Impact of Mining Extraction on Above-Ground Pipelines

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Abstract. The issue of the impact of subsoil deformations on above-ground steel pipelines, especially district heating pipelines, located in mining areas in Poland was discussed. The pipelines constructed from steel pipes joined by welding and supported by slide, guide and fixed rigid supports were taken into account. Expansion joints in district heating pipelines are installed due to significant changes in their length caused by temperature changes. Subsoil deformations in mining areas cause displacements of supports and thus pipelines are subjected to additional displacements, forces and bending moments. Pipelines are protected against this impact by the use of additional expansion joints or expansion joints with an increased operating range. In the article, the way of assessing the possibility of transferring mining deformations of the subsoil by existing above-ground pipelines was presented. Evaluation of the possibility considers: a. the assessment of the technical condition of the pipelines and supports based on the conducted inventory in the field, b. the assessment of the current ability to transmit the subsoil deformations by expansion joints, c. the kinematic analysis of the pipelines, taking into account the extreme values of support displacements, resulting from predicted values of mining deformations of the subsoil, d. the static and strength analysis for selected elements or sections of the pipelines.

1. Introduction

The utility networks are partly built of above-ground pipelines. In mining areas in Poland, these are mainly heating pipelines, as well as short sections of water and gas pipelines passing over obstacles, such as watercourses. Above-ground pipelines are laid on supports located in the subsoil.

In mining areas, the above-ground pipelines are subjected to the subsoil deformations, caused by underground extraction of the deposits. These deformations cause displacements of supports, and hence displacements and deformations, as well as additional loads of above-ground pipelines. The aim of the article is to analyse the impact of mining deformations of the subsoil on above-ground steel pipelines and the way of considering this impact.

2. Impact of underground mining extraction on the surface

Underground mining extraction causes deformations of the subsurface soil layer, such as:

- subsidence \( \psi \),
- tilt \( T \),
- horizontal displacement \( u \),
- horizontal strain \( \varepsilon \),
- curvature \( K \) of the surface with radius \( R \).
The symmetric distribution of mining deformations in the area of extraction edges in accordance with the Budryk-Knothe theory [1,2,3] is schematically presented in figure 1.

**Figure 1.** Distribution of mining deformations according to the Budryk-Knothe theory [1,2]

3. **Impact of underground mining extraction on above-ground pipelines**

In mining areas in Poland, above-ground district heating pipelines are mainly constructed of steel welded pipes laid on low supports (figure 1) and were built in the 20th century. These supports are made of reinforced concrete or steel. The district heating pipelines are equipped with thermal expansions joints, and in mining areas additionally with expansions joints which compensate the length changes caused by subsoil deformations.

The main structural elements of above-ground district heating pipeline are: fixed supports (figure 2, left), sliding supports – slip (figure 2, right) or roller bearing (figure 3, left), guide (figure 3, right), expansion joints – U-type expansion loop (figure 4), L and Z bends, bellows expansion joints – axial, transversal (figure 8) or universal.

**Figure 2.** Supports: fixed (left), sliding (right)
Expansion loops are the most commonly used to protect district heating pipelines with smaller diameters [4,5,6]. The general principle of installing a U-shape expansion loop on the section of the pipeline is shown in figure 5 [4,7,8]. Thermal expansion joints are pre-tensioned during installation, which is usually 50% of their range. As a result of the temperature change of the heating [5,7,8], pipelines are extended or shortened. The allowable change \( \Delta l_d \) in the length of the pipeline section between fixed supports in the U-type expansion loop may be calculated from the formula:

\[
\Delta l_d = \frac{k_g I_{xo}}{(h - y_o)mED}
\]  

(1)

where:

- \( k_g \) - the allowable bending stress,
- \( I_{xo} \) - the moment of inertia of the loop with respect to the horizontal axis passing through its centre of gravity,
- \( y_o \) - the distance between the centre of gravity of the loop and the axis of the pipeline,
- \( h \) - the loop height,
- \( D \) - the outer diameter of the pipeline,
- \( E \) - Young’s modulus,
\( m \) - the factor that takes into account the concentration of normal stresses when bending on curves, due to the change in the shape of the pipe cross-section, from circular to an oval cross-section.

**Figure 5.** The installation way of expansion loop and supports on heating pipeline and its basic dimensions [4,5], and the impact of horizontal and vertical displacements: 1) fixed support, 2) sliding support, 3) expansion loop, where: \( l \) – length of the section between fixed supports, \( \Delta l_g \) – change in the length \( l \), \( u_1, u_2 \) – displacements of fixed supports, \( a, b, h, R, l_r \) – dimensions of an expansion loop

Displacements of supports, due to mining extraction, cause displacements of the pipeline and deflections of expansion loops (figures 6 and 7).

**Figure 6.** Vertical expansion loop under compression in the mining area
Figure 7. Vertical expansion loop under tension in the mining area

Bellows expansion joints, for which it is necessary to build guide supports, are mainly used to protect large-diameter thermal mains [5], for example, 2 x DN800 (figure 8). These expansion joints have the capacity to transmit length changes $\Delta l_d$ of the pipeline which is specified by the producer. The pipeline is divided into sections and one or two axial expansion joints are installed between the two fixed supports (figure 9). To compensate angular deformations, hinged (figure 8) and gimbal bellows expansion joints are used that do not have the capacity to transmit length changes. The universal bellows expansion joints [4] have the ability to transmit simultaneously the length and angular deformations.

Figure 8. Hinged bellows expansion joint on the pipeline 2 x DN800

Figure 9. The example of the installation of axial bellows expansion joint and supports on a district heating pipeline: 1) fixed support, 2) bellows expansion joint, 3) guide support
Steel water and gas pipelines are also constructed as above-ground [9,10] especially when passing over obstacles, such as watercourses. In mining areas, above-ground sections of steel pipelines are divided into segments and connected by sleeve expansion joints, such as in water mains (figures 10 and 11). They are also laid on fixed and sliding supports. Expansion joints are used to protect pipelines against the impact of mining deformations of the subsoil.

**Figure 10.** Section of water main pipeline laid on four roller supports and the fixed support (central) between two sleeve expansion joints

**Figure 11.** Water main DN600 with a double-sided sleeve expansion joint

Horizontal displacements of sliding supports are not transferred to the pipelines, although they cause longitudinal forces in the segments between the sleeves, which in the case of corroded and contaminated elements of their construction can reach significant values. The longitudinal forces also result from the resistance between the pipes and the gasket of sleeve expansion joints. The extreme value of the longitudinal force in the pipeline segment can be calculated from the formula:

$$ T = \pm \left( T_k + T_p \right) $$  \hspace{1cm} (2)

- $T_k$ - the resistance force between the pipe and the gasket of sleeve expansion joint [5,7],
  $$ T_k = \pi D \psi \mu_u p b_u, $$
- $D$ - the outer diameter of the water pipe,
- $\psi$ - the coefficient dependent on the outer diameter of the pipe,
- $\mu_u$ - the friction coefficient of the gasket on the surface of the pipe,
- $p$ - the operating pressure,
- $b_u$ - the width of the gasket,
- $T_p$ - the resistance force of sliding supports [5,7], $T_p = \mu q L$,
- $\mu$ - the friction coefficient on the sliding support,
- $q$ - the unit weight of the pipeline,
- $L$ - the length of the pipeline between the fixed support and the sleeve expansion joint.
Due to the impact of underground extraction, uneven displacement of fixed supports occurs and the distance between them changes (figure 5). This distance is increased or decreased depending on the location of these supports relative to the extraction edge. It decreases over the extracted area (figure 1) and increases outside this area. This causes horizontal compression and tension of the pipeline. The change in the distance between fixed supports of the pipeline, taking into account thermal effects $\Delta l_t$, cannot be higher than the allowable range $\Delta l_d$.

$$\Delta l_e = \sqrt{(l + u_n - u_{n-1})^2 + (w_n - w_{n-1})^2} - l$$

where:
- $u_n, u_{n-1}$ - horizontal longitudinal displacements of the neighbouring fixed supports of the pipeline (measured, calculated or predicted),
- $w_n, w_{n-1}$ - subsidence of the neighbouring fixed supports of the pipeline (measured, calculated or predicted),
- $l$ - the distance between the neighbouring fixed supports of the pipeline.

If the change in the distance between the fixed supports is higher than the compensation range of the expansion joints, the pipeline may be damaged due to additional stresses in its elements and excessive forces acting on the fixed supports. The uneven vertical and horizontal displacements of the sliding supports also play an important role because they may even lead to the local loss of their support.

The additional deflections of expansion loops $\Delta l_e$ cause additional longitudinal forces $P_x$ acting on the fixed supports [5,7]:

$$P_x = \frac{E I \Delta l_e}{I_{x0}}$$

The longitudinal forces cause additional bending moments $M_{lr}$ and $M_B$ in the expansion loop [5,7]:

$$M_{lr} = P_x y_0$$

$$M_B = P_x (H - y_0)$$

Surface curvatures cause additional bending moments in pipelines, generally much smaller than those caused by horizontal displacements of fixed supports. The vertical curvature with radius $R$ also causes the vertical curve of the pipeline [2,3], which causes the bending moment $M_K$:

$$M_K = \frac{E I}{R}$$

where $I$ is the moment of inertia of the pipeline, in a vertical expansion loop $I$ equals to the moment of inertia $I_{x0}$ with respect to the horizontal axis passing through its centre of gravity.

Assessment of the possibility of transferring the impact of mining extraction by existing above-ground pipelines should include an assessment of their current capacity to compensate supports displacements forced by the subsoil deformations. Therefore, this assessment should demonstrate the safety of the pipeline for specific values of mining deformations of the subsoil. The safety is assessed by calculating the ultimate limit state and the serviceability limit state. For this purpose, the computer program “Pipelines”, which was developed in the Central Mining Institute, may be used. The program
enables the acquisition of inventory data about the characteristics of pipelines and their technical condition. This program allows the collection of information about the pipeline sections and their resistance to mining deformations of the subsoil and the comparison of this resistance with the predicted mining deformations.

4. Analysis of the calculation results

The analysis of the impact of mining extraction on the above-ground pipelines is presented on the base of the district heating pipeline and water main. The parameters of these above-ground pipelines are as follows:

- the steel district heating pipeline 2 x DN273 with vertical expansion loops – outer diameter $D_c = 273.0$ mm, wall thickness $g = 7.1$ mm, operating temperature $150^\circ$C, operating pressure $p = 1.6$ MPa, allowable bending stress $k_E = 200.0$ MPa and Young modulus in the operating temperature $E = 200$ GPa, distance between the fixed supports $l = 80.0$ m, dimensions of the expansion loops $a = 6.0$ m, $h = 4.0$ m, $R = 1.0$ m, $l_r = 10.9$ m, $y_0 = 1.27$ m, $L_{u0} = 180.06$ m$^2$, $\Delta l_{r} = 241.5$ mm,
- the steel water main DN1620 – outer diameter $D_c = 1620$ mm, wall thickness $g = 14.0$ mm, allowable tensile stress $k_d = 210.0$ MPa and $E = 210$ GPa, distance between the expansion joints $l = 60.0$ m, operating pressure $p = 1.2$ MPa, coefficient of friction in the sleeve expansion joint $\mu_0 = 0.45$ and coefficient of friction in the sliding (roller) supports $\mu = 0.1$, $\Delta l_{r} = 500.0$ mm.

The extreme values of the subsoil deformations, caused by mining extraction, that affect the pipelines are as follows:

- the calculated value of horizontal soil strain $\varepsilon = 2.2$ mm/m,
- the surface curvature of the radius $R_{min} = 10.0$ km,
- the horizontal displacement of the neighbouring fixed supports $u_2 = 0.32$ m, $u_1 = 0.15$ m,
- the subsidence of the neighbouring fixed supports $w_1 = 1.90$ m, $w_2 = 2.10$ m.

The calculation results of axial forces $P$, bending moments $M$ and additional longitudinal stresses $\sigma_l$, caused by the underground mining extraction, with the use of equations (1–7), are presented in tables 1 and 2.

Table 1. Values of additional axial forces, bending moments and stresses in the district heating pipeline 2 x DN273

| Nominal diameter | Material | $p$ MPa | $D_c$ mm | $g$ mm | $l$ m | $\Delta l_{r}$ mm | $P_l$ kN | $\sigma_{Ps}$ MPa | $M_{lr}$ MNm | $M_{l}$ MNm | $M_{K}$ MNm | $\sigma_{M_{max}}$ MPa |
|-----------------|----------|---------|----------|--------|------|------------------|--------|-----------------|-------------|-------------|-------------|---------------------|
| 2xDN273         | steel    | 1.6     | 273.0    | 7.1    | 80.0 | 170.3            | 5.16   | 1.72            | 0.01        | 0.02        | 3601.27     | 57.36               |

Table 2. Values of axial forces and additional stresses in the water pipeline DN1620

| Nominal diameter | Material | $p$ MPa | $D_c$ mm | $g$ mm | $l$ m | $\Delta l_{r}$ mm | $T_k$ kN | $T_p$ kN | $\sigma_{T}$ MPa | $M_{K}$ MNm | $\sigma_{Min}$ MPa |
|-----------------|----------|---------|----------|--------|------|------------------|--------|---------|-----------------|-------------|---------------------|
| DN1620          | steel    | 1.2     | 1620.0   | 14.0   | 60.0 | 170.3            | 480.7  | 76.2    | 7.89            | 0.48        | 17.01               |

The obtained calculation results show that subsoil deformations cause significant values of additional displacements and loads of the above-ground pipelines and should be taken into account. In the case of the lack of expansion joints in the water main pipeline, the value of additional extreme longitudinal stresses $\sigma_l$, calculated for the values of the strain $\varepsilon = 2.2$ mm/m, amounts to $\sigma_l = 462.0$ MPa $>> k_d = 210.0$ MPa. The calculated values of extreme longitudinal stress for continuous steel pipeline are much higher than allowable stress. This shows that the use of expansion joints is needed, although they are the most susceptible to failures in mining areas.
5. Conclusions
In mining areas, above-ground pipelines are protected against the influence of mining deformations of the subsoil mainly through the use of expansion joints. In district heating pipelines there are expansion loops and bellows expansion joints which both protect the pipelines against the thermal impact and additionally against mining impact. A typical above-ground pipeline consists of one, two or three lines laid on fixed and sliding supports, attached to low reinforced concrete or steel pillars. In mining areas sliding supports are displaced relative to the pipeline, and displacements of fixed supports are transferred to the pipelines and should be transmitted by expansion joints.

The impact of mining deformations of the subsoil causes additional forces and bending moments acting on the pipeline [11] and may cause the exhaustion of the possible range of compensation due to significant displacements of fixed supports. Assessment of the possibility of transferring the impact of underground mining extraction by above-ground pipelines should include:

- the assessment of the technical condition of the pipelines and supports based on the conducted inventory in the field,
- the assessment of the current ability to transmit the subsoil deformations by expansion joints,
- the kinematic analysis of the pipelines, taking into account the extreme values of support displacements, resulting from predicted values of mining deformations of the subsoil,
- the static and strength analysis for selected, characteristic elements or sections of the pipelines.

The assessment of the possibility of transferring the impact of underground mining extraction by the pipelines and the inventory work can be supported by the computer program with a suitable database.

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