive, only the results for the 3rd water tank are negative. However, other measurement series from that period give positive values for that building as well. One can assume that all objects can be considered as the rigid bodies.

The series 42 was conducted during the period of the fastest displacements. The condition of the rigid body is fulfilled only by some objects. Depending on the series from that period of time, the objects sometimes meet the condition, and sometimes not. Despite the measurements errors, it can mean that buildings are no longer the rigid bodies.

The series 77, in the end of the subsidence process, reveals that almost all constructions were damaged and cannot be longer considered as rigid bodies, most of the results are negative. This can be considered as an assumption for further investigation of construction. For series 77 only 5th reservoir fulfills the rigid body condition and 6th fulfills for k=3, and almost for k=2. But with other series from that period, one cannot confirm the buildings are still rigid bodies.

During the exploitation and subsidence process, the reservoirs were fully operational. In different times, they were filled up with water and emptied. Figure 6 presents periods of filling up water tanks. One can notice, that short after water release the subsidence doesn't occur or slower down (around days 350, 700 and 800). Around day 400, the first vertical movements are revealed. Highly recommended, and inevitable was to refill the tanks during the period of lowering movements. The influence of installation working (mass changes, the pressure of water on the reservoirs' walls) wasn't considered during the planning of exploitation, and in the displacement's measurements. The lack of data and scientific knowledge makes it impossible to establish only the influence of mining activity on reservoirs in case of occurrence of filled up/emptied factors.

The differences in the rigid body parameters between series can be caused by uneven vertical movements caused by stopping lwC, the work of reservoirs (filling up and emptying) during the process of deformation, damaging the control points and measurements errors and mistakes.

6. Concluding remarks

checking the condition of a rigid body on the object can bring information about the influence of underground exploitation on the buildings and installations on the surface. Due to the tensions constructions, may not remain rigid bodies. For the presented constructions results suggest, that all buildings were damaged. They will demand further inspection and repairs if they remain in working.

The reservoirs were lowering uneven due to the mistakes in the process of excavation. If lwC wasn't stopped in front of the object, the surface subsidence would be made even again. In another way, the constructions remained inclined in the direction north-west (to the lwB) and slightly to the south-west (lwC). Inclination can have further negative results due to future work of object e.g. damage caused by bigger water pressure only on the part of walls.

In the excavation with longwall system under the building important is to consequently remove a similar thickness of seams. In another way, it causes horizontal movements and tensions, causing bigger damages of the structures on the surface. The presented object was in the zone of extending movements. If the longwall C was finished, according to the plan, the whole object would be in the area free of tensions, with surface lowering equally.

The discrepancy of theoretical and practical values of inclination suggest investigating other factors during the subsidence process. One of them could be the changing mass of construction during the subsidence process due to filling/emptying with water. Stopping the use of reservoirs for the period of mining works and deformation process could help in preventing the occurrence of damages. Unfortunately, there are no plans for next excavations in this area due to the existing damages.

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CONFLICT OF INTEREST / *Конфликт интересов*

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ПРИМЕНЕНИЕ ТЕОРИИ КНОТЕ-БУДРИКА И УСЛОВИЯ ТВЕРДОГО ТЕЛА ДЛЯ ОЦЕНКИ ОСЕДАНИЯ

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Целью данного исследования является оценка поверхностного оседания в результате горнодобывающей деятельности на исследуемом участке в Верхней Силезии (Польша). Для этого использовались данные геодезического мониторинга временных рядов за трехлетний период (2009–2012 гг.). Теория Кноте-Будрика была принята для оценки влияния подземных горных работ на просадочность и наклон, в то время как для оценки устойчивости зданий использовался метод твердого тела. Конечные значения наклона, вычисленные по методу твердого тела, в несколько раз больше, чем прогнозы теории Кноте-Будрика. Следовательно, вычисление состояния твердого тела было бы правильным инструментом для проверки предсказанных наклонов из деформационных моделей, таких как теория Кнота–Будрика.

Ключевые слова: теория Кнота–Будрика, твердое тело, просадка, напряжение, резервуары, Польша.

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