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# The influence of underground coal mining on an overhead high-voltage power line

# Wpływ podziemnej eksploatacji pokładów węgla na linię elektroenergetyczną wysokiego napięcia

**Abstract**

The primary aim of this study is the analysis of the influence of multi-seam coal mining on a specific 110 kV overhead high-voltage power line. The paper presents the results of geodesic measurements of surface deformation in the area of the analysed location. The study also analyses mining-induced changes in the construction and the inclination of the transmission pylons. Some proposals for the reinforcement of the pylons are suggested. Additionally, pressing issues are identified indicating the necessity for the replacement of the existing pylon system of the overhead high-voltage power line.

**Keywords:** mining, surface deformations, power line protection

**Streszczenie:**

W artykule poddano analizie wpływ prowadzenia wielopokładowej eksploatacji węgla kamiennego na wybrany odcinek linii wysokiego napięcia 110 kV. W artykule zamieszczono geodezyjne wyniki deformacji powierzchni terenu w rejonie analizowanego obiektu. W dalszej części dokonano analizy zmian zachodzących w konstrukcji słupów oraz ich wychyleń w zależności od stopnia zaawansowania eksploatacji dokonanej i planowanej. Podano także przykłady wzmocnienia istniejących słupów oraz warunki, w których powinna nastąpić wymiana słupów linii wysokiego napięcia.

**Słowa kluczowe:** górnictwo, deformacje powierzchni, ochrona linii energetycznej

## 1. Introduction

Underground mining, particularly when executed without the backfilling of post-exploitation voids, usually causes surface deformation. In the case of multi-seam coal mining, such deformations are pronounced; hence, it is necessary to evaluate the impact of underground exploitation on the existing surface structures [6–8, 14]. Due to a high level of public safety risk, large structures – in particular, public buildings and blocks of flats or large industrial plants – are the focus for monitoring attention in these situations. Additionally, various types of transmission lines constitute an important element of surface infrastructure. In the case of overhead power lines, mining-induced uneven distribution of load on the supporting posts may occur – this is particularly dangerous. The significant height of high-voltage power line transmission pylons makes them especially vulnerable to surface inclination and horizontal surface displacement – these factors can cause changes in pylon span and power line cable tension. Such an increase in the construction-related internal forces may cause damage to an individual transmission pylon or even to the entire power line [1, 2, 4, 5].

For this reason, overhead high-voltage power lines designed and newly constructed in mining areas are fulfil far stricter standards and restrictions than those built elsewhere [11, 12, 13]. Such requirements may also include the need to increase the distance of the power lines from ground level and possible colliding elements by 1–2m, and to decrease tensioning of the electric lines to 0.8–0.9 permissible normal stress (for the line type AFL 6-240, permissible normal stress is 119.91 MPa), to protect the transmission plyon foundations against ground movement in locations designated as fourth-category mining areas and to refrain from the construction of any power lines in fifth-category mining areas or in areas with discontinuous deformation.

In areas subject to mining subsidence, it is hardly possible to build a power line which is completely protected against all negative consequences of mining activity. Therefore, in mining areas, the power transmission lines are monitored regularly and more frequently than elsewhere, this is stipulated in the related regulations. Currently, according to construction law in Poland, the span of time between two consecutive checks must not exceed five years [15]. The examinations are made by the institutions operating particular power lines and their main objective is to undertake adequate repairs and maintenance in order to avoid the occurrence of any critical circumstances.

This paper sets out to analyse the impact of multi-layer coal mining on a selected section of overhead high-voltage power transmission line. The results of geodesic measurements of surface deformation are presented as well as the analyses of changes in the construction and inclination of transmission pylons depending upon the degree of mining progression. Some examples of reinforcement of the currently existing pylons are also discussed and the critical boundary conditions in which the transmission pylons of the overhead high-voltage power line (110 kV) should be definitely replaced are determined.

## 2. Subject of research and observational study results

The analysed overhead power line (110 kV) runs through the area above an underground coal mine and is mostly fixed on the O24-series suspension lattice pylons supported on four independent foundations. Over the last three decades, the transmission pylons have been subject to the influence of mining activity; hence, geodesic measurements are routinely carried out in observation lines no. XIII–XIII and no. XV–XV as part of a regular monitoring scheme to evaluate the impact of exploitation. Line XIII–XIII consists of a total of 61 points and the measurements have been taken since 1997. In the case of line XV–XV, the measurements have been regularly carried out since 2011. Some points along line XIII–XIII, situated at spacings of 20–200 m from the transmission pylons, were used in this study (Fig. 1).

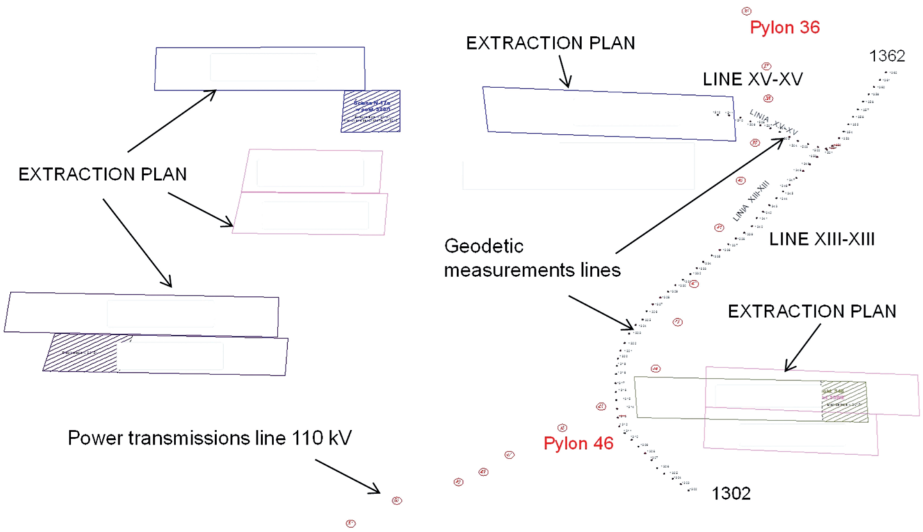


Fig. 1. Location of the power transmission line, measurements geodetic lines and the extraction plan to the year 2018

The measurement results indicate that there is a mining-induced surface subsidence in the range 3.0–6.0 m (Fig. 2, 3), depending upon which point was taken as the point of reference. A detailed analysis of the land survey point of reference proves that some transmission pylons subsided by as much as 4.0–5.0 m – this was a change which was not uniform over time and caused uneven subsidence of the pylons, i.e. their inclination from the vertical plane.

The observation study shows that the ground movements and varied direction of the strains (compressive and tensile) caused ground weakness i.e. discontinuous deformations. Mining induced changes occurring in the surface resulted in: changes of distances between the transmission pylon footings; the occurrence of cracks in spread footings; damage to reinforcement in transmission pylon footings; increase or decrease of the sag of overhead electrical conductors.

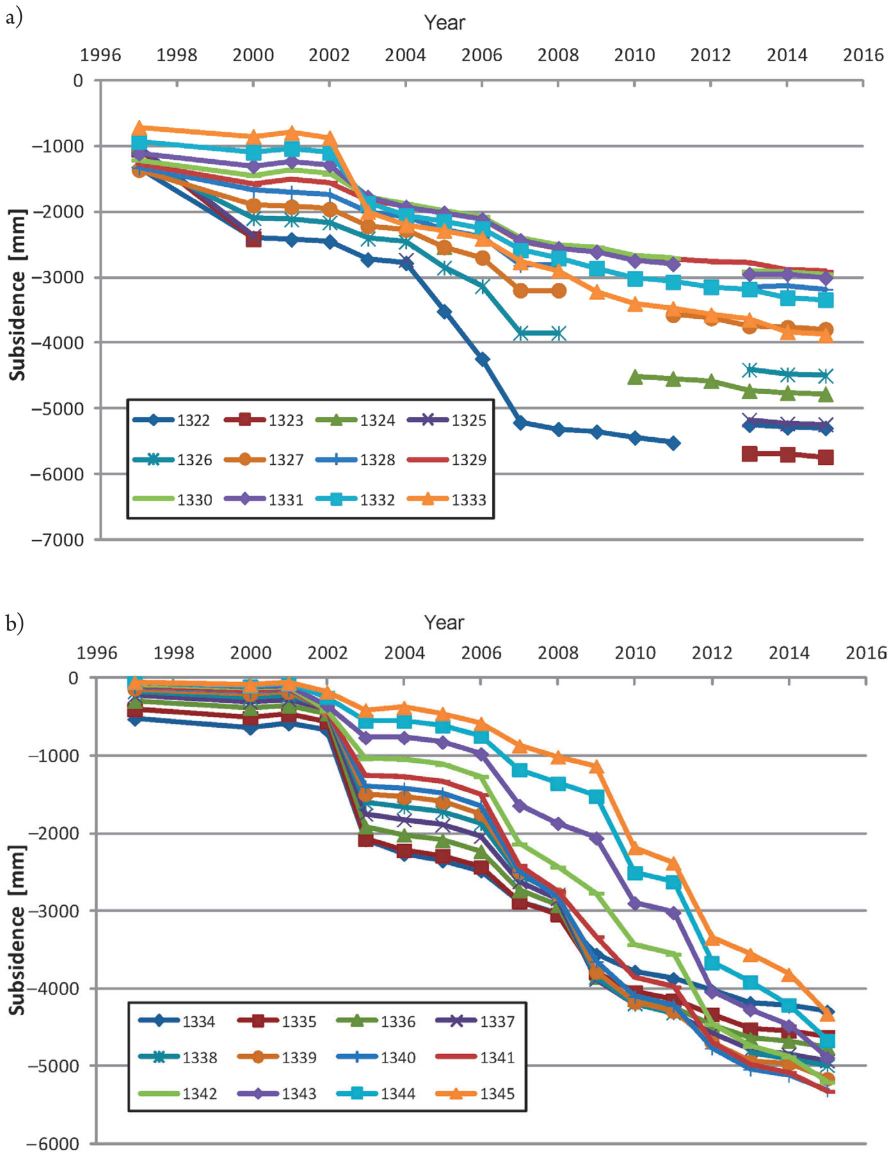


Fig. 2. Subsidence of selected points in measurement line XIII – XIII: a) for points 1322–1338; b) for points 1334–1345

As part of the observation study of the power line, measurements of transmission pylon inclinations were also carried out. According to the standards PN-84/B-03205 [9], horizontal deflection of the transmission pylon peak is H/50 where *H* is the height of the pylon ($tg\alpha = 0.02$). The latest standards [10] individually determined the permissible inclinations of pylons in the mining area. For these conditions the inclination $tg\alpha = 0.015$ for pylons was treated by electric power transmission's company owner power line as secure.

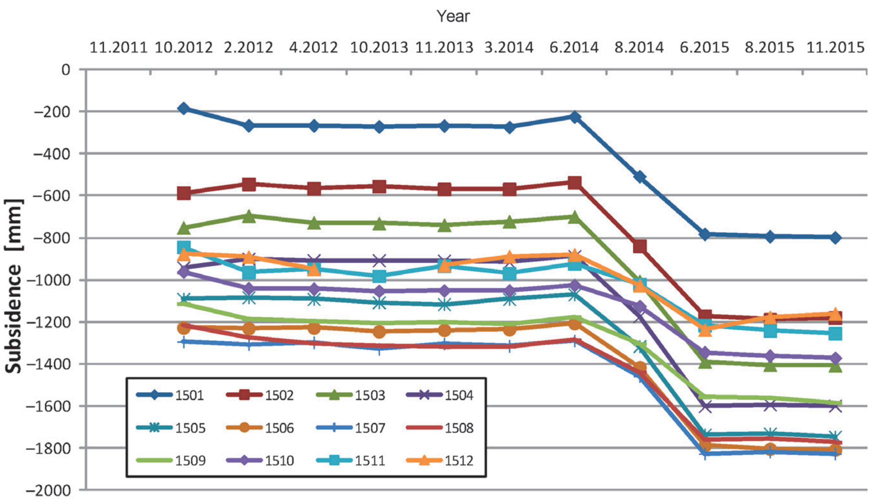

Fig. 3. Subsidence of points in measurement line XV–XV

Due to the varied height of each of the transmission pylons, a different value of displacement the top of pylons from the vertical axis was assumed for each of them. The results of measurements displacements of the tops of the pylons is shown in Table 1. In the year 2015, only transmission pylon no. 38 had exceeded the permissible value of inclination. It was subject to corrective action.

Analysis of measurements from the last 10 years indicates that over time, there are both increases and decreases in the inclination of the transmission pylons – this is related to the intensitiveness of the exploitation of the mining areas (Fig. 4). Large decreases in pylon inclination are related to works to restore them to the vertical (e.g. transmission pylon no. 45), and in the case of transmission pylon no. 39, this was due to its total replacement.

Table 1. The results of the inclination measurements in 2015

| No. | Pylon number | Height of the pylon [m] | Displacement of the top of the pylon [mm] | Inclination tgα |
|---|---|---|---|---|
| 1 | 37 | 23.40 | 178 | 0.0076 |
| 2 | 38 | 19.10 | 371 | 0.0194 |
| 3 | 39 | 40.53 | 126 | 0.0031 |
| 4 | 40 | 26.60 | 220 | 0.0083 |
| 5 | 41 | 25.10 | 370 | 0.0147 |
| 6 | 42 | 26.30 | 321 | 0.0122 |
| 7 | 43 | 23.60 | 66 | 0.0028 |
| 8 | 44 | 22.15 | 52 | 0.0024 |
| 9 | 45 | 26.20 | 54 | 0.0021 |
| 10 | 46 | 21.25 | 300 | 0.0141 |

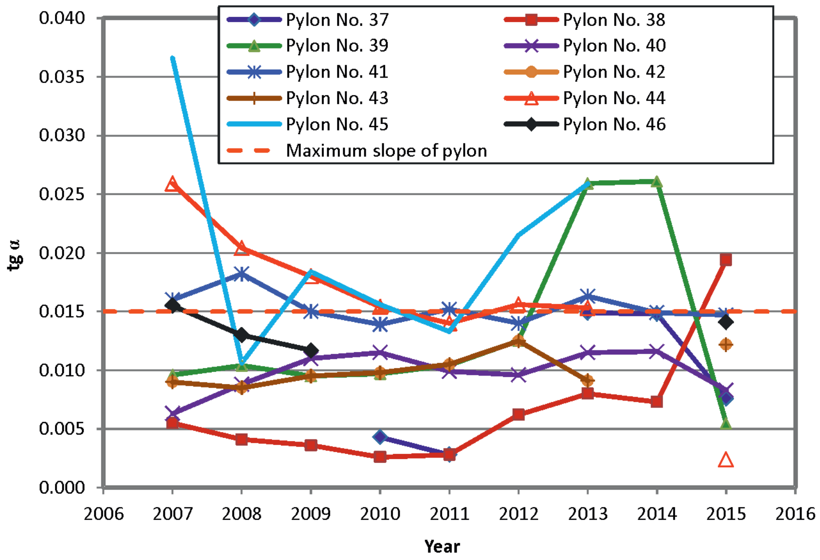


Fig. 4. Change of transmission pylon inclination over time

## 3. Prediction of the influence of the planned exploitation on the power line

In relation to the planned exploitation in the years 2015–2018, prognostic calculations of surface deformation in the area of the analysed power line were carried out. The day of the last measurements of pylon inclination was assumed as the beginning of the calculation period. The calculations of deformation indices were based on Budryk-Knothe theory [6].

A clockwise coordinate system to describe mining subsidence was adopted (Fig. 5):

- coordinate system ξη for the extracting area;
- coordinate system *xy* for the surface point *P*(*x*, *y*).

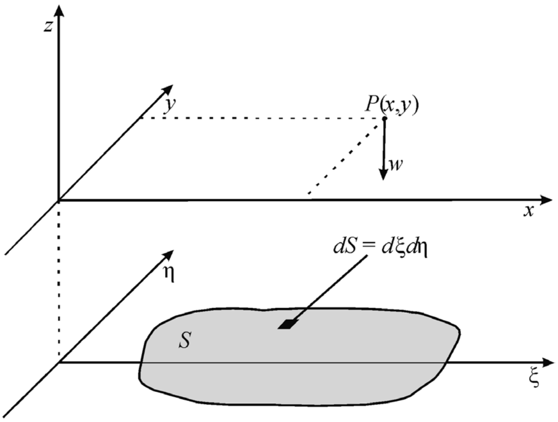


Fig. 5. Coordinate systems used to describe mining subsidence

Maths formulas for subsidence and surface tilt are follows:

- surface subsidence:

$$w(x,y)=\frac{w_{\max}}{r^2}\iint\limits_S \exp\left[-\frac{\pi}{r^2}\left[(\xi-x)^2+(\eta-y)^2\right]\right]dS \tag{1}$$

- surface tilt:

$$T_x=\frac{\partial w(x,y)}{\partial x} \qquad T_y=\frac{\partial w(x,y)}{\partial y} \tag{2}$$

$$T_\alpha=T_x\cos\alpha+T_y\sin\alpha \qquad T_\alpha=T_x\cos\alpha+T_y\sin\alpha \tag{3}$$

where:

$w(x, y)$ – surface subsidence in the point $P$, m;
$w_{\max}$ – maximum surface subsidence, $w_{\max} = a \cdot g$, m;
$a$ – subsidence factor depending from backfilling system, $a = 0.2 \div 0.9$,
$g$ – seam thickness, m;
$r$ – the radius of the zone of mining influence on surface, $r = H \cdot \mathrm{ctg}\beta$, m;
$H$ – seam depth, m;
$\beta$ – angle of draw, °;
$S$ – extracting area, $m^2$;
$\xi, \lambda$ – coordinates for the extracting area $dS$, m;
$x, y$ – coordinates for the points in the surface, m;
$T_x$, $T_y$ – surface tilt in directions $x$ and $y$, mm/m;
$T_\alpha$ – surface tilt in directions $\alpha$, mm/m;
$\alpha$ – angle between $x$ direction and object line (eg. power line), °.

The parameters of the model assumed for the calculations and specified below refer to the history of the coal mine: tangent of the angle of influence range in Knothe theory – $\mathrm{tg}\beta = 2.0$; subsidence factor dependent from backfilling system $a = 0.75$; the coefficient of proportionality between the vertical and horizontal deformation indices – $B = 0.40$.

Prognostic calculations indicate that the increase of deformation indices for the target situation will assume the highest value in the area of transmission pylons marked as 38, 39 and 44. In the immediate vicinity of pylon no. 44, the subsidence will reach approx. 0.7 m (Fig. 6), whereas in the area of the pylons nos. 38–40, 43 and 45, the surface subsidence will range between 0.2 and 0.5 m. Additionally, at a distance of approx. 500 m east from transmission pylon no. 44, the predicted subsidence slightly exceeds a value of 3.0 m.

All of the above should be reviewed with two flights to take account of wind load. The highest level of accuracy currently available is about 1.5 cm – this is sufficient for this purpose.

Surface tilt seems to be a crucial parameter from the perspective of transmission pylon safety. The prognostic calculations clearly indicate that the tilt will reach around 3.0–3.5 mm/m in the area of pylon no. 44, whereas in the case of the remaining pylons, the tilt should not exceed 2.5 mm/m (Fig. 7). The maximum value of this parameter is much higher and sligthly exceeds the value of 10 mm/m.

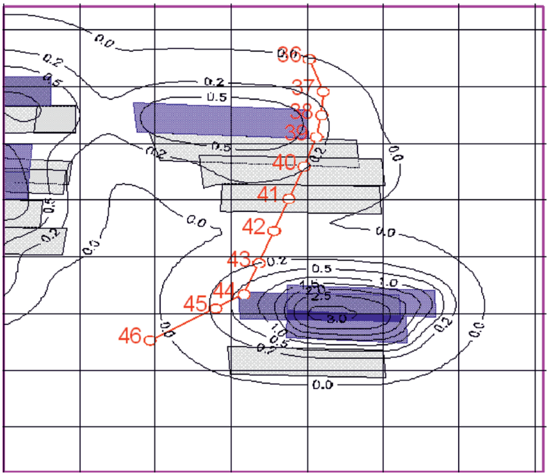


Fig. 6. Target increase of surface subsidence for the mining exploitation planned for the years 2015–2018

The prognostic calculations also indicate that the mining-induced increase of surface deformation in the period 2015–2018 will result in the increase of deformation indices in the area of the 110 kV high-voltage power line, especially in the vicinity of transmission pylons nos. 43–45 and, to a far lower degree, in the vicinity of pylons nos. 38–40. Hence, the mining exploitation will negatively affect their technical status as it will cause changes in the tension of the overhead transmission lines and, thus, increases in the inclinations of the transmission pylons.

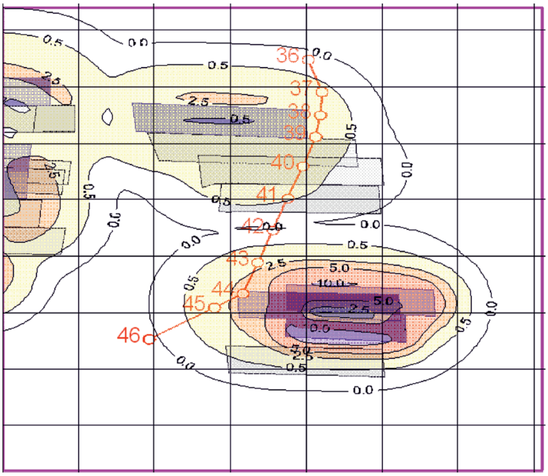


Fig. 7. Target increase of surface tilt for the mining exploitation planned for the years 2015–2018

In order to precisely predict the potential changes likely to occur around the transmission pylons of the analysed electric power line, prognostic calculations of surface deformation indices were carried out for the coordinates of the pylons' centres. This enabled the obtaining of information on the influence of the predicted direction of tilt on the inclination of particular transmission pylons. Depending on the location of the planned exploitation, it may cause either an increase or decrease of the hitherto recorded inclination.

With reference to the measurement results of the inclination of particular transmission pylons of the analysed 110 kV high-voltage power line, as well as on the basis of the calculations of the predicted increase of surface tilt, deformation and subsidence, it can be argued that as a result of the planned mining exploitation in the years 2015-2018, particular pylons are very likely to be affected by the changes specified in Table 2.

Table 2. Predicted changes of inclination of transmission pylons for the mining exploitation planned for the years 2015–2018

| No. | Pylon number | Current pylon inclination*) tgα | Predicted pylon inclination*) tgα |
|---|---|---|---|
| 1 | 37 | 0.0076 | 0.0085 |
| 2 | 38 | 0.0194 | 0.0201 |
| 3 | 39 | 0.0031 | 0.0047 |
| 4 | 40 | 0.0083 | 0.0091 |
| 5 | 41 | 0.0147 | 0.0146 |
| 6 | 42 | 0.0122 | 0.0122 |
| 7 | 43 | 0.0028 | 0.0019 |
| 8 | 44 | 0.0024 | 0.0052 |
| 9 | 45 | 0.0021 | 0.0037 |
| 10 | 46 | 0.0141 | 0.0141 |

*) boundary inclination of transmission pylons tgα > 0.015

In summary, the highest increase of inclination, also assuming their direction, are predicted for transmission lines nos. 38–40 and 43–45. Locally, a decrease of pylon inclination is expected relative to the existing inclination (pylon nos. 41 & 43). However, it is worth noting the fact that during the last measurement in September 2015, measurements that seriously exceeded the acceptable value of inclination were recorded for pylon no. 38; there were also values close to the critical point of inclination for pylons nos. 41 and 46. In those cases, it was absolutely necessary to employ some safety measures.

## 4. Preventive measures and repairs to electric power line

The prognostic calculations indicated that mining with roof caving planned in the area of the power line will cause the occurrence of further impacts on the terrain surface, such as the increase of surface subsidence and the appearance of additional increased horizontal deformation and surface tilt. Therefore, the powerline operator may expect that there will be a necessity to undertake additional repairs and servicing work. Such activities may embrace the need to reinforce the transmission pylon foundations, as well as the correction of the overhead cable tensioning.

Although the norm PN-E-05100-1:1998 [10] specifies instructions and recommendations for designing power lines in mining damage areas, in the case of large-scale deformations, engineers should, however, take into account the potential risk of exceeding the acceptable cable tensioning in power line conductors or increasing their sag to an extent that causes potentially dangerous proximity of electric conductors to ground level or other structures.

According to current regulations, the values of acceptable transmission pylon inclination are as follows:

- deviation from the vertical of the transmission pylon peak, standing without conductors, is H/300 (H – height of construction according to the standard BN-90/9056-01 [3]),
- exploitation-induced horizontal deflection of the transmission pylon peak is H/70 ($tg\alpha = 0.0143$ – according to the norm PN-84/B-03205 [9]).

Horizontal displacement and surface tilt in the locations of transmission pylon foundations are the factors causing marked changes in span length in calculations of tension. In the case of power lines with long spans running through a flat area, span length change caused by the pylon's subsidence may be ignored due to the relatively insignificant values of subsidence in relation to the powerline length. In addition, a dip, where particular transmission pylon foundations are erected, also usually causes subsidence of other objects in the immediate vicinity, hence the fact that there is a relatively low risk of a material proximity issue for power line conductors with respect to the ground or to other objects; furthermore, the potential increase of the sag of conductors seems unlikely to exceed the predicted buffer associated with the vertical distances. Free-hanging electric power conductors form the so-called catenary described by the hyperbolic function. Mining exploitation design takes into consideration the impact of mining-induced surface deformation on the functioning of electric power lines. The calculations suggest that for power lines running through areas of mining damage, one may expect levels of acceptable tensioning of powerline conductors to be exceeded or the excess of acceptable limits with regard to the inclination of transmission pylons. In the analysed case, the predicted horizontal displacement in the area of the observed transmission pylons did not exceed 0.3 m. Such factors as the elastic strain of pylons or their elements and the inclination of isolators may help mitigate the influence of span length changes on the tension of the power line conductors; however, analytical (quantitative) determination of the influence is difficult. The measurements of the sag of conductors and the inclination of transmission pylons should be periodically verified with *in situ* measurements in order to define proper preventive measures against power line damage.

Table 3 presents measurement results obtained before the planned mining exploitation in the years 2015–2018. The analysis proves that the measured sag of electric conductors is usually larger than the theoretical sag; only between the transmission pylons nos. 37–38 and 38–39, is it smaller. The above indicates irregular tension stringing in electric conductors, as well as the irregular load of steel structure pylons especially in the case of pylons nos. 39 and 38.

Table 3. Results of calculations and measurements of the sag of conductors between the transmission pylons of the high-voltage power line (110 kV)

| No. | Pylon number | Pylon span length [m] | Theoretical tension of working conductors [MPa] | Sag of conductors (theoretical) [m] | Sag of conductors (measured) [m] | Distance of working conductor from ground surface [m] |
|---|---|---|---|---|---|---|
| 1 | 37–38 | 216.1 | 73.6 | 4.1 | 3.4 | 10.7 |
| 2 | 38–39 | 180.0 | 73.6 | 2.8 | 1.1 | 13.6 |
| 3 | 39–40 | 310.6 | 73.6 | 8.4 | 10.1 | 10.6 |
| 4 | 40–41 | 298.9 | 73.6 | 7.8 | 8.5 | 8.9 |
| 5 | 41–42 | 299.1 | 73.6 | 7.8 | 8.6 | 9.8 |
| 6 | 42–43 | 303.2 | 73.6 | 8.0 | 8.8 | 9.3 |
| 7 | 43–44 | 290.7 | 73.6 | 7.3 | 8.2 | 8.9 |
| 8 | 44–45 | 223.9 | 73.6 | 4.4 | 6.1 | 10.4 |

The above-mentioned changes of the terrain surface, as well as their impact on the foundations and construction of transmission pylons and the sag of electric conductors made it necessary to carry out the following repair works:

- application of additional leg bracing of transmission pylons (Fig. 8a);
- application of bracing with the possibility of restoring the pylon to the vertical (Fig. 8b);
- replacement of old transmission pylons (Fig. 8c);
- regulation of tension stringing of powerline conductors (Fig. 8d).

Protecting the pylons against mining-induced deformation is achieved in the following way:

- a horizontal system of conductors suspended on transmission pylons is recommended in areas subject to mining influences;
- in the third or higher category areas, constructions with tall pylons adjusted to take account of the appropriate monolithic foundation technology, are recommended;
- in the first and second category areas, transmission pylons with narrow constructions, adjusted to cooperate with a monolithic foundation, are recommended. It is also possible to use pylons with broad bodies adjusted to cooperate with the working elements. In second category areas, it is recommended to protect the transmission pylon members against deformation by using frame bracing;
- for considerable horizontal surface displacement, it is necessary to apply a bracing system made of steel sections at the level of the transmission pylon legs; the connection between the frame and the foundation is made with the use of foundation steel braces; the diagonals between the foundations are additionally reinforced to avoid changes in the position of particular fundamental elements; the foundations can also be strengthened with reinforced concrete structures;
- it is recommended to design the connection of the transmission pylon body with the bolts in such a way that it allows for the restoration of the pylon to the vertical in situation where its inclination exceeds the allowed displacement assumed in the project.

a)

b)

c)

d)

Fig. 8. Examples of repairs of electric power line: a) bracing of the pylon leg, b) bracing of the leg with the possibility of restoring the pylon to the vertical; c) total replacement of the transmission pylon and its foundations; d) regulation of tension stringing of electric conductors

In the case of the inclination of pylons beyond acceptable levels as a result of mining exploitation, the following repair methods are applied depending on the type of transmission pylons and the extent of inclination:

- restoring the transmission pylon to the vertical (allowing for a safe usage of the construction) and fixing the bracing frame (if it was not used earlier);
- restoring the pylon to the vertical by means of steel spacer plates inserted between the curbs of the pylon head and the foundation bolt; the thickness of spacers depends upon the degree and direction of the transmission pylon's inclination from the vertical and the spacing of the bolts;
- restoring the transmission pylon to the vertical and replacement of all deformed elements of the construction;
- cutting out the ground under the foundation (only in exceptional situations);
- rebuilding the whole transmission pylon if its repair proves impossible.

## 5. Conclusions

The study indicates that such line object as electric power lines, especially high-voltage power lines, may be subject to negative impact of underground exploitation, hence such objects should be regularly monitored (with drone flights) in order to precisely identify all changes affecting their structure. In the case of planned exploitation, it seems absolutely necessary to carry out prognostic calculations of surface deformation and the evaluation of its impact on a particular transmission pylon. Such activities will allow for planning possible repair works in advance, and in extreme cases, they will help to avoid serious failures. The following detailed conclusions can be made on the basis of the analysed case:

- mining activities affecting the analysed fragment of electric power line, classified as third category, are of resistance to mining impact, were carried out in more than a dozen seams over a period of 30 years; the values of surface subsidence measured in the analysed area during the last 20 years ranged between approx. 5.0 and 6.0 m;
- the last measurements of the inclination of transmission pylons nos. 37–46 indicate that the excessive values of inclination (i.e. tg$\alpha$ above 0.015) occur in pylon no. 38 and amount to 0.0194; in pylons nos. 41, 42 and 46, the values assume the acceptable values (tg$\alpha$ = 0.0122–0.0147);
- prognostic calculations of surface deformation indices in place of the erection of the transmission pylons indicate that the subsidence may as a maximum reach 0.7 m in the area of pylon no. 44, whereas the surface tilt in this place may increase by 2–3 mm/m; slightly lower values of deformation indices will occur in the area of pylons nos. 38–40, 43 and 45;
- the inventory showed that the condition of transmission pylons and their foundations was relatively good. There are some symptoms of corrosion of both the steel and reinforced concrete elements. In addition, the damage to bracing was observed at the level the leg of pylon no. 38. Additionally, irregular cable tensioning between particular pylons is noticeable;
- in order to continue with the safe exploitation of the electric power line in the analysed area, it seems necessary to carry out continuous regular observations focusing on the inclination of transmission pylons; in the case of several pylons, it is necessary to restore them to the vertical or to regulate their cable tensioning.

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