Impact of Mining Subsidence on Natural Gas Pipeline Failures

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Abstract. The main goal of the paper is to present the influence of ground deformations, caused by mining subsidence, on natural gas pipelines. There are also presented characteristic examples of the gas pipelines failures in mining areas in Poland. Failures of buried natural gas pipelines pose a threat to people and the environment due to gas leaks. The main reasons of the leaks are corrosion of steel pipelines, mechanical damage as a result of construction works and unsealing of joints as well as expansion joints. In mining areas, the gas pipelines are influenced by ground deformations. Mining extraction induces subsidence, horizontal displacements, horizontal strains and curvatures of the subsurface ground layer where natural gas pipelines are buried. The horizontal strains are of significant importance for the considered issue. The mining-induced ground deformations cause displacements of pipelines as well as additional longitudinal tensile and compression loads. The load values depend on the soil-pipe friction coefficient, pipeline depth and pipeline section length subjected to horizontal strains. The load conditions also change in the transverse direction of pipelines. In Polish mining areas distribution gas pipelines are constructed with steel and polyethylene pipes. Transmission gas pipelines are constructed with steel pipes. The steel gas pipelines usually are equipped with built-in expansion joints to protect them and to transmit ground deformations. The polyethylene gas pipelines are flexible and are able to transmit mining ground deformations but polyethylene pipes can be used up to 1.0 MPa nominal pressure in natural gas systems. Mining extraction causes additional failures of the gas pipelines despite their above mentioned capacities. The failures occur most frequently in the steel gas pipelines, particularly in old ones. The main causes of gas leaks are wall breaks, mostly near welded areas, wall buckling and sealant damage of expansion joints. Mining deformations can also induce the buckling of polyethylene pipelines. Therefore, in mining areas additional inspections of the natural gas network are needed to detect the leaks early.

1. Introduction
The aim of the article is to present the effects of ground deformations, occurring in mining areas, on the natural gas pipelines. In Poland, in the areas affected by the underground mining of hard coal and copper ores, there is a natural gas network consisting of transmission and distribution gas pipelines.

The underground extraction of deposits causes subsidence $w$ and horizontal displacements $u$ of the surface, which cause tilts $T$ and curvatures $K$, and horizontal strains $\varepsilon$ of the subsurface soil layer (figure 1). The horizontal strains $\varepsilon$ cause horizontal tension (loosening) of the soil in the zone located outside the mined deposit and horizontal compression (compaction) of the soil in the zone located above the mined deposit. The range of these zones depends on the depth of mining and the parameters characterizing the rock mass.
Gas pipelines buried in the subsurface soil layer are subjected to additional external loads and undergo deformations and displacements, depending on their location in relation to the mined deposit.

2. Characteristics of natural gas pipelines in mining areas in Poland
Natural gas pipelines, due to the maximum operating pressure, are divided into [2]:
- low pressure gas pipelines - up to 10 kPa inclusive,
- medium-pressure gas pipelines - above 10 kPa to 0.5 MPa inclusive,
- increased medium-pressure gas pipelines - above 0.5 MPa up to 1.6 MPa inclusive,
- high-pressure gas pipelines - above 1.6 MPa to 10.0 MPa inclusive.

Regarding the materials used, the gas pipelines are divided into steel and plastic. The steel gas pipelines are built with the use of pipes with welded joints. The polyethylene pipes with butt or electrofusion welded joints are used for the construction of low and medium pressure gas pipelines. It is allowed to use polyethylene pipes of 80 and 100 grades (PE80 and PE100), and PE100 pipes for the construction of the increased medium pressure up to 1.0 MPa natural gas pipelines [3]. The gas pipelines of the pressure higher than 1.0 MPa are built exclusively from steel pipes.

The gas pipelines constructed in mining areas should be protected against the harmful effects of ground movements, and all welded connections checked by non-destructive testing [2]. The steel gas pipelines are secured by using expansion joints, spaced apart depending on their allowable movement, load bearing capacity of pipes and values of deformation indices [1]. The polythene gas networks, due to their flexibility, are not additionally protected against mining impact [3]. In the mining areas the use of PE100 pipes of standardized dimension ratio SDR 11 is recommended, which means the application of larger wall thickness of pipes.

The medium and low pressure gas pipelines in mining areas have been built from the steel pipelines that were used until the mid-1990s. For example, in 2009 in the area of the Upper Silesian Coal Basin (USCB) they accounted to 63.3% of the total length of the network amounted to 3259.5 km [4]. Currently, the polyethylene pipes are used to build new medium and low pressure gas pipelines and building connections, which share in the total length of the gas network is systematically increasing.
The analyzed in the mining area the gas network in Polkowice in 2017 was mostly composed of the polyethylene pipelines, which share amounted to 53.2% of the total length 66.8 km of the network.

In the mining areas, the natural gas pipeline network is composed of the following:
- steel pipelines of the sectional construction, equipped with expansion joints,
- polyethylene pipelines of the continuous construction,
- steel pipelines of the continuous construction without expansion joints, occurring occasionally.

3. Analysis of the impact of underground mining operations on the gas pipelines

Primary gas pipeline loads are caused by the soil, the ground surface load and the internal pressure, which cause circumferential and longitudinal stresses. The longitudinal stress in the gas pipeline is also caused by the differences between temperature of assembly and operation of the pipeline. The underground mining causes additional loads and displacements of the gas pipelines. These loads are the result of the ground deformations, among which significant importance play the horizontal displacement $u$ and the strain $\varepsilon$, and to a lesser extent also the curvatures of the ground $K$. The impact of ground deformations is considered in two main directions of the gas pipeline - longitudinal and transverse. The impact in the transverse direction causes changes in the soil pressure [5]. In case of the gas pipelines, the influence of deformations in the longitudinal direction is of primary importance. The longitudinal forces are caused by friction during displacement of grains of the soil over the outer surface of the gas pipeline and the impact of the soil on the anchoring elements, such as bends, tees, fittings, flanges and expansion joints.

The value of longitudinal forces acting on the gas pipeline is equal to the sum of the unit friction forces $t$ of the ground onto its external surface. The limit value $t_\text{g}$ of these forces can be calculated from the formula [6]:

$$ t_\text{g} = \pi D_z \left( \mu \sigma_{n} + \alpha c \right) $$

where:
- $D_z$ – outer diameter of the pipeline,
- $\sigma_{n}$ – normal stress on the outer surface of the pipeline,
- $\mu$ – coefficient of friction of the soil onto the external surface of the gas pipeline,
- $c$ – soil cohesion,
- $\alpha$ – adhesion factor.

The value of friction forces $t$ per unit length of the gas pipeline depends on the value of normal stresses $\sigma_{n}$ on its external surface and the coefficient of friction $\mu$ on the soil-pipe contact surface. In case of the cohesive soil adhesion also occurs. The average stress value $\sigma_{n,m}$ on the outer surface of the gas pipeline can be calculated from the formula:

$$ \sigma_{n,m} = \frac{(\gamma h + p)(1 + K)}{2} $$

where:
- $\gamma$ – bulk unit weight of the soil,
- $h$ – depth of the gas pipeline,
- $p$ – uniform load of the surcharge,
- $K$ – coefficient of the lateral soil pressure.

The steel gas pipelines in the mining areas are divided into sections connected with the use of expansion joints. In the zone of horizontal tensile of the soil, the sections of the pipeline are moving away, and in the zone of horizontal compression of the soil, they are approaching, which is taken over by the expansion joints. The impact of the underground mining operations on the gas pipeline equipped with expansion joints is shown in figure 2.
Figure 2. Impact of the underground mining operations on the steel gas pipeline equipped with expansion joints; $r$ - the radius of the main influence range

The length of sections between expansion joints should be calculated so that the value of stresses caused by the additional longitudinal axial forces does not cause exceedance of the values of stresses permissible for the material of the pipeline. The extreme value $N_{ext}$ of these forces is equal to the sum of the friction forces on the outer surface of the pipeline [1] and the expansion joint, and the force of anchorage of the expansion joint in the ground. The value of $N_{ext}$ is also influenced by the force of movement resistance in the expansion joint. The distribution of axial forces along the section of the pipeline between the expansion joints is shown in figure 3.

Figure 3. Distribution of axial forces along the section of the pipeline between the expansion joints

The extreme value $N_{ext}$ of longitudinal axial forces can be calculated from the formula:
where:
\( l \) – length of the considered section of the gas pipeline,
\( N_a \) – extreme anchoring force of the expansion joint into the soil (at tension or compression),
\( N_{ej} \) – extreme force of movement resistance in the expansion joint.

The additional longitudinal forces \( N_{ej} \), generated by the resistance forces in the expansion joints, depend on the internal pressure and the type of the expansion joint and its sealing. These forces can be relatively high, particularly in the old gas pipelines and should be taken into account when calculating extreme longitudinal forces and stresses in the pipeline [7]. In case of the steel gas pipelines of continuous construction, without built-in expansion joints, the values of extreme longitudinal forces are much higher. These forces should be calculated for section pipeline length comparable with the radius of the main influence range \( r \) according to the formula:

\[
N_{exr} = \pm rt_g
\]  

(4)

The curvatures of the surface induce bending moments along the length of the pipeline. Most often, the vertical curvature \( K \) of the ground of a radius \( R \) causes the same curvature of the pipeline [1,8]. Then the values of bending moments \( M \) can be calculated from the formula [1]:

\[
M = KEI
\]  

(5)

where:
\( K \) – curvature of the ground, \( K = 1/R \),
\( E \) – Young modulus of the pipeline material,
\( I \) – moment of inertia of the pipeline cross-section.

Knowing the values of forces and bending moments, it is possible to calculate the stress values in the pipeline walls, taking into account the safety factors. The ultimate limit state is checked by comparison of the extreme stress values, caused by external and internal loads, with the design values.

The expansion joints protecting the steel pipelines in the mining areas should have allowable movements adjusted to predicted values of the horizontal ground strain in the longitudinal direction of the gas pipeline. The range of the allowable movement \( \Delta l \) can be determined from the formula:

\[
\Delta l = \pm \frac{l_1 + l_2}{2} \varepsilon
\]  

(6)

where:
\( l_1, l_2 \) – length of neighbouring sections of the gas pipeline,
\( \varepsilon \) – extreme horizontal soil strain in the longitudinal direction of the gas pipeline.

The serviceability limit state is checked by the determination of deformations and displacements for the gas network objects and comparing them with the values considered as permissible for technological and utility reasons, and checking if this will not result in the loss of network functionality. In old steel gas pipelines, the loss of functionality can also occur as a result of permissible displacements in the slip type expansion joints, as this can cause loss in their tightness. This is a frequent cause of failures of older steel pipelines in the mining areas. In the period 2006-2009, it was registered 174 leaks of the expansion joints, which amounted to 38.8% of all failures of low and medium pressure gas pipelines in the Upper Silesian Coal Basin [4]. The total number of the expansion joint failures amounted to 189 (42.1%).

Polyethylene pipelines belong to the linear objects of continuous, flexible structures. The properties of polyethylene allow for the compensation of the mining deformations of the subsoil layer. The values
of longitudinal strains of the gas pipeline at the ends of the section affected by mining deformations differ from the values of horizontal strain of the soil along the axis of the gas pipeline (figure 4). The strain of the gas pipeline also appears in short sections outside the range of the ground deformation - the radius of the main impact range $r$. However, due to the flexibility of polyethylene it is assumed that the longitudinal strain of the gas pipeline will not be greater than the strain of the ground in this direction. Thus, it can be assumed that the extreme longitudinal strain of the polyethylene gas pipeline will be equal to the extreme horizontal ground strain $\varepsilon$. The longitudinal forces evoked by this strain cause stress $\sigma_f$, which can be calculated:

$$\sigma_f = E_p \varepsilon + \nu \sigma_o$$  \hspace{1cm} (7)

where:

- $E_p$ – elasticity modulus of polyethylene,
- $\sigma_o$ – circumferential stress caused by internal pressure,
- $\nu$ – Poisson’s ratio of polyethylene.

As shown by tests of the polyethylene properties, the strain value at the yield point for this material amounts to a ten percent, and breaking of samples occurs for strain amounting to several hundred percent. The value of permissible strain, adopted on the basis of tests of polyethylene pipes intended for the construction of gas pipelines, amounts to 3.0% [3]. Polyethylene is a material of visco-elastic properties. The stress undergoes relaxation, therefore it increases in time under constant strain. The forced longitudinal strain of the polyethylene gas pipeline causes increased stress which undergoes relaxation. However, circumferential stress is caused by the internal pressure and evoke circumferential creep of pipe. The suitability for the use of polyethylene pipes for the construction of pipelines in the
mining areas has been confirmed by the observations of the operation of the network. The polyethylene gas pipelines are more rarely damaged than the steel pipelines.

4. Analysis and discussion of calculation results

The analysis of the impact of mining operations on the gas pipelines has been presented on the base of the low-pressure steel gas pipeline DN200, the high-pressure steel gas pipeline DN200 and the medium pressure polyethylene gas pipeline DN225, buried at a depth of $h = 1.0$ m in the sand. It was assumed the bulk unit weight of the soil $\gamma = 20.0$ kN/m$^3$, internal friction angle $\phi = 30^\circ$ and the surcharge load $p = 5$ kPa. The parameters of these gas pipelines are as follows:

- steel low-pressure DN200 (built in 1975) – outer diameter $D_z = 219.0$ mm, wall thickness $g = 6.0$ mm, steel L210 with strength $f_d = 210.0$ MPa (normative yield strength $R_{0.5}$) and $E = 206$ GPa, distance between the expansion joints $l = 50.0$ m, coefficient of friction $\mu = 0.5$,
- steel high-pressure DN200 in a polyethylene cover (built in 2011) – outer diameter $D_z = 219.1$ mm, wall thickness $g = 5.6$ mm, steel L360MB with strength $f_d = 360.0$ MPa (normative yield strength $R_{0.5}$) and $E = 206$ GPa, distance between the expansion joints $l = 85.0$ m, maximum operating pressure $MOP = 6.3$ MPa, coefficient of friction $\mu = 0.45$,
- polyethylene medium pressure DN225 – outer diameter $D_z = 225.0$ mm, wall thickness $g = 20.5$ mm, PE100 with Minimum Required Strength ($MRS$) of $10.0$ MPa, short term modulus $E_p = 1000$ MPa, long term $E_{p50yr} = 260$ MPa (assumed 600 MPa for extraction edge movement of 5 m/day) [9], Poisson’s ratio $\nu = 0.45$, coefficient of friction $\mu = 0.45$.

The analyzed gas pipelines are affected by mining extraction carried out at a depth of 800 m and the radius of the main impact range $r = \pm 400$ m. The extraction has caused deformations of the pipeline substrate of the extreme values of the deformation indicators:

- horizontal soil strain calculation value $\varepsilon = 6.0$ mm/m,
- curvature $K$ of the gas pipelines of radius $R_{min} = 6.0$ km,
- horizontal ground displacement of the maximum value $u_{max} = 1.44$ m.

The results of calculations of axial forces $N_{max}$, bending moments $M_{max}$ and additional longitudinal stresses $\sigma_l$ caused by the underground mining extraction, with the use of equations (1-5) and (7) are shown in table 1.

| Nominal diameter | Material | MOP MPa | $D_z$ mm | $g$ mm | $l$ m | $tg$ kN/m | $N_s$ kN | $N_l$ kN | $N_{max}$ kN | $\sigma_N$ MPa | $M_{max}$ MPa | $\sigma_M$ MPa |
|-----------------|----------|---------|----------|--------|------|----------|--------|--------|------------|-------------|-------------|-------------|
| DN200 steel L210 | 0.01 | 219.0 | 6.0 | 50.0 | 6.45 | 5.83 | 10.00 | 174.09 | 43.3 8 0.78 | 3.76 |
| DN200 steel L360MB | 6.3 | 219.1 | 5.6 | 85.0 | 5.80 | 8.88 | 201.06 | 452.20 | 120.45 | 0.73 | 3.76 |
| DN225 PE100 | 0.5 | 225.0 | 20.5 | - | 5.96 | - | - | 62.07 | 4.73 | 0.01 | 0.01 |

In case of the absence of expansion joints, the value of additional extreme longitudinal stresses $\sigma_l$, calculated for the radius of the main influence range $r = \pm 400$ m, amounts to:

- steel low-pressure gas pipeline DN200 - $\sigma_l = 642.6$ MPa $> f_d = 210.0$ MPa,
- steel high-pressure gas pipeline DN200 - $\sigma_l = 618.5$ MPa $> f_d = 360.0$ MPa.

The calculated values of extreme longitudinal stresses for continuous steel pipelines DN200 are much higher than the strength of steel. Therefore, in such cases, cracks in steel gas pipelines (figure 5) occur in the horizontal tensile zone of the ground, and wrinkling [10] and buckling of the wall in the horizontal compression zone. The buckling is not only caused by mining extraction but also by different soil movements [11,12,13]. Buckling of shallow buried gas pipelines causes even local elevation above the
ground surface. Wrinkling of the walls mainly occurs on gas pipelines of larger diameters, e.g. DN400 (figure 6), and buckling mainly occurs for gas pipelines of smaller diameters. For example, in the period 2006-2009, the number of weld breaks of the gas pipelines amounted to 81, and the breaks in connections to buildings amounted to 35. Totally they constituted of 25.9% of all failures which occurred in the low- and medium-pressure steel gas pipelines in the Upper Silesian Coal Basin [4]. The frequent cause of failures is also the damage to gas connections to buildings which amounted to 45 (10.0%) and wrinkling of the steel gas pipelines, the occurring in number 48 (10.7%).

Figure 5. Crack in the steel pipeline DN150 with the displacement of pipes [4]  
Figure 6. Wrinkling of the wall of the DN400 steel gas pipeline [4,10]

Polyethylene gas pipelines are anchored to the soil in the zones of horizontal tensile and compression strains and the longitudinal strain of the pipeline will be equal to the extreme horizontal ground strain \( \varepsilon \) (figure 4). For example the anchor length of the DN225 medium pressure gas pipeline is about 8.1 m for assumed above conditions. Buckling also occurs on the polyethylene gas pipelines in the horizontal compression zone. Horizontal deformations of the ground can cause the significant increase in value of the longitudinal stress in the polyethylene gas pipelines (table 1). Buckling causes pushing the gas pipeline towards the surface (figure 7), often blocking the natural gas flow. For example, in the period 2006-2009 there were 4 such failures [4]. These failures amounted to only 0.9% of all failures, and the share of the polyethylene gas pipelines amounted to circa 36.7% of total length of the network in the USCB mining areas. There are also failures of the passages of the polyethylene gas pipelines to the steel pipelines, totally 5 such cases were registered (1.1%). This results from the significant difference in the longitudinal stiffness of two types of pipelines submitted to compression.

The underground mining will cause dislocations of sections of the DN200 steel gas pipelines with built-in expansion joints which values for the assumed above conditions of ground and mining:

- steel low-pressure gas pipeline DN200 - \( \Delta l = \pm 300 \text{ mm} < \Delta l_{\text{allm}} = \pm 360 \text{ mm} \),
- steel high-pressure gas pipeline DN200 - \( \Delta l = \pm 510 \text{ mm} > \Delta l_{\text{allm}} = \pm 400 \text{ mm} \).

The calculated values of displacements of the gas pipeline sections are close to, or even greater than, the slip type expansion joint ranges of allowable movement \( \Delta l_{\text{allm}} \). The values of angular deviation are inconsiderable because the vertical load by the soil causes bending of the gas pipelines, which reduce the value of these deviations. In practice, relatively small horizontal displacements of the gas pipeline sections in the expansion joints are observed. For example, for the mentioned above low-pressure DN200 steel gas pipeline subjected to the impact of hard coal mining, the longitudinal displacements have been observed, amounting up to 30 mm (figure 8) for sections up to 50.0 m long.
The effect of the underground mining extraction on the natural gas pipelines causes additional damage to the network. This leads to a danger for the surface users. Therefore, it is necessary to protect properly the gas pipelines in mining areas and to conduct their inspection. It is extremely important to conduct additional supervisions and inspections with the use of modern leak detection techniques for the gas pipelines. These techniques shall ensure speed and efficiency of the measurements and shall allow for the quick detection of the leak, enabling its immediate repair. Such possibilities are provided by the use of drones (UAV) equipped with appropriate detectors, allowing the detection of the natural gas from the height of several meters. Frequency of the additional inspections of the gas pipelines shall be adjusted to the intensity of revealing mining deformations of the ground.

5. Conclusions

The underground mining extraction of deposits causes deformations of the subsoil, in which the natural gas pipelines are buried. These deformations cause additional loads to the gas pipelines, which result in the additional stresses. Following the analysis of the performed calculations, in some cases the stresses can reach high values, higher than the design values and even strength of the materials. The additional longitudinal stresses sum up with the stresses resulting from the internal pressure and changes in temperature [8]. Moreover, the gas pipelines undergo displacements and deformations. The displacements of the sections of the steel gas pipelines, protected against the unfavourable effects of mining operations, are taken over by expansion joints. However, these displacements also cause additional longitudinal forces of values that should be considered in the static-stress analysis, particularly for the high pressure gas pipelines. The values of these forces are generally not taken into account when designing the gas pipelines.

The most frequent cause of damage to the natural gas pipelines in the mining areas are leaks of the older expansion joints, resulting from the deterioration of the sealant properties caused by movement of the pipeline sections. Based on experience from the operation of steel gas pipelines in the mining areas, other failures of the expansion joints are rarely observed. The frequent causes of damage to the gas pipelines in the mining areas are cracks of the steel gas pipelines because of their tension and wrinkling and buckling of the steel and polyethylene gas pipelines in the zone of horizontal compression of the soil. The additional failures of the gas pipelines cause danger to the people and the environment. Therefore, it is necessary to properly secure them and carry out inspections. In the mining areas it is extremely important to conduct additional supervisions and inspections with the use of modern leak detection techniques for the gas pipelines.
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References
[1] J. Kwiatek, “Obiekty budowlane na terenach górniczych” (“Construction objects in the mining areas”), Wydawnictwo Głównego Instytutu Górnictwa (Published by the Central Mining Institute), Katowice, 2007.
[2] Rozporządzenie Ministra Gospodarki z dnia 26 kwietnia 2013 r. w sprawie warunków technicznych, jakim powinny odpowiadać sieci gazowe (Dz. U. 2013 poz. 640) (Regulation of the Minister of Economy of 26 April 2013 on technical conditions to be met by gas networks (Journal of Laws of 2013, item 640)).
[3] A. Barczyński i inni, “Sieci gazowe polietylenowe. Projektowanie, budowa, użytkowanie” (“Polyethylene gas networks. Designing, construction, operation”), Wydawnictwo SITPNiG – Ośrodek Szkolenia i Rzeczoznawstwa w Poznaniu – Grupa Terenowa Rzeczoznawców (Published by SITPNiG - Training and Expertizing Center in Poznań - Local Experts Group), Poznań, 2006.
[4] K. Jachim, P. Kalisz, „Awarie sieci gazowej na terenach górniczych” (“Failures of gas network in mining areas”), Górnictwo i Środowisko (Mining and Environment), kwartał 4/2010, Wydawnictwo Głównego Instytutu Górnictwa (Published by the Central Mining Institute), Katowice, pp. 95-105, 2010.
[5] P. Kalisz, M. Zięba, “Impact of mining exploitation on pipelines”. Acta Montanistica Slovaca, 2014, 19, 111-117.
[6] Guidelines for constructing natural gas and liquid hydrocarbon pipelines through areas prone to landslide and subsidence hazards. Final Report. Prepared for the Design, Materials, and Construction Committee of Pipeline Research Council International, Inc. Prepared by: C-CORE D.G. Honegger Consulting SSD, Inc. January 2009.
[7] B. Kliszczewicz, R. Mokrosz, “Projektowanie zabezpieczeń gazociągów na terenach górniczych. Ochrona obiektów na terenach górniczych” (“Designing of means of security for the gas pipelines in the mining areas. Protection of objects in the mining areas”), Praca zbiorowa pod red. A. Kowalskiego (Collective work edited by A. Kowalski), Wydawnictwo Głównego Instytutu Górnictwa (Published by the Central Mining Institute), Katowice, pp. 133-140, 2012.
[8] Y. Luo, S.S. Peng and H.J. Chen, “Protection of pipelines affected by surface subsidence”, Transactions of Society for Mining, Metallurgy and Exploration, Inc., Vol. 302, pp. 98-103.
[9] L-E. Janson, “Plastics Pipes for Water Supply and Sewage Disposal”. 3rd edition. Stockholm 1999.
[10] M. Wójcikowski, W. Machowicz, “Ochrona gazociągów na terenach objętych wpływem naprężeń górotworu wynikających z podziemnej eksploatacji górniczej” (“Protection of gas pipelines in the areas affected by impact of rock mass stresses come from underground mining extraction”), Górnictwo i Geoinżynieria (Mining and Geoengineering). Rok 32 (Year 32). Zeszyt 4, pp. 83-84. Kraków 2008.
[11] R. B. Francini, ”A Pipeliner’s Perspective on Longwall Mining”, 30th International Conference on Ground Control in Mining.
[12] A. S. H. Makhlouf, M. Aliofkhazraei et al., “Handbook of Materials Failure Analysis With Case Studies from the Oil and Gas Industry”, Elsevier, 2016.
[13] M. J. O’Rourke, X. Liu, ”Response of Buried Pipelines Subject to Earthquake Effects”, Monograph Series, Published by the Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, 1999.