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ASSESING THE POTENTIAL OF DIGITAL TERRAIN MODELS FOR MONITORING ADDITIONAL SUBSIDENCE OF COMMUNICATION EMBANKMENTS IN MINING AREAS – A CASE STUDY

OCENA MOŻLIWOŚCI NUMERYCZNYCH MODELI TERENU DO MONITOROWANIA DODATKOWYCH OBNIŻEŃ NASYPÓW KOMUNIKACYJNYCH NA TERENACH GÓRNICZYCH – STUDIUM PRZYPADKU

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Abstract

Today's technologies make it possible to capture certain phenomena that were very difficult or impossible to observe in terms of classical measurements. One of them is the so-called sinking of embankments. It is common in mining areas. It consists in the additional subsidence of the embankments into the ground, above the value of the lowering of the adjacent area. It takes place primarily in the zone of horizontal tensile deformations. The paper presents the results of comparative DTM (Digital Terrain Model) analyzes from 2001, 2014, 2018 and 2021. Their aim was to assess the usefulness of DTM data for monitoring the additional sinking of the communication embankment on the example of the northern bypass of Bytom. The authors analyzed digital terrain models generated in the process of rasterization of data from ALS (Airborn Laser Scanning).

Keywords: mining subsidence, digital terrain model, communication embankments, post-mining areas

Streszczenie

Dzisiejsze technologie pozwalają wychwycić pewne zjawiska, które w ujęciu pomiarów klasycznych były bardzo trudne lub też niemożliwe do zaobserwowania. Jednym z nich jest zjawisko tzw. tonięcia nasypów. Występuje ono powszechnie na terenach górniczych. Polega na dodatkowym zagłębianiu się budowli w podłoże, ponad wartość obniżenia terenu przyległego. Ma ono miejsce przede wszystkim w strefie poziomych odkształceń rozciągających. W pracy przedstawiono wyniki analiz porównawczych NMT z lat 2001, 2014, 2018 i 2021. Ich celem była ocena przydatności danych z NMT do monitorowania dodatkowego zagłębiania nasypu komunikacyjnego na przykładzie północnej obwodnicy Bytomia. Autorzy poddali analizom numeryczne modele terenu wygenerowane w procesie rasteryzacji danych pochodzących głównie z lotniczego skanowania laserowego ALS.

Słowa kluczowe: osiadania górnicze, numeryczny model terenu, nasypy komunikacyjne, tereny poeksploatacyjne

1. INTRODUCTION

Mining activities can lead to negative environmental impacts in the area of road infrastructure and safety of engineering structures [1-5]. For this reason, monitoring activities are being undertaken [6]. Geographic information systems (GIS) is a digital

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technology that enables the collection, management, analysis and presentation of spatial data for a wide range of applications, including mining [7]. GIS provides effective support for classical surveying in the process of monitoring hazards caused by mining operations [8]. The digital terrain models (DTMs) included in the GIS database, which are the result of laser scanning, can be used to observe phenomena within the road infrastructure, till now difficult to monitor. One of them is the so-called sinking of embankments. It commonly occurs in mining areas. It consists in additional sinking of embankment structures into the ground, above the value of lowering the adjacent land [9, 10].

This paper presents the results of comparative analyses of DTMs from 2012, 2018 and 2021, with the aim of assessing the suitability of DTM data for monitoring the additional sinking of the traffic embankment of Bytom's northern ring road. The numerical terrain models subjected to analysis were generated by rasterization of airborne laser scanning (ALS) data.

2. THEORETICAL BACKGROUND

The phenomenon of so-called embankment sinking, consisting of additional lowering of structures into the subsoil, above the value of the adjacent ground depression, occurs primarily in the zone of horizontal tensile strain of the subsoil in the boundary zone of the depression basin. It arises when the ultimate bearing capacity of the subsoil is exceeded due to the redistribution of the horizontal components of the state of stress [9-10]. The theoretical basis of the phenomenon of additional embankment subsidence has been known since the 1970s. The first publications in this area in the Polish literature are the works of: Szumierz [11], Litvinowicz [12] or Rosikon [13]. The description of changes in the state of stress in the subsoil loaded with a traffic embankment is presented, among others, in the work of Klosek [14].

In the subsoil loaded with an embankment, there is a state of stress caused by the dead weight of the soil medium and the weight of the embankment. The stress relation in soil takes the form [14]:

$$\sigma_{ik} = \gamma_0 \cdot h \cdot \begin{vmatrix} 1 & 0 & 0 \\ 0 & (m-1) & 0 \\ 0 & 0 & (m-1) \end{vmatrix}$$

where:
γ_0 – average volumetric soil mass;
h – the depth of the point under examination;
m – the transverse deformation coefficient of the soil.

$$m = \frac{1}{\vartheta}$$

ϑ – Poisson coefficient.

Horizontal tensile strains induce changes in the stress components of the stress state. The increments of the stress state components for the principal directions can be written in the form of a tensor:

$$\Delta\sigma_{ik} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & \frac{2G(m+\rho)}{m-1}\varepsilon_{22} & 0 \\ 0 & 0 & \frac{2G(1+m\rho)}{m-1}\varepsilon_{22} \end{vmatrix}$$

where:
ρ – ratio of horizontal deformations in the principal directions:

$$\rho = \frac{\varepsilon_{33}}{\varepsilon_{22}}$$

G – transverse modulus of elasticity of the soil:

$$G = \frac{E_\varepsilon \cdot m}{2m+1}$$

E_ε – modulus of elasticity of soil under conditions of ground strain.
Assuming that the vertical stress does not change significantly during horizontal strain, it is primarily the horizontal stress that is redistributed according to the relationship:

$$\sigma_{ik} = \sigma_{22} - \Delta\sigma_{ik} \geq \sigma_{gr}^{22} = \sigma_{min}^{22}$$

where:
$\sigma_{gr}{}^{22}$ – minimum value of the horizontal stress ($\sigma_{\min}{}^{22}$) in the total active Rankine state [15].

The theory presented above dates back to the 1980s. The introduction of widespread computerization at the beginning of the 21st century gave the opportunity to use FEM models to model the phenomenon of cooperation of structures with the mining ground. Recognition of the phenomenon of cooperation of structures with the ground in terms of soil mechanics is still the subject of research by many authors. Guidelines for the construction of FEM models are presented in the works of Fedorowicz: [16-18]. Selected results of numerical analyses describing the phenomenon of cooperation of traffic embankments with the subsoil are presented in [19-21], among others.

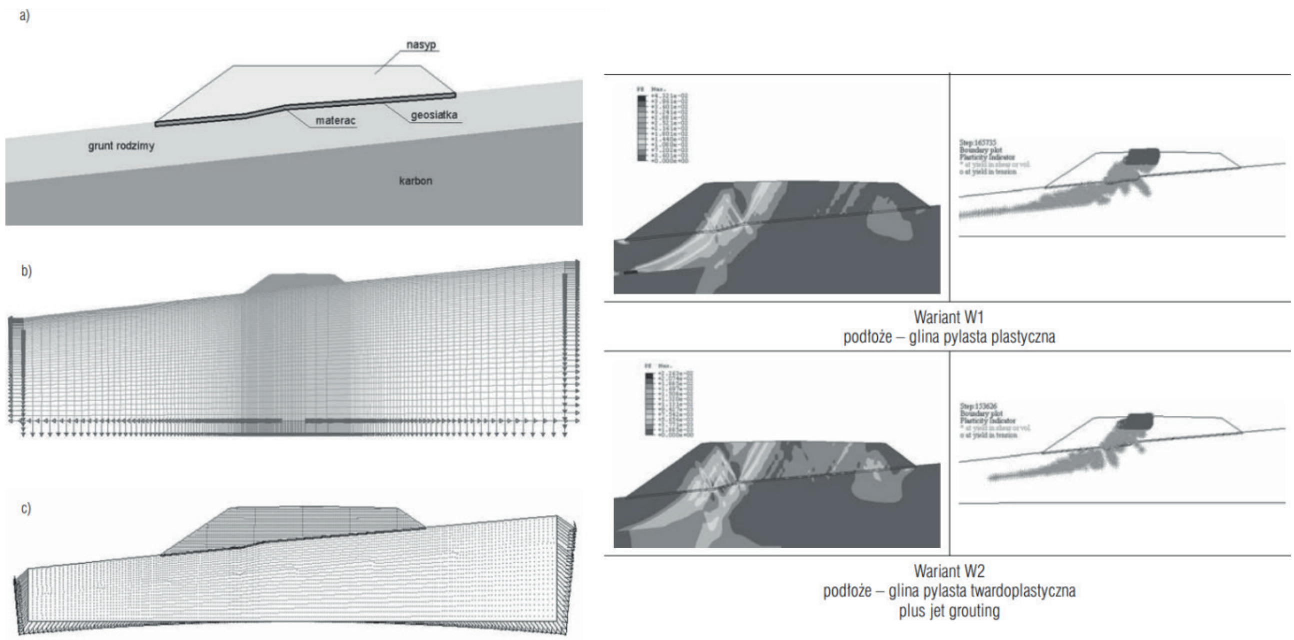

Fig. 1. Examples of published FEM numerical analyses for embankment construction on mining ground [20, 21]

3. GEODETIC MONITORING OF THE PHENOMENON OF EMBANKMENT DEFORMATION IN MINING AREAS

Classical geodetic measurements are a very valuable source of information about the behavior of the surface of a mining area with development [22, 23]. Thanks to the results collected in nature, it is possible to recognize the mechanics of the occurrence of a given phenomenon in greater depth and thus calibrate FEM computational models representing the problem under study [24].

For years, surveying work has been carried out for linear objects in mining areas. In the National literature one can find many studies of the results of classical geodetic surveys conducted for the purpose of inventorying changes in the geometry of transportation routes in mining areas. The results of geodetic measurements are a fundamental argument in assessing the impact of land surface deformation on buildings, including infrastructure facilities. Therefore, they are widespread. In terms of classical geodesy, measurements of deformation of a mining area are mostly carried out on field lines [25], possibly on so-called rosettes [26]. The results obtained in the form of deformation indices are characterized by high accuracy. Their disadvantage is that indicator values are obtained only for one direction – on the direction of the measuring line. In the case of deformation of transportation routes in mining areas, running on embankments, only the magnitude of deformation of the pavement is known. However, the changes in the geometry of the embankment itself are not known. This is because the measurement lines run in the crown of the embankment, parallel to the axis of the route. The results of the measurements are strongly concentrated on the pavement itself. As an example, Figure 2 shows the shape of one of the field lines monitored for changes in the geometry of the route in the mining area – the Bytom bypass.

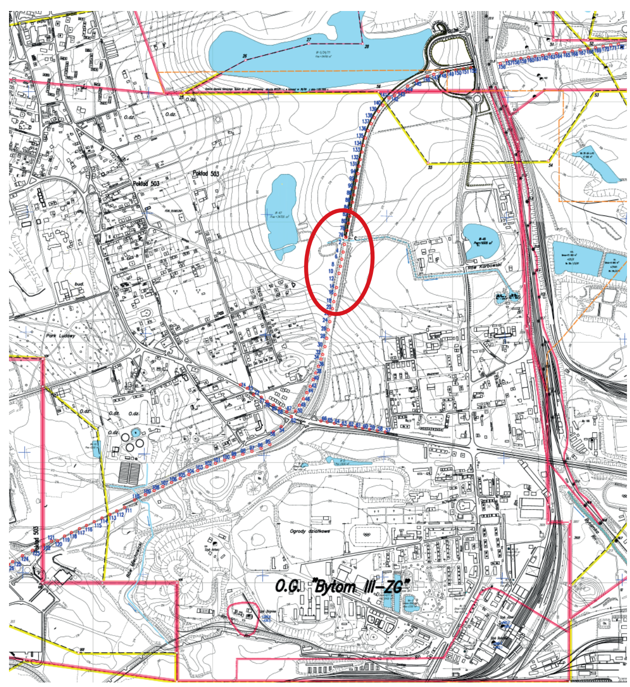

Fig. 2. Survey line (blue color) stabilized to monitor changes in the geometry of the City's ring road [45]

However, in the context of the study of additional embankment subsidence in mining areas, measurements must be carried out more extensively, including outside the crown of the embankment. Measurement works focused on the problem of additional embankment subsidence are already much fewer. However, as early as the 1980s, the first publications appeared showing the scale in the effect of sinking embankments in nature (Fig. 3) [27].

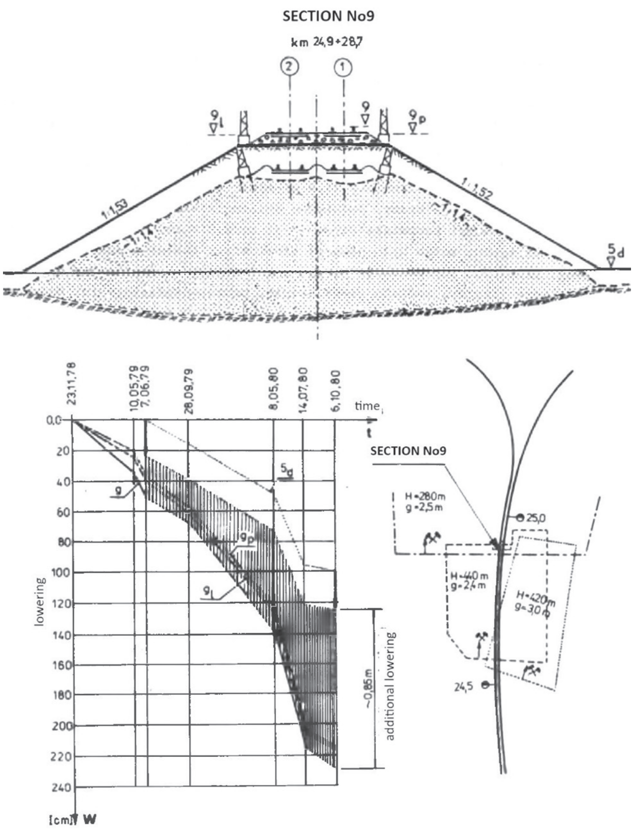

Fig. 3. Results of geodetic observations for the railroad embankment in the crawl space [27]

For the analyzed example, the results indicate the occurrence of additional subsidence of more than 90 cm for a railroad embankment with a height of 10 m located in a zone where horizontal tensile strains of 3-4 mm/m were recorded [27].

It is difficult to carry out such observations using classical measurement techniques. First of all, because observations are made at specific points representing cross sections, defined even before the deformation is revealed – mainly on the basis of forecasts, which, as is well known, are not error-free. Global navigation satellite system (GNSS) surveying techniques introduced in recent decades have become an alternative to measuring deformation of objects in mining areas. Already at the beginning of the 21st century, the first textbooks were written describing the usefulness of satellite techniques for deformation measurements [28]. Today, satellite techniques are displacing classical measurements in most surveying work. They are also one of the basic tools for measuring deformation of mining areas. Publications in this field constitute a very large group of works. The cited examples represent only a part of them [29-34]. GNSS techniques are also widely used to monitor changes in the shape of transportation routes in mining areas, including major strategic facilities, such as the A4 highway in Poland [35].

Rapidly developing laser scanning is also of great importance in observing changes in the shape of the surface of a mining area [36]. Aerial scanning is mainly used in the inventory of changes in the shape of the mining area surface. The paper [38] analyzed data from ALS laser scanning and precision leveling for the city of Bytom to assess the compatibility of the two measurement methods in the context of analysis of land subsidence caused by mining activity. When comparing the two measurement time periods, the deviations at the reference points were within the absolute accuracy of ALS measurements. The suitability of ALS technology for monitoring the subsidence of extensive areas with relatively large increments was rightly pointed out. Similar observations were made in [39], which emphasized the usefulness of ALS technology for comprehensive measures of the impact of mining activities. Besides, remote methods of monitoring land deformation such as interferometric synthetic aperture radar (InSAR) are also intensively developing [37]. For several years, one can notice a widening interest in multi-criteria GIS analyses, which, according to [40, 42], effectively help to assess land subsidence risks or identify subsidence of post-mining basins by analyzing factors related to the geometry and characteristics of the analyzed area (slopes, drift depth, groundwater level, ground permeability and others). Current and archival thematic maps and their derivative products, stored as successive spatial information layers in GIS, provide a rich source of data that can be effectively used in protecting the surface of a mining area [41].

4. STUDY AREA

4.1. Characteristics of the studied traffic embankment

Within Poland, it is in areas affected by mining that the road network is one of the most dense. This is

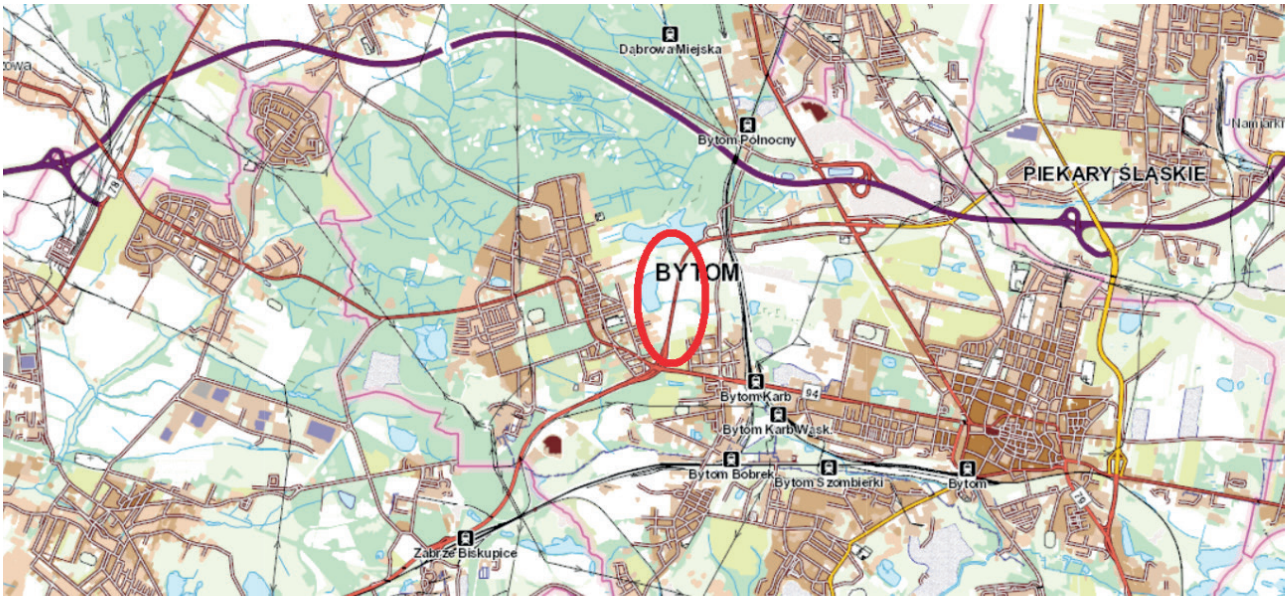

Fig. 4. Location of the study object

due to the fact that the area of Upper Silesia, which is a large mining ground, is also densely populated [43]. One of the most interesting locations in terms of studying the impact of deforming mining ground on infrastructure is the city of Bytom. Many years of coalseam mining there have caused depressions that have already reached more than 30 meters over the past sixty years [44]. The Northern Bypass of the Upper Silesian Agglomeration constructed in 2012, which is a connection between the DK88 and the A1 highway, is located in this difficult terrain (Fig. 4).

In the north-south direction, the route of the bypass follows an embankment with an average height of about 6.0 m (Fig. 5). This is the main object of interest in this work.

The embankment construction was completed in 2012. Figure 6 illustrates the progress of embankment erection between 2009 and 2012.

Fig. 5. Northern bypass of the Upper Silesia Agglomeration in Bytom, a section of the route that runs on an embankment visible in the distance, October 2018

Fig. 6. Orthophotos from the years: 2009, 2011 and 2012 – completion of embankment construction source: http://geoportal.gov.pl

4.2. Performance data

The facility was subjected to the impacts of two longwall operations immediately after construction. The first of these took place in 2014-16 (Fig. 7a). Mining was carried out with two walls: a longwall of about 400 m (east) and a longwall of about 550 m (west), located directly under the analyzed bypass and the discussed road embankment. The depth of mining was about 710 m, the average thickness of the seam was 1.8 m, and there is mining with caving carried out. The second caving exploration mining started in September 2018 was carried out with a longwall of 280 m. Total run-out – 1630 m. Average thickness of the mined layer – 3.0 m, average depth of mining (650-700 m). In May 2019, a runout of about 830 m (1/2 of the total runout length) was reached here. Exploitation runs from north to south, approximately parallel to the axis of the bypass (Fig. 7b).

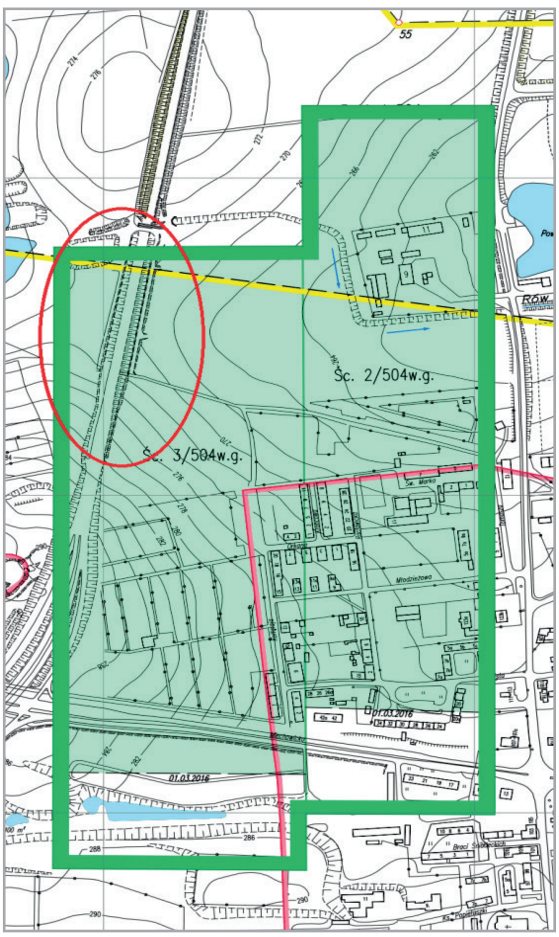

Fig. 7a. Location of the facility in relation to the parcel of land exploited in 2014-16 (green indicates the location of the exploitation front on 1.03.2016) [45]

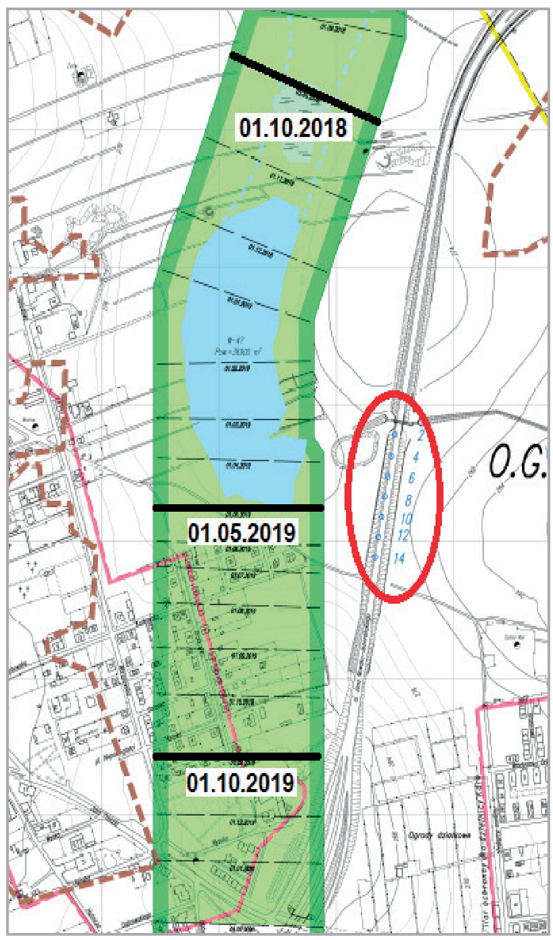

Fig. 7b. Location of the bypass in relation to the long wall in operation in the period 2018-20 [45]

5. PREPARATION OF THE DTMS

Comparison of DTMs from different time periods makes it possible to catch the appearance of depressions in the terrain, and consequently prevent potential hazards. In the present study, numerical terrain models for the city of Bytom subjected to subsequent analysis were generated by rasterization of airborne laser scanning (ALS) data (excluding the 2001 digital terrain model, which were created after processing aerial photos). The data were sampled at a density of no less than 6 pts/m^2, and the average elevation error for the ALS data and the surveyed durations was no greater than 0.15 m. Based on the processed point clouds from LiDAR, numerical terrain and land cover models were developed in ASCII GRID format with an average error of m_h = 0.25 m. Processed results from airborne laser scanning were made available for research by the Department of Geodesy of the City Hall in Bytom. Due to the large time span of the acquired DTM data, the raster models figured in different elevation systems. Harmonization of the data to the current PL-EVRF2007-NH elevation system in effect in Poland and all analyses based on raster algebra were carried out in the open source software Qgis.

Figures 8-10 summarize the results of the analyses in the form of DTM comparisons from 2001-21, 2012-21 and 2018-21.

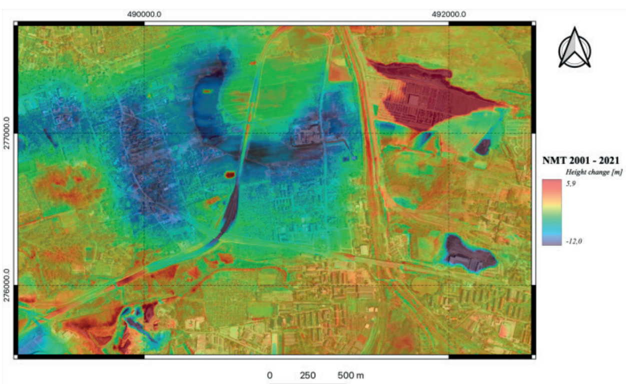

Fig. 8. DTM comparison results for the years: 2001-2021

The comparison shown in Figure 8 was generated to show the shape of the Bytom Basin over 20 years. All uplifts are the result of anthropogenic activity. The areas highlighted in red mostly have sharp edges and their shapes are strongly constrained. These zones should be interpreted as embankments. The blue zones visible in the interior, with their blurred contours, are the result of mining activities. This is an image of a subsidence basin formed over a period of 20 years.

The colour palette in the following figures should be interpreted similarly: 9 and 10. In particular, in Figure 9 it is clear that the traffic embankment of the Bytom Ring Road analysed in the paper is located in a zone of additional subsidence caused by mining activities. The light blue zone located at the site of the analysed embankment roughly coincides with the shape of the parcel of land mined at this site in 2015-16 (Fig. 7a). The dark blue zone located to the west of the analysed embankment is also the image of a basin, caused by the exploitation of another wall. In this case, the thickness of the mined layer was 3.0 m, which caused subsidence greater than in the embankment case, where the thickness of the seam was 1.8 m.

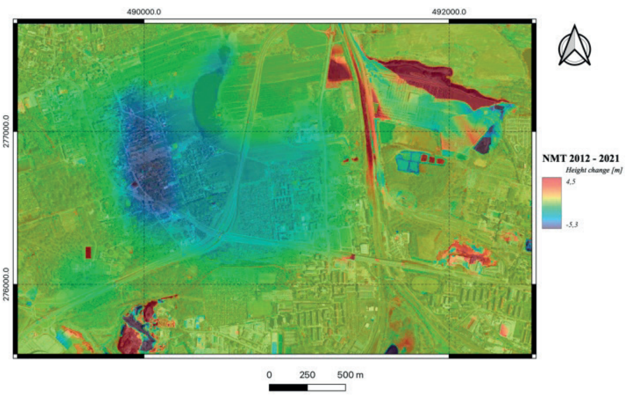

Fig. 9. DTM comparison results for the years: 2012-2021

In Figure 9 to the west of the analyzed road embankment, the effect of the beginning of the formation of a subsidence basin from the mining of wall 4 is visible – Figure 7b. Its exploitation took place in 2018-19. In this case, the final shape of the subsidence basin has not yet fully revealed itself on the ground surface. The 2021 DTM was generated on the basis of scans carried out in May. By this period, the final subsidence had not yet been observed on the ground surface.

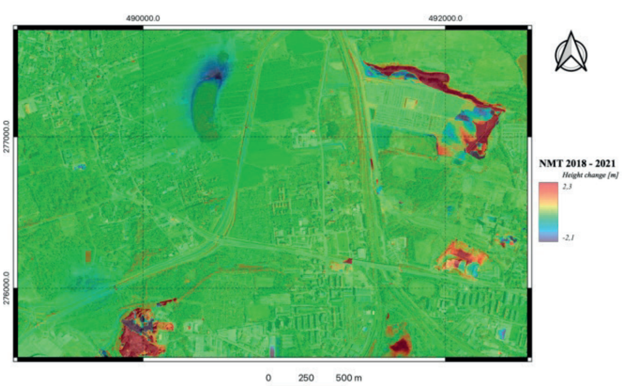

Fig 10. DTM comparison results for the years: 2018-2021

6. DTM VERIFICATION

In order to verify the DTMs analyzed in this paper, the results of classical surveying measurements conducted by an independent team [45] were used. The results of cyclic precision leveling measurements made on the field line stabilized in the crown of the embankment along which the bypass of the city of Bytom runs (Fig. 2) showed the appearance of subsidence. In this article, attention is focused on a section of the line between measurement points: 2-16, representing the surveyed road embankment (Figs. 5, 6). The graph (Fig. 11) shows the progress of the lowering of the individual line reperes in the period: 06.2018 - 08.2020.

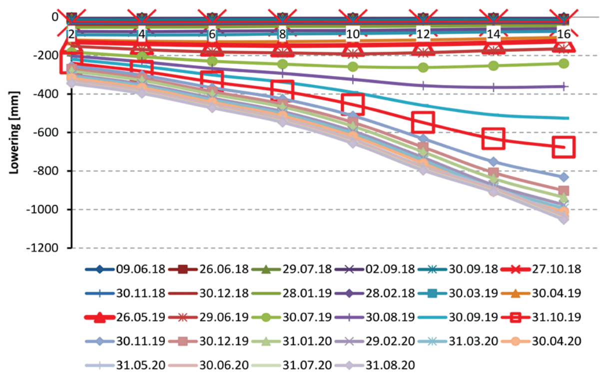

Fig. 11. Decreases of the survey benchmarks on the road embankment (source: own elaboration based on survey results [45])

In order to verify the correctness of the DTM 2018 prepared by the authors, a longitudinal cross-section through the crown of the embankment was generated (black curve – Fig. 12). Then the obtained shape of the longitudinal section was compared with the results of independent surveying measurements. Figure 12 shows a summary of the results.

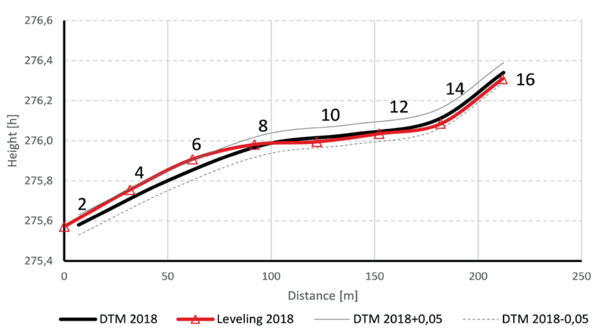

Fig. 12. Comparison of longitudinal sections through the crown of the analyzed embankment obtained from geometric leveling [46] and from the author's DTM

The shape of the two cross sections is very similar. Differences in elevation ordinates differ by a maximum of 5 cm (the gray curves in Figure 12 represent differences of +/-5 cm). A similar comparison of the shapes of the longitudinal cross-section through the crown of the embankment was made on the basis of the 2021 DTM (Fig. 13).

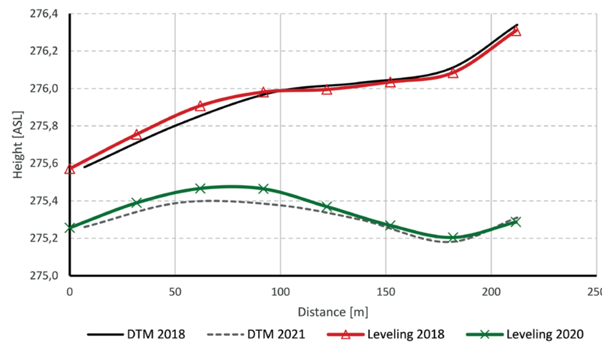

Fig. 13. Comparison of ground elevations for the DTMs analyzed in the paper with independent geodetic results

The following two curves, placed in the graph (Fig. 13) above, also follow a similar course. These are the results of leveling at points 2-16 taken on 30/08/2020 and the cross-section through the DTM taken from the May 12, 2021 images. Such a comparison, despite the shift in time, is shown because the results from Figure 11 show that the effects of mining activities on the analyzed embankment practically ceased in August 2020.

The next verification step is to compare the results of lowering the crown of the embankment over time. Figure 14 shows the result of embankment lowering obtained from two independent measurements, as a result of leveling measurements [45] and as a result of comparing changes in ground ordinates from the Author's DTM (2018-2021 – Fig. 10).

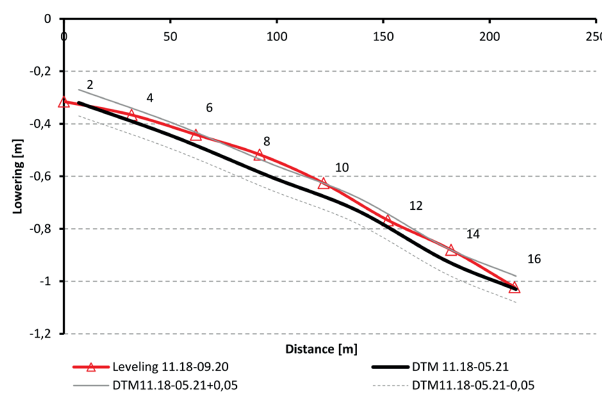

Fig. 14. Lowering of the crown of the embankment in the longitudinal section obtained from precision leveling and from the DTM

It can be seen from the graph (Fig. 14) that the reductions in the crown of the embankment obtained from comparing the two DTMs from the years: 2018-21 give a very similar picture to that obtained from independent leveling measurements. The values of the depressions obtained from the DTMs (black curve – Fig. 14) are only slightly larger than those derived from leveling. In part, this can be explained by the fact that the red curve representing the lowering of the embankment from leveling measurements shows lowering values over a slightly shorter time interval. In general, however, it should be noted that the differences in the subsidence obtained from the DTM are at most only a few centimeters greater than those from independent leveling measurements.

The author's verification of the DTM performed in a longitudinal section through the crown of the embankment showed that the image of the shape of the route running along the embankment obtained from the DTM is very close to the reality represented here by the much more accurate leveling measurements.

7. REPRESENTATION OF ADDITIONAL LOWERING OF THE EMBANKMENT CREST ON THE DTM

After positively verifying the prepared DTMs in the next step, the results were used to illustrate additional reductions in the crown of the embankment. This is clearly an advantage of classical leveling measurements, conducted on a line running along the pavement. Using DTMs, which are in fact a model of the terrain surface in the form of a 1×1 m mesh, it is possible to generate and thus observe any cross sections. One of the interesting places along the route of the bypass is cross-section A-A (Fig. 15).

Fig. 15. Location of cross-section A-A (the place where the greatest damage is revealed)

This is the zone where the greatest damage to the asphalt surface has occurred. The corpus of the embankment has also suffered damage that reveals itself in the form of cracks (Figs. 16, 17).

Fig. 16. Longitudinal crack in the crown of the embankment along with the deformed road barrier

Fig. 17. Vertical slots in the embankment corpus

Based on the cross sections generated from the 2012, 18 and 2021 DTMs, vertical and horizontal movements can be observed at any arbitrary location, including the interesting cross section A-A (Fig. 15). The results of land subsidence for cross-section A-A obtained from the DTM comparisons are shown in Figure 18.

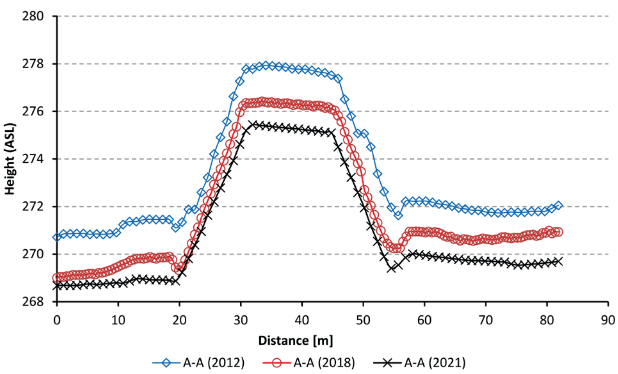

Fig. 18. Cross-section through the embankment (A-A) generated from DTM from 2014, 2018 and 2021

Based on the known ordinates of the points: representing the surface of the adjacent terrain and the points lying in the crown of the embankment for the studied section, the average ordinates of the terrain: the base and crown of the embankment were calculated. This allowed us to control the change in the height of the embankment over time. The results of the calculations are shown in Table 1.

Table 1. Calculations of changes in embankment height over time

Section A-A	2012	2018	2021
Average base ordinate	271.35	269.98	269.16
Average crown height	277.83	276.32	275.29
Height of the embankment (m)	**6.48**	**6.34**	**6.13**

Calculations generated from the DTM of the cross sections show that the height of the embankment at cross section A-A is decreasing over time. This is certainly related to the ongoing mining operations. This decreasing height can be interpreted in this case as a sinking phenomenon of the embankment. The embankment has been in the zone of land deformation twice. During the first mining operation in 2014-16, the mining front passed under the embankment (Fig. 7a). During the second operation (Fig. 7b), the embankment was already on the edge of the basin, which, according to the theory [46], is a zone of horizontal tensile deformations, particularly dangerous due to the additional lowering of the embankment [14, 47, 48]. Comparing the lowering of the cross-sectional control points in the mesh generated, it is clear that the lowering of the points outside the embankment is slightly more than 2 meters, while the crown of the embankment lowered by 2.5 meters (Fig. 19 – middle zone).

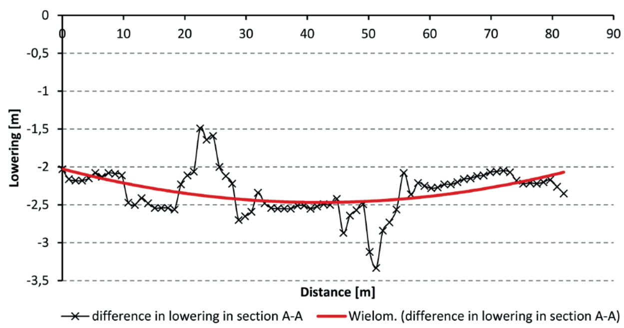

Fig. 19. Decrease in the characteristic points of cross-section A-A with DTM over time (2012-2021)

In addition to the subsidence, the influence of horizontal strain can also be seen in the graph (Fig. 19). The embankment has shifted in the direction of the exploited parcel (exploitation in 2018-2020) (Fig. 7b – to the left). Comparing the depressions, it can be seen that the points next to the embankment have suffered uplifts and others (to the right) have suffered strong depressions. In fact, these places are the slopes of the embankment. As a result of the horizontal shift, the embankment in 2014 is in a different place than in 2021. If the embankment moved only vertically, the graph of vertical strain would be undisturbed by the effect of the horizontal shift. Introducing the trend line into the obtained depressions, it is clear that its character is concave (parabolic), suggesting depressions greater in the middle zone of the section – at the site of the embankment. This result confirms the fact of depicting the sinking effect of the object.

8. SUMMARY

The extensive data set collected in GIS databases now offers new possibilities. DTM numerical terrain models allow imaging of phenomena previously difficult to observe with classical techniques. One such issue is additional lowering of embankments in areas of active mining activity. Monitoring this phenomenon for the analyzed embankment would be difficult to implement based on classical techniques. Thanks to DTM analyses, the possibility of its recognition on a larger scale than before opens up. In the present study, the average error of height estimation from the digital terrain model relative to reference data in the form of precision leveling was about $m_h = 0.05$ m (Fig. 13). This result confirms the usefulness of DTM for observing phenomena in areas of mining activity when the area of analysis has little spatial variation.

The advantage of classical measurements is certainly accuracy. Consequently, the significant limitation of DTM comparative analyses is the obtained result accuracy and the variability over time of the height determination error components in the form of field, instrumental and environmental factors. Nevertheless, technological advances and increasingly widespread access to laser scanning systems for unmanned aerial vehicles are likely to address previous shortcomings related to the accuracy and repeatability of obtained observations from ALS [49]. The DTM verification presented in the paper gave satisfactory results in this regard. Of course, measurement errors at the level of a few cm are in many cases an unacceptable threshold. Nevertheless, in the case of capturing the phenomenon of additional lowering of embankments, the quantities sought can exceed the measurement error resulting from the quality of the DTM product.

It is worth mentioning that DTM comparative analyses can also be useful for imaging sinkholes and differential subsidence over time caused by a mechanism other than mining activity. This is because the data stored in GIS databases allows for backward analyses of so-called weak points, i.e. places where damage has occurred. The results of DTM comparative analysis can be an important input in research work aimed at determining the causes of failure of road embankments in the zone of deforming ground surface. The end products derived from ALS data can reveal masked sinkholes and identify the most active ones, which should be monitored in detail.

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