

Forecasting of stresses in overhead power lines running through area affected by the mining damage

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Abstract. The article presents the methodology of determining the impact of subsidence resulting from underground mining activity on the operation of overhead power lines. Exemplary results of calculations of stress in conductors has been presented. Also the method of defining the influence of factors that can mitigate the effects of land deformation, such as inclination of insulator chains and elastic deformation of overhead line towers and their crossarms, has been discussed.

1. Introduction

The planning of underground mining should take into account the impact of subsidence on buildings and technical infrastructure, including power lines. Forecasting of this impact requires knowledge of surface deformation indicators in the analyzed region in particular stages (years) of planned exploitation. Deformations may cause hazards to power lines that run through the area affected by mining damage. These hazards include the possibility of breaking the line due to exceeding the tensile strength of conductors, damaging the transmission support structures and excessive proximity of the power cables to the ground or other crossed objects. The paper presents the method of forecasting of the subsidence impact on power lines, assessment of the influence of factors that can mitigate the effects of deformation on conductors' stresses and conclusions resulting from exemplary calculations.

2. Theoretical foundations and assumptions used in calculations

The basic guidelines for the design and construction of overhead power lines can be found in the standard [1], which was withdrawn in 2003 without substitution, however most of power lines in Poland have been constructed in accordance with the requirements specified there. This standard comprises, among others, general recommendations regarding the operation of the lines running through the mining damage areas, however, the methodology for determining (calculating) the impact of subsidence on the existing line has not been defined in this standard.

During assembly of the line, the conductor should be so stretched that, under operating conditions, no maximum permissible stress is exceeded at any point of the line. The stress should not exceed elastic limit in two conditions causing the occurrence of maximum stress:

- temperature $-25\text{ }^{\circ}\text{C}$ without the ice loading,
- temperature $-5\text{ }^{\circ}\text{C}$ with the ice loading.

In the case of short spans, the greatest stress is caused by frost ($-25\text{ }^{\circ}\text{C}$) whereas for longer spans, higher stresses are caused by ice loading ($-5\text{ }^{\circ}\text{C}$). In exceptional weather conditions that occur rarely and last for a short time, the conductor may be covered by double ice loading (with a weight twice as



large as normal rime). The stress under these conditions may be greater than the allowable normal stress, but it shouldn't exceed permissible extreme stress. The second quantity subject to the normative requirements is the ground clearance of the conductors. The distance between conductors and the ground (or crossed objects) depends on the sag defined as the vertical distance between the lowest point of the conductor and the straight line connecting the suspension points of the line. The maximum sag may occur for the conductor with ice loading at $-5\text{ }^{\circ}\text{C}$ or at the maximum operating temperature.

The subsidence above the underground operation may include horizontal and vertical displacements as well as ground tilt changes at supports location. Therefore, the increase or decrease of the span length due to land deformation should be taken into account. The standard [1] comprises guidelines and recommendations for designing overhead lines in mining damage areas, but regardless of this, in the case of large deformations, exceeding the permissible stresses in the conductors is possible. Also increased sag may cause excessive proximity of conductors to the ground or other objects [2].

The basic assumption when analyzing the mechanics of conductor is to consider the change in the span length as an equivalent to the length change of the conductor with the opposite sign [2, 3]. Thus, increasing the span length by Δa is regarded as shortening the length of the conductor by Δa without change of the span length and vice versa.

The factors characterizing the terrain deformation include (figure 1):

- tilt of the terrain T ($\%$),
- horizontal deformation ε ($\%$),
- radius of deformation curvature r (m) or its reciprocal – curvature (m^{-1}),
- vertical displacement (lowering of the terrain) W (m),
- horizontal displacement u (m).

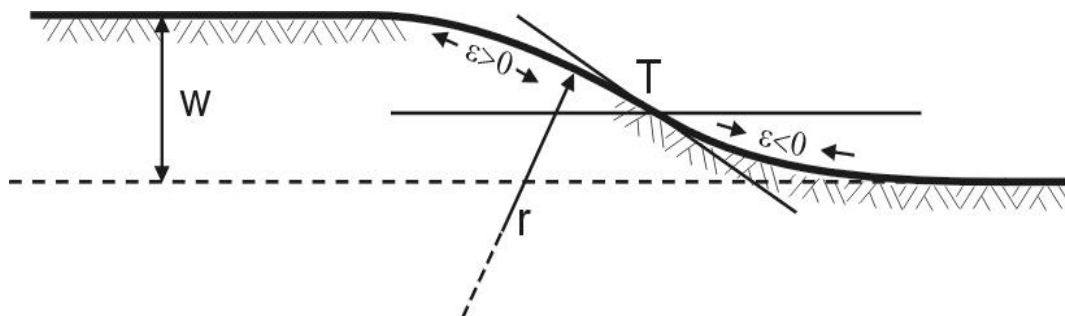


Figure 1. An example of terrain deformation and its parameters.

Only horizontal displacements and tilt at the support location can be considered as significant factors causing changes of span length in the conductor stress calculation. In most cases the change of the span length caused by the lowering the support can be omitted due to relatively small values of vertical displacements in comparison to the span length. In addition, the lowering of the area on which the support stands, usually also causes the lowering of objects under the overhead line, therefore it shouldn't cause the significant increase of the conductors' proximity to these objects.

The conductor suspended between supports is arranged in the shape of catenary curve described by the hyperbolic function. In the practical calculations, when expanding this function into a power series, only first two terms can be taken into account [4], so the hyperbolic function can be replaced by parabolic one. The stress in the conductor can be calculated from the equation of state of a conductor, in the form [2]:

$$\sigma^3 - A'\sigma^2 - B = 0 \quad (1)$$

where:

$$A' = \sigma_1 - \frac{a^2 g_1^2}{24\beta \cdot \sigma_1^2} + \frac{\alpha}{\beta} (t_1 - t) + \frac{\Delta a}{\alpha\beta} \quad (2)$$

$$B = \frac{a^2 \cdot g_0^2}{24\beta} \quad (3)$$

$$\sigma_1 = \sigma_0 - \frac{a^2 g_1^2}{8\sigma_0} \quad (4)$$

The following symbols have been adopted in the above equations:

σ - horizontal stress of a conductor (MPa),

σ_0 - stress in initial (designing) conditions (MPa),

σ_1 - horizontal stress in initial conditions (MPa),

g_1 - volumetric load in initial conditions (MN/m³),

g_0 - volumetric load in given conditions (load with the mass of the conductor g_n , load with the mass of conductor with ice loading g_s or load with the mass of conductor with double ice loading g_{sk}) (MN/m³),

a - initial span length (m),

Δa - change in the span length due to horizontal displacement and supports inclination (m),

α - conductor's thermal expansion coefficient (K⁻¹),

β - conductor's elastic elongation coefficient (m²/N),

t_1 - temperature in initial conditions, (°C),

t - temperature at which the stress σ is calculated, (°C).

Knowing the stress in the conductor under given conditions, the corresponding sag is calculated from the expression:

$$f = \frac{a^2 \cdot g_0}{8\sigma} \quad (5)$$

3. Sample calculations of conductor's stress and sag

As an example of the application of the above methodology, the results of calculations of the selected span of the actual 110 kV overhead line crossing the area with planned underground exploitation has been presented (table 1). The design span length $a=218.4$ m, the calculations refer to the AFL-6-240 conductor suspended at a height of 23.6 m. Both supports forming the span have suspension (hanging) insulators. Other data necessary for calculations were adopted in accordance with the design and assembly documentation. The planned exploitation covers a period of 16 years and the second column of table 1 presents the changes in the span length caused by terrain deformation in subsequent years (parameters determining deformation are calculated on the basis of operational plans, depth, thickness and slope of extracted beds, method of roof control etc.). Depending on the span length, the conditions under which the stress takes the maximum value have been determined (A – ice loading at -5°C, B – temperature -25°C without ice loading). Following columns of table 1 include the initial (design) conductor stress σ and corresponding sag f (under conditions A or B), stress σ_{sk} and sag f_{sk} for double ice loading as well as stress σ_{40} and sag f_{40} at 40°C.

Table 1. Results of calculations of maximum stress and sag in the exemplary span of the 110 kV overhead line

Year	Δa	Conditions	σ	f	σ_{sk}	f_{sk}	σ_{40}	f_{40}
–	(m)	–	(MPa)	(m)	(MPa)	(m)	(MPa)	(m)
1	0.13	A	71.87	5.48	96.97	5.99	34.22	6.01
2	0.22	A	79.70	4.94	105.33	5.52	37.86	5.43
3	0.17	A	75.21	5.23	100.60	5.78	35.76	5.75
4	0.24	A	82.14	4.79	107.86	5.39	39.02	5.27
5	0.32	B	<i>140.41</i>	1.46	159.30	3.65	73.08	2.81
6	0.35	B	<i>149.85</i>	1.37	165.64	3.51	78.89	2.61
7	0.43	B	<i>173.42</i>	1.19	182.20	3.19	95.41	2.16
8	0.65	B	<i>245.85</i>	0.84	239.53	2.43	158.34	1.30
9	0.67	B	<i>253.56</i>	0.81	<i>246.11</i>	2.36	165.62	1.24
10	0.64	B	<i>242.17</i>	0.85	<i>236.42</i>	2.46	154.89	1.33
11	0.63	B	<i>241.96</i>	0.85	<i>236.24</i>	2.46	154.69	1.33
12	0.63	B	<i>241.96</i>	0.85	<i>236.24</i>	2.46	154.69	1.33
13	0.92	B	<i>337.68</i>	0.61	321.68	1.81	247.37	0.83
14	1.17	B	<i>424.10</i>	0.48	403.65	1.44	333.05	0.62
15	1.07	B	<i>390.20</i>	0.53	371.17	1.57	299.35	0.69
16	1.00	B	<i>366.23</i>	0.56	348.43	1.67	275.58	0.75

According to the standard [1], the maximum permissible normal stress σ_{dn} of the steel reinforced aluminium conductor equals 40% of the tensile strength σ_m of the aluminium wires, while the maximum permissible normal disastrous stress (for double ice loading) σ_{dnk} equals $0.8 \cdot \sigma_m$. For the AFL-6-240 conductor, $\sigma_{dn} = 119.91$ MPa and $\sigma_{dnk} = 239.82$ MPa. Table 1 shows (values in italic font) that after five years from the beginning of exploitation, the extension of the span caused by terrain deformation will exceed the allowable normal stress, and after nine years also the normal disastrous stress under the double ice loading. After 13 years (values in bold font) stress may exceed the tensile strength of the conductor, which may cause the line to break.

4. Factors mitigating the subsidence effects

The assumption has been made in the above calculations that the suspension points of the conductors are fixed and the supports are rigid constructions. In fact, elastic deformation of supports and their crossarms due to unbalanced longitudinal loads as well as the change in the angle of inclination of a suspension insulators reduce the stress and maximum sag [3].

The above factors can be interrelated. For example, the elastic deformation of the support depends not only on the parameters of this support and its type (tension support with strain insulators or intermediate support with suspension insulators), but also on the distribution of tension forces on both sides of support. The aforementioned interdependence of these factors makes it difficult to accurately (analytically) define their impact on decreasing conductors' stress. It is however possible to preset the range of compensation of span length changes. The limits of this range depend on the type of support forming the span under consideration. Thus, the lower limit of distance $\Delta a'_{min}$, by which the change in the span length will be reduced, can be determined by following principles:

- for a span bounded by two intermediate supports, $\Delta a'_{min}$ will be equal to half the sum of the inclination of the insulator chains on both supports and half of the sum of the elastic deformations of the crossarms:

$$\Delta a'_{min} = 0,5(\Delta a_{i1} + \Delta a_{i2}) + 0,5(\Delta a_{c1} + \Delta a_{c2}) \quad (6)$$

- for a span bounded by intermediate support from one side and tension support from the other, $\Delta a'_{min}$ will be equal to half the sum of the inclination of the suspension insulator, half of the

elastic deformation of the tension support (at the height of the crossarm) and half of the elastic deformation of the crossarms of both supports:

$$\Delta a'_{min} = 0,5(\Delta a_i)_s + 0,5(\Delta a_i)_a + 0,5(\Delta a_c)_s + 0,5(\Delta a_c)_a \quad (7)$$

- for a span bounded by two tension supports, $\Delta a'_{min}$ will be equal to half the sum of elastic deformation of both supports and their crossarms:

$$\Delta a'_{min} = 0,5(\Delta a_{t1} + \Delta a_{t2}) + 0,5(\Delta a_{c1} + \Delta a_{c2}) \quad (8)$$

The upper limit of distance $\Delta a'_{max}$, by which the change in the span length will be reduced, can be determined as follows:

- for a span bounded by two intermediate supports:

$$\Delta a'_{max} = \Delta a_{i1} + \Delta a_{i2} + \Delta a_{c1} + \Delta a_{c2} \quad (9)$$

- for a span bounded by intermediate support and tension support:

$$\Delta a'_{max} = (\Delta a_i)_s + (\Delta a_c)_s + (\Delta a_i)_a + (\Delta a_c)_a \quad (10)$$

- for a span bounded by two tension supports:

$$\Delta a'_{max} = (\Delta a_{t1} + \Delta a_{t2}) + (\Delta a_{c1} + \Delta a_{c2}) \quad (11)$$

The following designations have been adopted in the above formulas:

Δa_t – elastic deformation of support's top,

Δa_c – elastic deformation of support's crossarm,

Δa_i – change of the span length due to inclination of suspension insulator,

s, a – indexes denoting intermediate support (s) and tension support (a).

Maximum values of above quantities for steel lattice towers can be adopted on the basis of the standard [5]:

- elastic deformation of intermediate support:

$$\Delta a_t = \frac{H_t}{70} \quad (12)$$

- elastic deformation of tension support:

$$\Delta a_t = \frac{H_t}{90} \quad (13)$$

- elastic deformation of support at the height of crossarm (index u denotes upper, l – lower crossarm)

$$\Delta a_{tu,l} = \Delta a_t \cdot k_{u,l} \quad (14)$$

where

$$k_{u,l} = \left| -\frac{3}{2} \cdot \left(\frac{H_{u,l}}{H_t} \right)^2 + \frac{1}{2} \cdot \left(\frac{H_{u,l}}{H_t} \right)^3 \right| \quad (15)$$

H_b, H_u, H_l – accordingly support's height, height at the upper crossarm mounting, height at the lower crossarm mounting,

- elastic deformation of crossarm

$$\Delta a_c = \frac{q}{50} \quad \text{for intermediate supports}$$

$$\Delta a_c = \frac{q}{70} \quad \text{for tension supports}$$

where q – length of a crossarm,

- maximum change of the span length due to inclination of suspension insulators depends on the length of insulator chain and maximum angle of inclination; for 110 kV lines $\Delta a_i = 0.63$ m.

Applying above principles, the values of elastic deformations of supports and the resulting length changes $\Delta a'_{min}$ and $\Delta a'_{max}$ for the exemplary span were calculated:

$$\Delta a'_{min} = 0.69 \text{ m} \qquad \Delta a'_{max} = 1.38 \text{ m}$$

Comparison of the mitigating effect of supports elasticity and insulators inclination with the expected change of the span length (second column of the table 1) shows, that the extension of the span due to terrain deformation can be partially or fully compensated. It should be emphasized that the abovementioned forecasting can only be preliminary. It is necessary to verify the results of calculations with the observation of the behavior of the line, especially in the initial stages of exploitation, when land deformations are not yet so large. Periodic inspections of power lines consist of, among others, on an approximate assessment of inclination of supports or measuring the angle of their inclination. However, it should be noted that the share of support inclination in the change of the span's length is relatively small (as a rule it does not exceed several percent) and the observation of only the angle of support inclination is not sufficient to obtain information about the increasing stress in the conductors. It is necessary to measure the span lengths and/or values of sag. Another advanced and more sophisticated techniques are available for monitoring the ground subsidence utilizing radars, GPS, satellites etc. [6]. The dates of performing control measurements should be coordinated with the course of underground mining activity.

5. Conclusions

The impact of subsidence on the operation of overhead power lines must be considered when planning underground exploitation, especially for high voltage lines, as they are important for the reliability of supply of mines. The results of calculations show, that in real lines operated in the area affected by mining damage, exceeding of the permissible stresses in conductors is possible. This situation can lead to breaking the lines or damage to the towers. Elastic deformations of towers and their crossbars as well as the inclination of suspension insulators can mitigate the effect of increasing the span's length, however analytical (quantitative) determination of this effect is difficult. Calculations results of stress and sag should be periodically verified by field observations to determine measures that should be taken to prevent damage to the line.

References

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