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ORIGINAL ARTICLE

The use of geodetic measurements in the assessment of the technical condition of road pavement – case study

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Abstract

Technical infrastructure is exposed to environmental impacts throughout its entire life cycle. For linear objects, such as roads, additional impacts resulting from their continuous use – vehicle traffic – are distinguished. Due to their communication function, these facilities are subject to ongoing condition monitoring. This procedure allows to identify any damage and indicate appropriate protective measures. Observations of the terrain as well as the road surface can be carried out using commonly used geodetic measurements. Cyclic monitoring applies especially to facilities in mining areas, where impacts in the form of continuous and discontinuous deformations significantly contribute to their damage. The research presents the results of selected geodetic measurements made on a deformed road surface affected by underground mining. The aim of the observations was to use both classic and modern measurement techniques to determine, among others, the shape of the surface or identify damage. The applied measurements included commonly used total station measurements and GNSS satellite positioning. Additionally, low-ceiling photogrammetry using an unmanned aerial vehicle and laser scanning were used to illustrate the shape of the road surface. Finally, a comparison was made of selected methods; their advantages and disadvantages allowed us to determine their usefulness in monitoring the condition of the pavement.

Key words: road pavements, geodetic monitoring, damage identification

1 Introduction

Linear objects such as roads are subject to constant environmental impacts. Designed for vehicular traffic, they are exposed to cyclical loads, which later results in deterioration of the quality of the surface used. Due to their communication function, roads should be subject to inspection of their technical condition (Hedel et al., 2018). This particularly applies to roads running in mining areas, where we are dealing with additional impacts, among others, of slopes and deformations of the ground, as was written about, among others, in Bell and Donnelly (2006); Boginska et al. (2020); Grygierek and Kalisz (2018); Kratzsch and Fleming (2007); Kwiatek (2007).

Deformations significantly worsen the condition of the road surface, threatening the safety of use. If discontinuous deformations are revealed – understood as a break in the continuity of the soil – the layers constituting the pavement structure loosen, and thus its stiffness decreases. All this reduces the fatigue life of the surface, which results in frequent repairs (Grygierek, 2017).

The pavement condition is assessed based on measurements of the technical and operational characteristics of the surface (Pavement Condition Diagnostics, 2019). The basic features of the pavement include load-bearing capacity, evenness, anti-slip properties and surface features. The data obtained on the technical condition of the pavement, together with information on vehicle traffic, are an important element used in the road management process. For example, in the case of assessing changes in the load-bearing capacity of the pavement, a Falling Weight Deflectometer (FWD) dynamic deflectometer can be used. The FWD device enables the measurement of pavement deflections as a response of the tested structure to an impact of a known force value. The deflection results can be used, among other things, to determine pavement weakening zones (Grygierek and J. Sternik, 2020).

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Geometric data of the road surface and, therefore, its shape can be obtained using geodetic measurements. Geodetic measurements enable the calculation of current road parameters in longitudinal and cross-section. These parameters should meet the requirements specified in technical documents, including legal regulations (Regulation, 2022). The most important geometric elements of the road assessed include: the longitudinal slope of the grade line, the radii of vertical curves, the length of the visible section on the vertical curve and the transverse slope of the road. In the case of mining areas, due to the dynamics of changes in surface shape, measurements monitoring the condition of road surfaces are performed periodically.

The paper presents the results of selected geodetic measurements performed on a deformed road surface affected by underground mining. The aim of the research was to use both classic and modern measurement techniques to determine the shape of the surface and identify any damage. The measurements included tachymetry, GNSS satellite positioning, low-ceiling photogrammetry using an unmanned aircraft, and laser scanning. Their usefulness in monitoring pavement condition is presented in this article.

2 Characteristics of measurement methods used in mining areas

In mining areas, deformation is monitored mainly by classical measurements of vertical and horizontal displacements. In practice, technical or precise leveling is most often used to determine vertical displacements, depending on the required measurement accuracy (Kulupa et al., 2021). Average precision leveling errors range from 0.3 mm to 2 mm per 1 km of the leveling line, while for technical leveling they range from 4 mm to 20 mm per 1 km of the line (depending on the required measurement class). However, GNSS positioning measurements, including Real Time Kinematic (RTK) measurements, are most commonly used to determine both horizontal and vertical displacements (Vrublova et al., 2016). Due to the speed of measurement and sufficient accuracy, GPS measurements are widely used in mining areas. The average measurement errors reach 8 mm + 1 ppm for the horizontal position and 15 mm + 1 ppm for the height position. To obtain more accurate measurement results, total station is used (Artese and Perrelli, 2018; Baykal et al., 2005). The accuracy of the obtained data will depend on the accuracy of measuring the distance to the prism (assumed 1 mm + 1 ppm ÷ 2 mm + 2 ppm) and the accuracy of reading the horizontal and vertical directions (1” ÷ 5”).

The development of new technologies has enabled the use of scanning devices such as terrestrial laser scanning, which allows obtaining a large amount of measurement data, the so-called point clouds (Monserrat and Crosetto, 2008). A similar effect can be achieved using photogrammetry, including low-ceiling photogrammetry by unmanned aerial vehicles (Karsznia, 2017; Ren et al., 2019). Remote techniques also include airborne laser scanning (ALS) (Lay et al., 2019) and radar interferometry (InSAR) (Nam et al., 2020), being a good measurement solution for large areas subject to deformation. In addition, the basic measurements used in road construction that are sensitive to the effects of mining include: longitudinal evenness measurements, transverse evenness measurements and surface deflection measurements (Wróblewska and Grygierek, 2022), the results of which are used to estimate the fatigue life of the pavement. Thanks to the significant development of measurement techniques using fiber optic sensors, it has recently become possible to use sensors to observe vertical displacements (Bzówka et al., 2021), which can describe deformations of the ground of linear objects, including road embankments (Bednarski et al., 2021).

Figure 1. Example of the deformed surface of the tested road section

Figure 2. An example of pavement damage in the form of linear, discontinuous surface deformations

Measurement accuracies in the case of modern measurement techniques such as laser scanning or low-ceiling photogrammetry will depend on many factors, including:

- accuracy parameters of the equipment used,
- weather conditions during the measurements,
- adopted measurement settings/flight parameters,
- options used when processing measurement data.

Additionally, in the case of low-ceiling photogrammetry, there is the issue of aligning the photos from the raid and matching them to the tie points.

Comparison of modern measurement methods together with accuracy analyzes on the example of monitoring terrain and facilities, including construction, was carried out in many research works, including: Bęcek et al. (2015); Dreier et al. (2022); Hayakawa et al. (2016); Muszyński and Rybak (2017); Wróblewska and Grygierek (2022). Existing studies of object deformation with low-ceiling photogrammetry using a drone most often indicate accuracies of up to 3 cm for situational measurements and up to 5 cm for height measurements. In the case of terrestrial laser scanning, the results depend on the distance to the measured object, usually in the range of 2 ÷ 6 mm per 10 m.

3 Assessment of deformation of the pavement under the influence of mining

3.1 Characteristics of the research object

Observations of pavement deformations were carried out on a section of a provincial road in the southern part of Poland. The road, put into use in 2017, consists of two lanes with traffic category KR6 (Judycki et al., 2017), which corresponds to the penultimate category of the highest traffic load. Since 1974, the area has been affected by underground mining, currently carried out at depths of over 1000 m. The mining impacts reach category IV of the mining area, which contributed to the deformation of the area, including damage to the road surface. The observed impacts include surface unevenness (Figure 1) and transverse cracks of considerable width and mutual displacement of the surface edges in the vertical plane (Figure 2).

Figure 3. Stabilization of points along the right-of-way

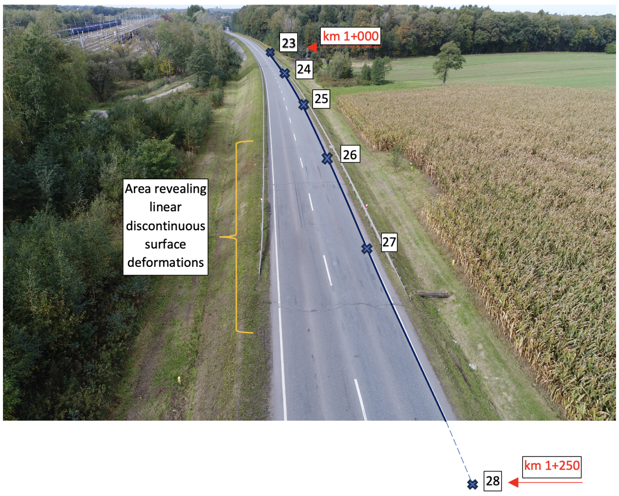


Figure 4. The course of the tested road section along with the area revealing linear discontinuous deformations of the pavement

3.2 Geodetic measurements

The research program included part of the observation line consisting of a total of 37 points permanently stabilized along the edge of the road (Figure 3). The distance between the points was 50 m. Observations were carried out over a distance of 250 m, starting from 1+000 km of the road. This section was characterized by a deformed pavement with the disclosure of linear discontinuous surface deformations (Figure 4).

In accordance with common practice, the measurements began with the use of the GNSS satellite method at measurement points located every 50 m on the left side of the road (according to the increase in mileage). For this purpose, the RTK technique was used. Then, condensing the measurement points every 25 m, marking them with paint, classic measurements were performed – using a total station. Points were measured both on the left and right sides and in the road axis. In order to determine the coordinates of the points, a geodetic network was established consisting of the station and two reference points, previously measured using the static GNSS method. Both methods such as GNSS and total station made it possible to determine the coordinates of individual measurement points.

Low-ceiling photogrammetry and laser scanning were used to image the road surface in much detail. The techniques used enabled the creation of a dense point cloud. A multi-rotor aircraft equipped with a camera with a 1-inch 20 MP matrix was used to perform low-ceiling photogrammetric measurements over the considered area. The flight parameters included: double flight trajectory – usually dedicated to 3D models, height of 30 m – giving a resolution of 0.83 cm/pix, and longitudinal and transverse photo coverage of

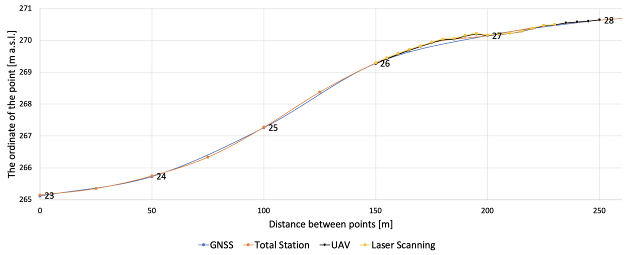


Figure 5. Graph of point ordinates for the observed measurement line divided into the measurement methods used

80%. The post-processing stage included aligning the photos and matching them to ground reference points (measured using GNSS techniques). The final point cloud density of 515 points/m^2 was obtained.

For scanning, a 1 kg laser scanner equipped with a 3-camera 15.1 MP system was used. The accuracy of 3D measurement is approximately 6 mm/10 m; 8 mm/ 20 m. The maximum range was 60 m, so measurements were taken from 7 positions. The data obtained from individual positions were combined to obtain a dense point cloud.

GNSS and total station measurements were made at points marked in the field. In the case of photogrammetric measurements and laser scanning, points were concentrated along the measurement line (every 5 m) based on point clouds.

3.3 Measurement results, comparative analysis

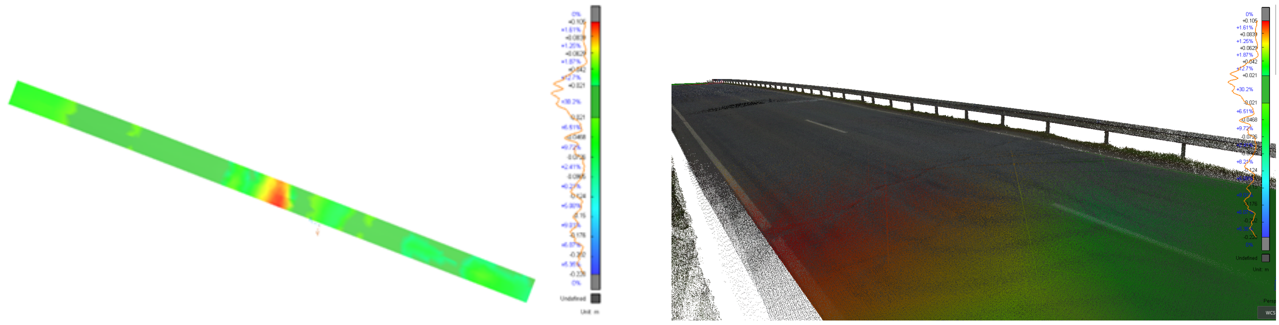
a) Observations along the survey line

The assessment of changes in surface shape began with determining the road grade based on the obtained measurement ordinates. The results obtained, divided into the measurement methods used, are summarized in Figure 5. This summary shows good compliance of the measurement methods used. Additionally, it was noticed that for the 50 m point spacing (GNSS) the surface deformations were not captured sufficiently. Therefore, in the further part of the analysis, the possibilities of using data from total station, low-ceiling photogrammetry and laser scanning were examined for detailed identification of the resulting zones of linear deformation.

b) Surface observations of the pavement

In order to compare the measurement methods used for detailed observation of the deformed surface, the measurement results from total station measurement with low-ceiling photogrammetry (Figure 6) and low-ceiling photogrammetry with laser scanning (Figure 7) were compared. These illustrations allowed us to notice that where linear discontinuous surface deformations are revealed, there is a discrepancy of up to 10 cm between the total station measurement performed every 25 m and the photogrammetric measurement. Nevertheless, the advantage is the remaining area showing significant measurement agreement between both methods used.

The comparison also concerned the generated point clouds in the case of photogrammetry and laser scanning. The expected result was high compliance of both methods, also in the discontinuity zone itself, reaching practically to zero.



(a) (b)

Figure 6. Comparison of total station and photogrammetric measurement results to illustrate the surface of the deformed road: (a) – view from above, (b) – 3D view

c) Analysis of discontinuity zones

The most favorable analysis of discontinuity zones involves calculating the surface curvature and then distributing the standard deviation for the next 4 values (Wróblewska and Grygierek, 2022). For this purpose, the deformation index in the form of curvature was calculated based on the height data of measurement points (Figure 8) in accordance with the formula:

$$K = \frac{w_A - 2w_B + w_C}{d_{av}^2} \tag{1}$$

where:

K – curvature between two segments AB and BC,
w_A, w_B, w_C – subsidence of points A, B and C,
d_{av} – average distance between points A, B and C,
$A, B, C...$ – consecutive measurement points in the measurement line.

Then the standard deviation was calculated according to the formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(K_i - K_{av})^2}{(n-1)}} \tag{2}$$

where:

σ – standard deviation,
K_i – consecutive curvature values,
K_{av} – arithmetic average of the curvature values,
n – number of points.

The normal distribution is a measure of the observed surface roughness (Figure 9). In this case, the standard deviation outside the deformation region is $\sigma < 1{,}0\ \mathrm{km}^{-1}$, and in the area of inequality, it is maximum $\sigma = 3{,}4\ \mathrm{km}^{-1}$, which is a difference over 300%. The shape of the obtained distributions is similar for both point clouds obtained, i.e. from photogrammetric measurement and laser scanning.

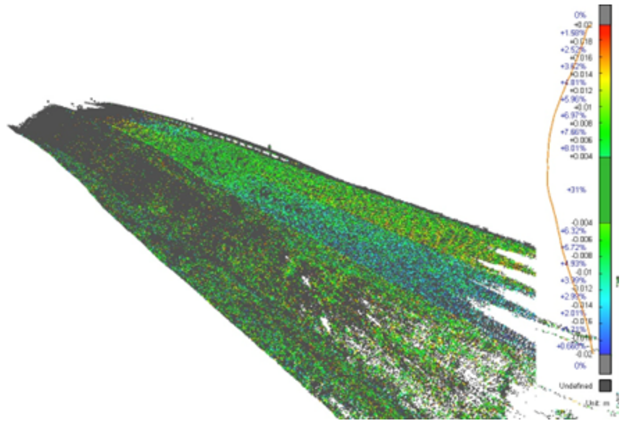


Figure 7. Comparison of photogrammetric measurement results with laser scanning to illustrate the surface of a deformed road

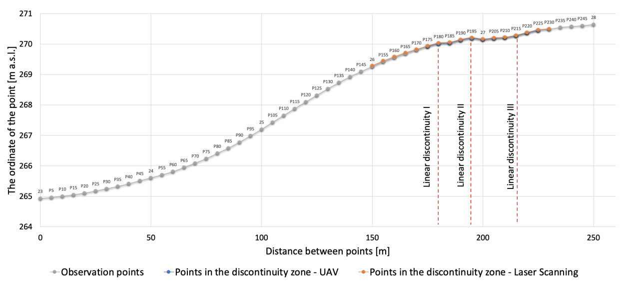


Figure 8. Graph of point ordinates for the observed measurement line along the tested road section with the zone of observed discontinuities

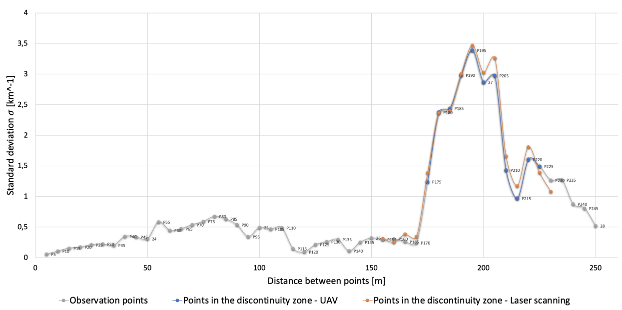


Figure 9. Distribution of standard deviation along the tested road section along with the zone of observed discontinuities, divided into UAV measurement and laser scanning

4 Summary

The effects of mining exploitation occurring in the communication area require constant observations. The basic observation methods include geodetic measurements on stabilized points in the field and determining their X, Y, Z coordinates. Today, these standard measurements can be supplemented with data from new measurement technologies, including low-ceiling photogrammetry and laser scanning, thus obtaining data with incomparably higher resolution than in the case of classic measurement methods.

The ability to identify damage on the road surface will largely depend on the density of measurement points. Therefore, operations on dense point clouds allow for a detailed determination of road surface deformation and, therefore, the scope of required repair of road features describing its course in the longitudinal and transverse profiles. As a result, a deformed area was observed, where, according to the analysis, a normal distribution of curvature exceeding 300% was captured.

Both methods used for the examined object, i.e. UAV measurement and laser scanning, enabled the identification of damage with appropriate detail. Accuracy of the order of millimeters for laser scanning and centimeters for UAV measurements should be indicated. Undoubtedly, the amount of field work needed to collect the necessary data for the research area, which is roads, is much greater for 3D scanning technology than needed to take photos from an unmanned aerial vehicle. Data processing also showed a huge amount of "noise" resulting from the constant movement of vehicles. Nevertheless, the direct product we obtain after scanning is a ready point cloud, and in the case of photogrammetry we need to perform several necessary processing steps. In both cases, the process of georeferencing the point cloud must be taken into account, which unfortunately requires measurement using traditional geodetic methods. Despite the preparatory work, both methods significantly exceed the capabilities of traditional measurement technologies, making it much easier to perform more measurements.

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