Impact of mining exploitation on pipelines

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Article describes the issues related to the impact of underground mining exploitation on pipelines in Poland. For this purpose there was conducted the impact analysis of horizontal strains, curvatures and tilt changes of the surface on loads and displacements of these objects. Ground deformations can cause pipelines failures and thereby reduce their reliability. In addition, the examples of typical failures of sewage system, water and gas supply systems in mining areas were presented.

Key words: *pipelines, failures, mining areas*

Introduction

The aim of the article is to present the issues concerning the impact of underground mining exploitation on pipelines in the Upper Silesian Coal Basin in Poland. Mining exploitation causes deformations of soil layer adjacent to the surface in which pipelines are buried. Hence these objects are subjected to additional loads and displacements. This impact causes pipelines failures which can reduce their reliability. Sometimes it can be important for the safety of surface users and also cause environmental hazards. Therefore, the problems related to pipelines protection, their control during the occurring of mining exploitation impact and failures repair are important issues in the surface protection in mining areas.

General characteristic of pipelines

Pipelines in longitudinal direction can be divided into continuous and segmental construction taking into consideration the impact of mining ground deformations. Continuous pipelines are built of pipes with welded joints which occur primarily in water and gas supply systems. Segmental pipelines are built of short pipes with lengths typically up to several meters and gasket joints. These pipes are used in water supply systems (cast iron, PVC - polyvinyl chloride, GRP - Glass Reinforced Plastic) and sewage systems (plastics, stoneware, concrete and reinforced concrete). Such pipelines can also consist of pipe segments and compensators installed between them and they occur in steel water and gas supply systems located in mining areas.

Pipelines can be divided into flexible (deformable) which are mainly made of plastic and low flexible (low deformable) taking into consideration the interaction between these objects and subsoil. It concerns longitudinal and transverse direction of pipelines.

Water supply systems are usually made of steel, plastics (polyethylene - PE80 and PE100) and also cast iron pipes. To a lesser extent these pipelines are made of plastics such as polyester resins reinforced with glass fibres (GRP) or polyvinyl chloride. Older water supply systems are rarely constructed of reinforced concrete, prestressed concrete and asbestos cement pipes.

Gas supply systems are built of steel and plastics pipes. For the construction of low and medium pressure gas pipelines in Poland is permitted to use polyethylene pipes - PE80 and PE100, and for higher medium pressure gas pipelines with nominal pressure up to 1,0 MPa - PE100 [1]. Gas pipelines with pressure higher than 1,0 MPa are built exclusively of steel pipes.

Sewage systems are usually constructed of pipes with length from 1 m to 6 m. These pipes are mostly made of stoneware, concrete or reinforced concrete and plastics (such as polyvinyl chloride, polyethylene, polypropylene with full or structural walls and polyester resins). Cast iron is rarely used for the construction of these systems. In recent years the share of plastics has increased, because pipes made of these materials are currently the most widely used for the construction of new and the reconstruction of damaged sewage systems.

Pipes used for the construction of sewage systems have mostly circular cross-section and socket joints (stoneware, concrete and reinforced concrete, cast iron, plastics), overlap or butt joints (concrete and reinforced concrete) and sleeve joints (plastics, stoneware jacking pipes).

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Impact of mining ground deformations on pipelines

Impact of continuous mining deformations of soil layer adjacent to the surface on pipelines is considered in two specific directions: parallel and perpendicular to their longitudinal axis as schematically shown in Fig. 1. Oblique direction of this impact is a combination of these two directions.

Horizontal strains cause changes in earth pressure on pipes walls in their cross-section direction. In the case of soil loosening their values decrease (Fig. 1b) and during soil thickening their values increase (Fig. 1c). The additional axial forces (tensile and compressive) occur in longitudinal direction of pipelines, especially with continuous constructions. In the case of segmental pipelines occur pipes displacements which are compensate in joints or compensators (Fig. 1).

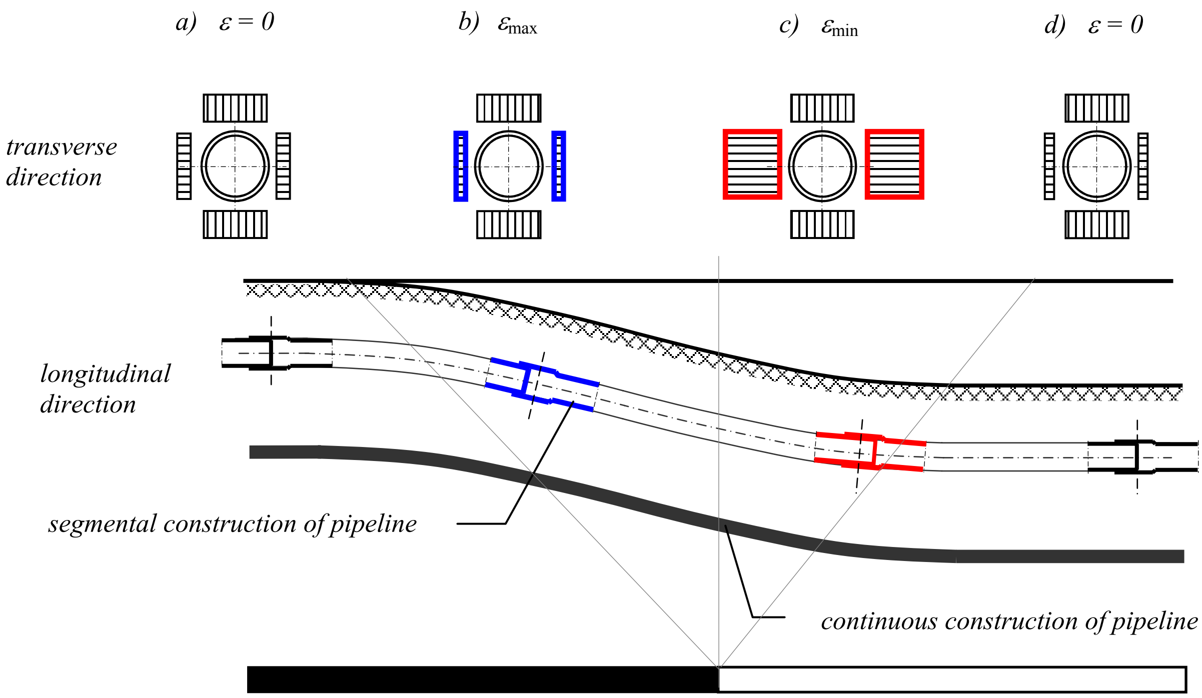

Fig. 1. Impact of underground mining exploitation on pipelines.

Dynamic impacts of underground exploitation are also important in pipelines protection in mining areas. They cause additional loads in the form of increased stresses as well as additional transverse and longitudinal displacements of pipes. Mining tremors in unfavourable loads conditions of pipelines subjected to continuous mining deformations can lead to additional failures [2]. It especially concerns pipes made of brittle materials such as stoneware, concrete and grey cast iron. In most cases, the values of soil deformations caused by mining tremors are much smaller than these resulting from the continuous impacts of mining exploitation [9]. Sometimes local failures of pipelines are caused by discontinuous deformations occurring in the form of fissures, thresholds and sinkholes.

Longitudinal direction of pipelines

In determining the values of longitudinal forces N, occurring in segmental and continuous pipelines, it must be considered tangential forces caused by the soil friction on the surface of pipelines and forces connected with the anchorage of pipeline elements such as sockets and fittings

$$N = N_t + N_k = \frac{N_k + \tau_g l}{2} \tag{1}$$

where: N_t – longitudinal force caused by soil friction on the outer surface of pipes,
N_k – longitudinal force caused by anchorage of pipeline elements such as compensators,
τ_g – unitary tangential force caused by soil friction $\tau_g = \sigma_n f$ or its shearing,
σ_n – soil pressure on the side surface of pipeline,
f – coefficient of soil friction on the side surface of pipeline,
l – length of considered segment.

Limit values of tangential forces must also be taken into account in determining the forces and maximum lengths of segments between compensators [7]. In the case of flexible pipelines, made of polyethylene or polypropylene and joined by butt welding, electric resistance welding or extrusion welding, compensation changes in lengths follow by their deformations. Deformations of such pipelines in mining areas are almost equal along their entire length to the soil layer deformations. Range of permissible deformations for these materials is not generally higher than horizontal strains of soil layer adjacent to the surface in mining areas of categories 0 ÷ V which permissible values are shown in Tab. 1.

Tab. 1. Categories of mining areas with the values of horizontal strains and radii of curvatures (in Poland).

Category of mining area	**Values of horizontal strains ε [mm/m]**	**Values of radii of curvatures R [km]**
0	$\lvert\varepsilon\rvert \le 0{,}3$	$\lvert R\rvert \ge 40$
I	$0{,}3 < \lvert\varepsilon\rvert \le 1{,}5$	$40 > \lvert R\rvert \ge 20$
II	$1{,}5 < \lvert\varepsilon\rvert \le 3$	$20 > \lvert R\rvert \ge 12$
III	$3 < \lvert\varepsilon\rvert \le 6$	$12 > \lvert R\rvert \ge 6$
IV	$6 < \lvert\varepsilon\rvert \le 9$	$6 > \lvert R\rvert \ge 4$
V	$\lvert\varepsilon\rvert > 9$	$\lvert R\rvert < 4$

Horizontal strains of soil layer adjacent to the surface induce bending moments in the vicinity of pipelines bends and branches which can cause the exceeding of load capacity and their failures. Bending moments are also caused by the ground curvatures [11] which are primarily important in the case of pipelines with larger diameters (over 600 mm).

Horizontal strains of soil layer adjacent to the surface in the longitudinal direction of pipelines with socket and sleeve joints or compensators cause the displacements of individual pipes what can lead to the loss of their tightness. To avoid the unfavourable effects of mining exploitations, joints and compensators should have some possibility for overtaking the length changes of pipelines in appropriate range. Deformation indicators are characterized by a large random dispersion and therefore their absolute values in mining area can be much higher than predicted ones. Extreme values of ground layer deformations that can impact with a certain probability on pipeline segment with a length l, assuming a normal distribution, can be determined by the formula [10, 13]

$$\varepsilon_{ekstr} = \varepsilon[1 + nM(l)] \tag{2}$$

where:

ε – value of predicted extreme horizontal strains,

n – factor which depends on the probability that the extreme values are not exceeded, for probability 0,95 it equals n = 1,645,

$M(l)$ – variation coefficient, $M(l) = \frac{s}{\varepsilon}$, according to Batkiewicz [10, 13]

$$M(l) = M(l_0)\sqrt{\frac{l_0}{l}},$$

s – standard deviation of deformation indicator,

$M(l_0)$ – variation coefficient of strains for standard measuring base,

l_0 – length of standard measuring base, usually 25 m.

Variation coefficients of horizontal strains were defined for standard measuring bases on the basis of carried out statistical analyses of measurement results of horizontal strains ε for loosening and thickening of soil. These analyses were carried out in Polish deep mines of coal and copper ore. These variation coefficients are respectively equal to $M(l_0)_r = 0{,}2$ and $M(l_0)_z = 0{,}3$ according to [13] and $M(l_0)_z = 0{,}26$ from the studies of [14]. Minimum length Δl of joints and compensators with respect to random dispersion of horizontal strains ε and appropriate probability of their reliable work can be determined by the formula [5]

$$\Delta l \ge 2\varepsilon l[1 + n\frac{\sqrt{M(l_0)_r^2 + M(l_0)_z^2}}{2}\sqrt{\frac{l_0}{l}}] \tag{3}$$

where l is the length of considered pipe segment.

Transverse direction of pipelines

Horizontal strains of rock mass layer adjacent to the surface play also central role in the impact of underground mining exploitation in transverse direction to the longitudinal axis of pipeline. These strains cause changes in earth pressure on pipes [5, 8] what lead to additional bending moments and circumferential forces acting on their walls. Soil loosening causes the reduction of earth pressure on pipe walls and in non-cohesive soil layer occurs almost immediately active limit state (Fig. 1b). Soil thickening causes the significant increase in earth pressure on pipe walls (Fig. 1c) and it is more unfavourable than soil loosening in the case of mining deformations which correspond to III and IV category of mining area (Table 1). The greater the value of soil strains, the greater pressure.

Changes of transverse loads in the case of flexible pipes can also cause the excessive deflections of their cross-sections. The state of soil strains around the cross-sections of pipelines is shown in Fig. 2 where a dash line presents the state of soil strains around the flexible pipe.

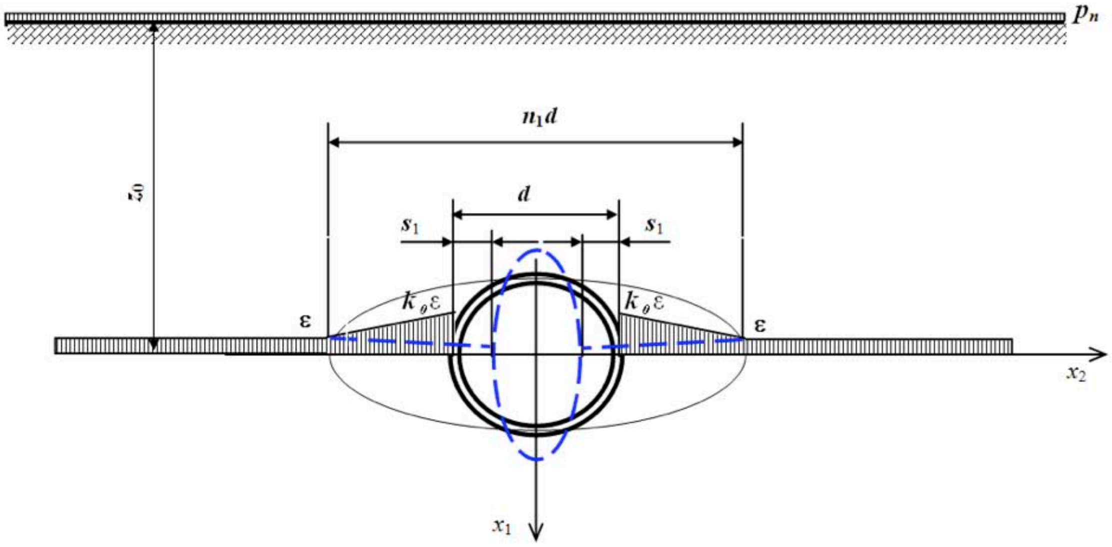

Fig. 2. Distribution of horizontal strains around the cross-sections of pipelines.

In the zone directly adjacent to pipeline with low flexible walls occurs the concentration of soil strains which can be characterized by a factor $k_0 \geq 1,0$. In the zone directly adjacent to pipelines with flexible cross-sections the values of strains are smaller, because their walls move under the soil pressure. Coefficient k_0 can be determined by the formula

$$k_0 = \frac{n_1 + 1 - 2\alpha_1}{n_1 - 1} \tag{4}$$

where:

n_1 – multiple of pipe diameter d, according to Fig. 2,

α_1 – deflection of pipe cross-section per the unit of soil strain, coefficient dependent on the flexibility of pipe cross-section, for rigid pipes $\alpha_1 = 0$ [5, 6], for pipes with a very high flexibility $\alpha_1 = 2$.

Knowing the value of strains for soil thickening near pipelines walls it can be calculated the increased value of loads which impact on them [5]:

$$\sigma_{22} = \sigma_{220} + \Delta\sigma_{22} = \xi_0\sigma_{11} + \Delta\sigma_{22} \tag{5}$$

$$\Delta\sigma_{22} = (\xi_z - \xi_0)\left[1 - \left(1 - \frac{k_0\varepsilon}{\varepsilon^z_{kr}}\right)^m\right]\sigma_{11} \tag{6}$$

where: ξ – lateral earth pressure coefficient,

ξ_z – passive earth pressure coefficient,

ξ_0 – at rest earth pressure coefficient,

ε^z_{kr} – critical strain during the soil thickening; above this value of strain occurs passive pressure, for non-cohesive ground it equals 31 mm/m [8],

m – experimental coefficient, for non-cohesive soil it can be assumed $m = 3,1$ [8],

σ_{11} – vertical load, $\sigma_{11} = \gamma z_0 + p_n$,

γ – unit weight of soil,

z_0 – depth of buried pipeline,

p_n – surcharge load.

Failures of pipelines in mining areas

Water supply pipelines

Impact of mining exploitation causes mostly the failures in steel water supply pipelines and to a much lesser extent in plastic ones which are generally much younger.

Forces induced by mining exploitation lead to stresses increase in walls of steel pipes what causes their strength exceed. In addition, occurs walls deformation and it is also a factor which intensifies the corrosion processes of steel pipelines [4]. In extreme cases, in the zones where pipelines are subjected to tensile forces, occur the cracks of their walls. In the zones where pipelines are subjected to compressive forces occur frequently the deformations and folds of their walls. Cracks of tensioned pipelines are noticed almost immediately due to the loss of their tightness. Unfortunately, deformations of compressed pipelines may be not noticed for a long time. Zones where occur bends and walls deformations of steel pipelines are more vulnerable to corrosion processes. In these zones occur the structure changes of material (microcracks and plasticization of material) as well as the failures of insulating coats. The results are the occurrence of accelerated corrosion and pits, eventually the holes in pipelines walls. The example of above-mentioned failures of steel pipelines in mining areas is shown in Fig 3.

Fig. 3. Damaged section of steel pipeline Ø100 - folding of wall, damaged insulation, corrosion pits and holes [15].

Sewerage pipelines

The results of mining exploitation impact on sewerage pipelines are the construction failures of sewers and the loss of their tightness as well as their unfavourable slopes changes. Failures of sewage systems are often detected after a long time since their occurrence. In many areas they repeat by years causing a threat to the environment, because it is connected with the sewage outflow into the ground. Leaks can also be the cause of supplying the sanitary sewage system with rainwater and groundwater. Unfavourable changes in sewers slopes contribute to problems with sewage and rainwater outflow and their backwater. The adjustment of sewers slopes is possible through their complete rebuilding which is often justified only after the end of mining exploitation. Example of the course of sewers slopes within the Gliwicka Street in Katowice after the long period of mining exploitation impact is presented in Fig. 4.

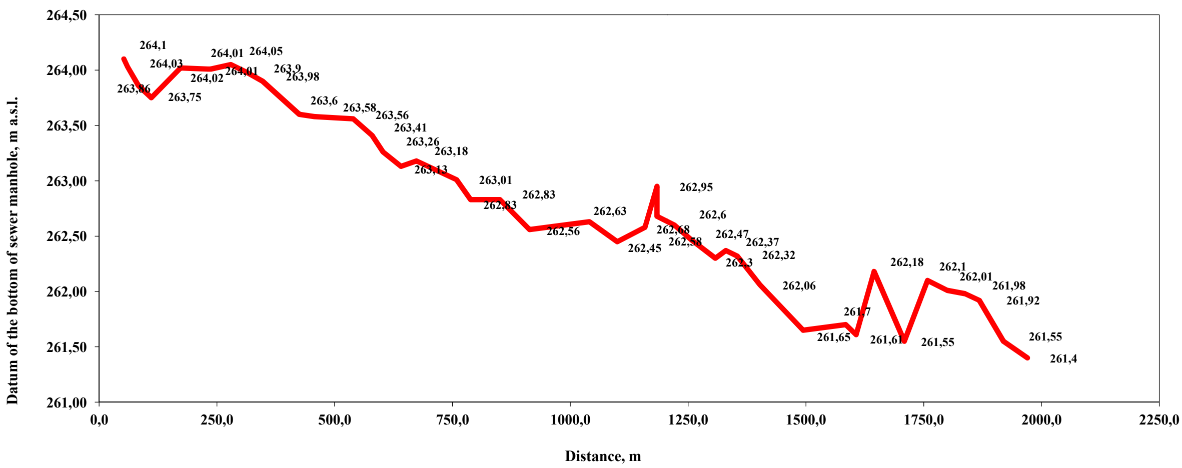

Fig. 4. Course of sewers slopes within Gliwicka Street in Katowice.

Above-mentioned damage occurred in stoneware and concrete sewers of sewage system in the centre of Katowice (Fig. 5). This system was mostly built in the years 1907-1935 without any protection to the impact of mining exploitation.

Fig. 5. Damage of stoneware sewer [12].

Gas supply pipelines

Failures of gas supply pipelines in mining areas are mainly connected with these which are made of steel. The most common failures in these systems are damaged compensators resulting from the ware of sealants [3]. Gas leak is rarely caused by the exhaustion of their compensation ability. The results of tensile forces are cracks of welds which also takes place in connection with gas pipeline branches. In the area of compressive horizontal strains of soil occur the walls deformations of steel pipelines which often lead to the loss of their tightness due to corrosion. Significant deformations of these pipelines are also observed on branches and in bend zones because of the influence of additional axial forces and bending moments.

In the compression zone exist also bucklings of gas pipelines which are usually bent toward the surface and even pushed up above it. This mainly applies to polyethylene gas pipelines and also steel ones with small diameters. In the case of polyethylene gas supply systems the closure of pipelines cross-sections and the loss of their flow capacity occur as shown in Fig. 6. However, polyethylene gas pipelines rarely are damaged and nowadays they are widely used for the construction of low and medium pressure gas supply systems in mining areas.

Fig. 6. Deformation of medium pressure gas supply pipeline PE Ø160 [3,15]

Conclusions

Impact of underground mining exploitation causes changes in primary conditions of pipelines foundation in the soil layer adjacent to the surface. Ground deformations cause additional loads and displacements of these objects which must be taken into account during their designing, protection and also resistance assessment in mining areas. Therefore, in mining areas there should be used properly prepared pipes for pipelines constructions and also appropriate design solutions that enable to transfer soil deformations. This will allow the safe working of utility networks with the maintenance of proper reliability level.

The presented examples of utility networks failures concern mainly old and unprotected pipelines to the impact of mining exploitations as in the case of above-mentioned sewage system in Katowice. In sewerage occur adverse changes in slopes which should be considered during designing. In the case of existing networks with incorrect slopes it is required their reconstruction but sometimes the sufficient solution is to build sewage pumping station. The greatest failures occur in older steel water and gas supply pipelines, including those equipped with compensators. The compensators are often the places of leak, but without them it would be impossible the functioning of steel pipelines in mining areas as they protect them from serious failures. Water and gas supply systems made of polyethylene pipes are rarely damaged.

To guarantee the appropriate level of utility networks reliability in mining areas is also needed the control of occurring mining influence on the surface. For maintenance of networks usability and safety of surface users it is important the fast detection and repair of failures what is also connected with easy access to pipelines. It should be taken into account during resistance assessing of pipelines to the impact of mining exploitations.

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