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THE INFLUENCE OF SELECTED FACTORS ON THE FAILURE RATE OF THE WATER PIPELINES LOCATED ON THE AREA OF THE IMPACT OF MINING TREMORS

WPŁYW WYBRANYCH CZYNNIKÓW NA INTENSYWNOŚĆ USZKODZEŃ PRZEWODÓW PODSYSTEMU DYSTRYBUCJI WODY, ZLOKALIZOWANYCH NA TERENIE ODDZIAŁYWANIA WSTRZĄSÓW POCHODZENIA GÓRNICZEGO*

The article presents the influence of the selected factors, including mining tremors, described by the parameter PGV_{Hmax} on the failure rate of the water distribution pipelines. In created multiple regression models, the following independent variables were used: diameter and material from which the pipes were made, operation time without failure, the age of pipes, the value of pressure and PGV_{Hmax}. The values of PGV_{Hmax} in places with damaged water pipelines were determined by constructed the seismic wave propagation models. The analysis was carried out for a random sample of all water pipelines and extracted from this sample new groups: steel and gray cast iron pipes, their diameters, diameters and materials, and their construction time.

Keywords: *water distribution system, mining tremors, failure rate of water pipelines.*

W artykule przedstawiono badania wpływu wybranych czynników, w tym wstrząsów pochodzenia górniczego, opisanych za pomocą parametru PGV_{Hmax} na intensywność uszkodzeń przewodów podsystemu dystrybucji wody. Jako zmienne niezależne w utworzonych modelach regresji wielorakiej przyjęto: średnicę i materiał z którego wykonane są przewody, czas pracy bezuszkodzeniowej, wiek przewodów, wysokość ciśnienia i PGV_{Hmax}. Wartości PGV_{Hmax} w miejscach występowania awarii przewodów wodociągowych, wyznaczone zostały na podstawie zbudowanych modeli propagacji fali drgań w ośrodku gruntowym. Analiza przeprowadzona została dla próby losowej obejmującej sumarycznie wszystkie przewody sieci wodociągowej magistralnej, rozdzielczej i przyłącza oraz dla wyodrębnionych z tej grupy prób losowych obejmujących: przewody zbudowane ze stali i z żeliwa szarego, przewody z uwzględnieniem ich średnicy, średnicy i materiału oraz z uwzględnieniem czasu ich budowy.

Słowa kluczowe: *podsystem dystrybucji wody, wstrząsy górnicze, intensywność uszkodzeń przewodów sieci wodociągowej.*

1. Introduction

Water supply systems are a key part of the technical infrastructure for the functioning of the economy and society. The main tasks of water supply systems are: supply of water in the required quantity, quality and under appropriate pressure [51]. Maintaining the functionality and continuity of operation of these systems require ensuring their appropriate level of safety [30,53,34,46], which is obligated, among others, by Council Directive 2008/114/EC [8] and the Act of 26 April 2007 on crisis management [50]. Critical infrastructure protection procedures, to which water supply has been qualified, as well as procedures for determining the reliability and security of water supply to recipients, include in the first place identification of all hazardous factors [7,9,4,34,35,43,44,45] .

Many analyzes of the impact of various factors on the damage intensity of the water distribution system have described in the literature [5,15,17,29,35,40]. The following factors have analyzed: diameter, material, temperature of water in the water pipelines, temperature of ambient, length of pipes, average rainfall, type of pipes, depth of pipes, operation time without failure, pressure, type of ground, aggressiveness of the water and soil as well as the impact of mining, defined only as a qualitative variable (zero - one). The influence of mining tremors on the water pipe failure has not been analyzed yet.

Accordingly, in order to complete the analysis of pipe failures and reliability of systems located in mining areas, it is necessary to include in the analyzes a accordingly described factor, informing about the impact of mining tremors.

Mining exploitation is very often carried out in Poland under highly urbanized areas, densely armed with underground, linear technical infrastructure, like networks of: water, sewage, gas, heating, telecommunication. This creates numerous threats both for surface cubage objects and for the underground utilities network.

Water supply networks are characterized by various constructional and material solutions, connection methods, their age and technical condition are different. For these reasons, the pipelines are characterized by a varied dynamic response to additional loads resulting from the mining deformed area and surface vibrations induced by mining tremors. In addition, it is very difficult to identify the technical condition of individual pipelines, like their real load resistance, which makes it very difficult to carry out advanced analyzes.

For seismic areas, dependencies describing the impact of earthquakes with specific parameters on the damage intensity of water supply pipelines have been developed. The conducted research [23.39] has shown that PGV (Peak Ground Velocity) better correlates with pipelines damage caused by earthquakes than PGA (Peak Ground Acceleration). It was shown that PGV is directionally correlated with maximum ground deformations - the main cause of pipelines damage during propagation of the seismic wave. PGA better correlates with inertia forces that do not affect underground objects. Pineda - Poras and Ordaz [42] showed that the model of prediction of failure intensi-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** ty of water network pipes, based on the PGV parameter, overestimates the number of failures caused by earthquakes magnitude 8.0 - 8.1 and smaller and underestimate the number of pipe failures for stronger earthquakes. The parameter defined like PGV^2/PGA describes the relationship between earthquakes and the failure intensity of pipelines in a better way.

In addition to building of empirical models, many other studies have been carried out on the impact of earthquake parameters on pipelines buried in the ground. For example, Wang and Cheng [52] demonstrated by constructing a static numerical model that the behavior of the earthquake - laden pipeline depends on the wave transition time as well as the inhomogeneity of the ground in which the pipe is buried. Takada and Tanabe [48] have developed a three - dimensional static numerical model for pipelines and their connections load by large earthquakes. It was shown that the propagation of waves vibration at individual locations is characterized by peak values as well as by the speed of wave propagation. O'Rourke and Liu [37] analyzed the deformations and the curvature of the ground formed during the earthquake wave propagation, depending on the various ground conditions, on the formation of surface deformations. Temporary surface deformations of the ground are considered the most important from the point of view of the impact of seismic waves propagation on underground linear objects, like pipelines and tunnels. Lee [33] analyzed the history of earthquakes and on its basis investigated the impact of earthquake parameters on a buried gas pipeline in the ground including: type of pipeline material (plastic, brittle), diameter, ground properties, depth of gaz pipeline including location (residential and industrial area, public road, port areas - pipeline submerged, etc.). O'Rourke and Ayala, [36] have shown that pipelines made of flexible materials are more resistant to earthquakes than fragile pipelines. Similarly, Bouziou and O'Rourke [4] pointed out that the most resistant material of water pipelines to earthquake that occurred on 22 February 2011 in Christchurch was polyvinyl chloride (PVC). O'Rourke and others [38] analyzed the behavior of the ground at the interface with the pipeline under the influence of ground deformation caused by earthquakes. The tests have shown that it is necessary to change the design assumptions (static and strength calculations) for the forces occurring from the bottom of the pipeline.

The impact of earthquakes on underground, linear objects of technical infrastructure is relatively well described in many literature items around the world. The problem of the models of seismic waves propagation is still the accuracy of models, which are affected by a large variety of factors contributing to the creation of a specific impact of earthquakes on the surface and the objects.

Considering the significant differences between earthquakes and mining tremors, the implementation of dependencies developed for the earthquakes may be difficult and requires accordingly analysis. However, this does not change the fact that rich studies on seismic waves can provide an excellent source of knowledge for analysis of the impact of mining tremors on underground, linear technical objects.

Differences between earthquakes and mining tremors are caused among other by [55]:

1. size and intensity - strong mining tremors can only be compared with small earthquakes,
2. duration of kinematic extort - the duration of mining tremors is a few seconds, whereas an earthquake can last 10 - 30 seconds,
3. properties of spectral records - which is the reason for significant differences in the impact of phenomena on building objects,
4. peaks of ground movement (PGA, PGV, PGD - permanent deformation of the ground),
5. differences between the vertical and horizontal components of ground vibrations.

It is relatively easy to identify damage of pipelines caused by earthquakes. This is possible due to the scale of the phenomenon's impact, as well as the ability to correlate its occurrence with the flow increase (based on data from monitoring system), informing about the increase of the number of water distribution system failures. In addition, the location of the failure can be simpler, due to the size and intensity of the water outflow from the damaged pipes.

In the case of pipeline failures that may be caused by the impact of mining tremors, the situation is more complicated because it can only refer to unit damages, which due to insufficient research, it is difficult to distinguish from a group of other causes of failures.

In the literature, it has often pointed out that the impact of mining tremors on linear objects buried in the ground is not sufficiently known [20, 21, 22] or is treated as secondary [28]. The paper [22] indicates that unambiguous determination of the impact of mining tremors on pipeline damage was difficult, due to the possible time shift of the cause and effect of damage. In spite of this, publications presenting research results (mainly numerical or static - endurance analyzes) concerning the impact of mining tremors on linear objects are met.

Dulińska [11] examined the effect of surface vibrations on the structure of the gas pipeline, by calculating the dynamic response of the object from strong tremors. The analyzes considered a 100 m section of the gas pipeline, three variants of the soil were considered: dry sands, clay loons and sandy gravels. Elastic cooperation of the pipe with soil in vertical and horizontal direction was assumed. The model of uneven kinematic extortion was tested (at each point of the pipeline at the same moment there is different kinematic exclusion). The analysis showed that higher dynamic responses to kinematic excitations are obtained for lower wave propagation velocities. The frequency structure of ground vibrations affects the size of the gas pipeline response, even at approximated maximum vibration amplitudes at different frequency structures. Max stresses in the gas pipeline under the influence of the tremor were 18 MPa or 10% steel strength. In the works [24] and [25], attention was paid to the necessity of each time analyzing the impact of ground vibrations on gas pipelines and to examine their dynamic response to the existing vibrations. This is to prevent possible consequences of damage to old steel pipelines. Dulińska and Jasińska [12] investigated using numerical methods the maintenance of a 100 m steel pipeline on concrete supports during a seismic tremor. The propagation of the wave vibration along the pipeline was analyzed. In the pipeline, depending on the assumed model, cracks occurred at the location of the concrete supports. Boron P., Dulińska J., [3] analyzed the numerical response of joints (including bolts, flanges and retaining block) of steel pipelines to the impact of seismic tremor. Obtained deformation of the bolts indicated the occurrence of high values of bending forces at the pipeline connection points. The paper [25] presents an analysis of impact of tremor with energy $8 \cdot 10^7$ J on steel gas pipe DN200, low pressure, equipped with gland compensators and characterized by good technical condition. As a part of the work, a static - strength and kinematic analysis was carried out for a section of a straight gas pipeline with a length of 50 m and a 90° arc. The conducted analysis showed that the forces (displacements, tensions and strains) reacting on the gas pipeline take values lower than those caused by continuous deformation of the ground. Kurzeja J. [26] investigated the impact of mining tremors on the Piekary Śląskie (Poland) A1 motorway junction. The analysis indicated that there is no negative impact of mining tremors on the motorway. The inference was based on systematic observations of the state of the motorway.

The aimed of the research presented in this article is the identification of the relationship between mining tremors described by the PGV_{Hmax} and the damage intensity of water distribution subsystem, taking into account: diameter and material from which pipelines were made, construction time, operation time without failure and water pressure. These are the first results of this type of analysis published in the literature.

The developed dependencies can be used to forecast damage to water supply network pipes in the analyzed region, under the influence of dynamic loads of mining operations.

2. Methodology of the research

The subject of the research was the water distribution subsystem, located in the area with the impact of dynamic stresses, caused by mining tremors. The research included analysis of all failures of the water distribution subsystem and recorded mining tremors with energy $E \geq 10^6$ J, occurring in 2011-2014.

The scope of research included:

1. determination of the local attenuation relations for mining tremors described by the PGV_{Hmax} parameter,
2. determining the value of PGV_{Hmax} in places where the failures of water pipes occoured,
3. construction of multiple regression models to identify factors affecting the damage intensity of the water distribution subsystem.

2.1. Local attenuation relation for the mining tremors describes by the PGV_{Hmax}

In literature [1, 6, 14, 19, 26], many attempts have been made to determine the empirical relationship between seismic parameter and factors affecting it's size. These dependencies were determined both for mining tremors and for earthquakes.

In 1999, Si H. and Midorikawa S. [48] developed a regression model in which the following factors were adopted as a factors influencing the magnitude of the seismic effect: energy of tremor, the mechanism of the source of tremor, the distance from the source of the tremor, and for the first time: the geological structure of the soil.

The model has the following form:

$$logA = b - logR - k \cdot R \tag{1}$$

where:

A – seismic parameter for example: PGV (Peak Ground Velocity), PGA (Peak Ground Acceleration) or PGD (Peak Ground Displacement),

R – the distance from the source of the tremor, [m],

$$R = \sqrt{d^2 + h^2} \tag{2}$$

d – distance from the hypocenter, [m],

h – pseudo depth determined by regression which provides non - linearity of the relationship for a small distance from the source, [m],

k – coefficient that accepts the following values: for PGV – 0,002 and for PGA – 0,003, [-],

b – offset factor, [-],

$$b = a \cdot logE + c \cdot R + \sum d_i \cdot S_i + e + \varepsilon \tag{3}$$

where:

a, c, d, e – regression parameters estimated from seismometric measurements, [-],

E – energy of tremor, [J],

Si – ground type, quality variable, distance di dependence on the number of ground types i, adopted in this research in accordance with Eurocode 8 (Tab. 1) [13], [-]

ε – random factor, [-].

R – like in equation (1)

The parameter adopted in this analysis for the description of ground vibrations (seismic parameter) was the maximum amplitude of horizontal vibrations velocity, determined as the horizontal maximum of the vibration length of the ground vibration (PGV_{Hmax}).

Model (1) became the basis for the development of the attenuation relations for the area in which the water distribution subsystem is located and for determining the seismic parameter value in places where the water supply failures occured.

Table 1. Ground type classification in accordance with Eurocode 8 [13]. $V_{S,30}$ - average speed of propagation of S waves in soil layers up to a depth of 30 m.

Ground type	Description of stratigraphic profile	$V_{s,30}$, m/s
A	Rock or other rock-like geological formation, including at most 5m of weaker material at the surface	>800
B	Deposits of very dense sand, gravel or very stiff clay, at least several tens of meters in thickness, characterized by a gradual increase of mechanical properties with depth	360-800
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of meters	180-360
D	Deposits of loose-to-medium cohesion less soil (with or without some soft cohesive layers) or of predominantly soft-to-firm cohesive soil	<180
E	A soil profile consisting of a surface alluvium layer with Vs values of type C or D and thickness varying between about 5m and 20m, underlain by stiffer material with Vs>800 m/s	-

2.2. Determination of PGV_{Hmax} values in places where water supply was failure

The procedure required assigning to each mining tremors the water supply failures caused by them. For this purpose, it was necessary to adopt the following assumption: mining tremor may be the cause of any water supply failure occurring up to 30 days after the tremor.

The necessity of adopting this assumption was caused by the type of the date of water supply failures owned by the water supply company. The analyzed database had only information about time of start repair the pipelines after failure. For the purpose of the study, it was important to obtain information about the time of failure. The moment of failure due to the large number of unknowns and the low accuracy of measuring devices is not possible to determine precisely at the moment. According to the above, the 30 days established is a kind of buffer in which the failure could have started.

In the research, no spatial restriction concerning the maximum distance between the tremor and the failure of the water pipe was accepted, due to the unknown effective range of impact of mining tremors on underground linear objects.

Determination of the PGV_{Hmax} value in the place where the water pipe failures, using the model created on the basis of equation (1), required: conducting ground classification in the place of individual failures, according to Eurocode 8 [13] and determining the epicentric distance (between mining tremors and water supply failures) based on geographical coordinates.

In the case when the same water supply failure was assigned to the various mining tremors, the “tremor-failure” pair was left in the analysis in which the PGV_{Hmax} parameter assumed a higher value. Finally, 993 “tremor - failure” pairs were obtained. Fig. 1 shows the spatial distribution of all analyzed mining tremors and failures of the water distribution subsystem.

Fig. 1. The spatial distribution of mining tremors (of $E > 10^6 J$) and failure of the water supply network in 2011-2014

2.3. The influence of selected factors on the damage intensity of the water distribution subsystem

In the next stage of the research for individual water pipes, characterized by parameters: number of failures, diameter, material, age, etc., the average value of PGV_{Hmax} was assigned from all water supply failure locations on the same pipeline. In the research, through the water pipe were understood, the sections of the main and distribution water supply network and connections, characterized by: diameter, material and time of construction. The analysis of the impact of selected factors on the failure intensity of water distribution subsystems was conducted for a group of 792 pipes.

In the multiple regression model, the impact of selected factors on the unit failure intensity of water distribution subsystem, the following variables were adopted:

- unit failure intensity rate (λ) - dependent variable of the built regression models,
- and independent variables:
- material (M) and diameter of individual pipelines (DN),
- average pressure in the place of failure on a pipeline (P),
- average age of the pipeline at the time of damage (W),
- operation time without failure of the pipeline in the analyzed time (Tp),
- PGV_{Hmax}.

The most commonly parameters used for assessing the failure frequency of water pipes are: stream of failure ω (t) or damage intensity λ (t). Assuming that the stream of failures is a stream: without consequences (damages occurring at particular times Δt are independent), single (probability of more than one damage on any small part of time goes to zero) and stationary (probability of k damage in the time interval Δt, depends only on this interval, and does not depend on the position on the time axis), the equality of this parameter with the intensity of damage λ (t) = ω (t) = const is obtained [50.52]. Based on the presented assumption, in the conducted research the failure frequency of the water pipes was described using the failure intensity indicator.

The unit failure intensity λ(Δt) for linear elements (pipelines) is expressed in equation [31.53]:

$$\lambda(\Delta t) = \frac{n(\Delta t)}{L\,\Delta t} \quad [\text{damage}/(\text{km}\cdot\text{a})] \tag{4}$$

where:

- λ (Δt) – unit failure intensity to linear objects, [damaged/(km a)],
- n (Δt) – number of failures in the time interval Δt,
- L – average length of analyzed pipelines in the time interval Δt, [km],
- Δt – the time interval for which the observation period has divided, [a].

Failure intensity of the analyzed water supply network pipelines was λmaxs = 200 damaged/(km·4 years), median = 8.8 damaged/(km·4 years), and the failure intensity of connection λmaxp = 2000 damage/(km·4 year), median = 93.9 damage/(km·4 years).

The water supply system can be treated as a renewable (cyclically occurring states of work and disability), from the point of view of reliability theory. It is called the „binary model with non-zero renovation” [31.53]. In the case of non-damaged operation time has an exponential distribution:

$$T_p = \frac{1}{\lambda} \tag{5}$$

where:

- T_p – average operation time without failure of the linear object, [years]
- λ – damage intensity of the linear object, [damage / (km year)],

In the analysis, the operation time without failure was within the range (26 - 730) days. It should be noted that most of the pipelines (in particular the connections) were damaged once in the analyzed time and the operation time without failure assumed the same value equal 730 days (median).

The pressure at the place where the water pipes failure was calculated based on the knowledge (from the monitoring data) of the pressure at the point supplying the pipeline or the area of the water supply network where the pipeline was located and the height difference between the supply point and the place of failure (read from numeric terrain model). For individual pipelines, the pressure was determined as the arithmetic average of the pressure from all failures locations on a same pipeline.

The pressure for all analyzed pipelines was within the range (13.39 - 86.87) m, while the median was: 44.48 m.

Regression models have been developed for a random sample consisting of: main, distribution and connection water pipelines and groups of pipes extracted from this random sample: steel pipes, gray cast iron pipes, DN80, DN100, DN150 , DN100 made of steel, DN100 made of gray cast iron, DN150 made of steel, pipes built in the following time intervals: 1885-1920, 1922-1938, 1939-1961, 1962-1978, 1979-1994, 1995-2012.

The analysis was performed in the Statistica software package (Statsoft) using multiple regression.

2.4. Characteristics of the analyzed water distribution subsystem

The water distribution subsystem is located in Upper Silesia (Poland) and is responsible for the supply of water to approximately 160 000 residents of the commune (163 thousand inhabitants in 2011 and 157 thousand in 2014). The source of water supply for the distribution subsystem are groundwater and surface water intakes owned by Górnośląskie Przedsiębiorstwo Wodociągów S. A. (GPW). The sup-

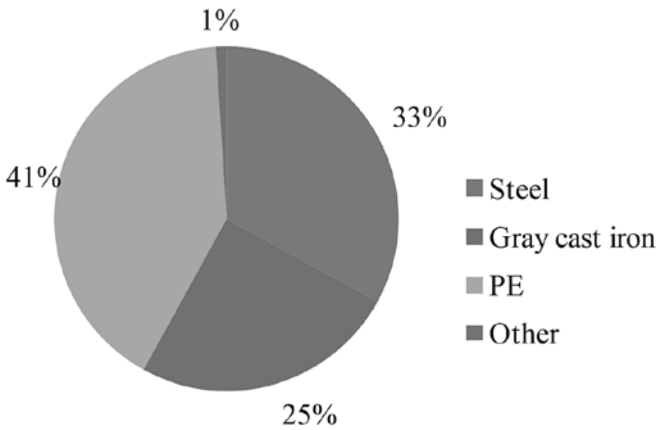

Fig. 2. The material composition of water supply system in 2014. On the graphs: "Other" – asbestos and PVC

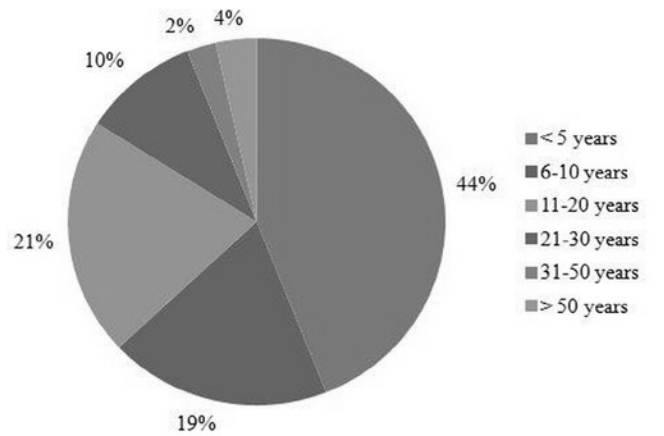

Fig. 3. The age structure of pipelines in 2014

ply of water from the GPW takes place through 56 chambers and on average in the analyzed years from 2011 to 2014 it was 7.3 million m^3/year, while water supply to residents amounted to average approximately 6.2 million m^3/year.

The water supply network in the diameter range DN20 - DN600 is approximately 450 km long, of which approximately 200 km is located in the mining area. Water supply pipelines are mainly made of: polyethylene, steel and gray cast iron (Fig. 2), and are mostly operated (60%) for less than 10 years (Fig. 3).

The value of the failure intensity indicator for the analyzed water distribution subsystem in particular years (Tab. 2) indicates a high failure rate of water pipelines λ> 0.5 damage/(km·year).

Table 2. Damage intensity for the water distribution subsystem in 2011-2014

Year	Number of failure	Lenght of the network; km	Unit failure intensity rate λ; damage/(km·year)
2011	445	443,9	1,00
2012	532	444,9	1,20
2013	299	456,4	0,66
2014	285	454,6	0,63

2.5. Characteristics of mining tremors occurring in the analyzed area

The analyzed water distribution subsystem is located in the commune, where active mining operations have been conducted since the 19th century.

At present, mining tremors are registered on 7 measurement stations equipped with Amax-GSI equipment, manufactured at the Central Mining Institute. The Amax-GSI apparatus [41] is a multi-channel specialized apparatus used for direct measurement of vibrations on the surface. The registration of earth vibration accelerations takes place using a recorder and a three-component piezoelectric accelerometer assembly. Thanks to the integration of the signal, a vibration velocity record is obtained in three perpendicular planes. The energy range recorded in the analyzed tremors region ranges from $1{\cdot}10^2$ to $1{\cdot}10^7$ J (Fig. 4).

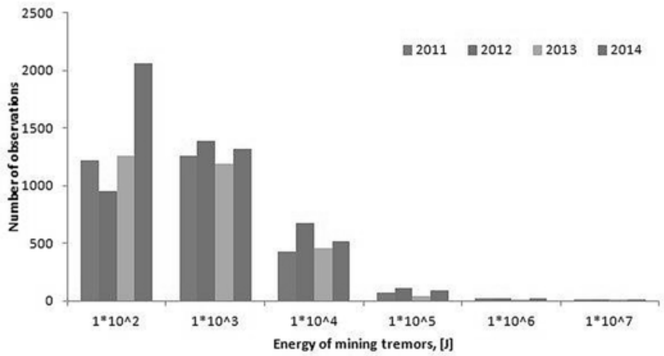

Fig. 4. Mining tremors registered in the mining area in the energy range from $1{\cdot}10^2$ to $1{\cdot}10^7$ J in 2011-2014.

In the analyzed area, the most tremors are weak, imperceptible by humans (E <10^4 J) and registered only by specialist equipment.

As part of the study, only tremors with E ≥ 10^6 J were recorded on 6 measuring stations due to the large number of incomplete recorded at one of the measuring station. Finally, 113 mining tremors (252 registrations) were adopted for the analysis, whose energy range is presented in Fig. 5.

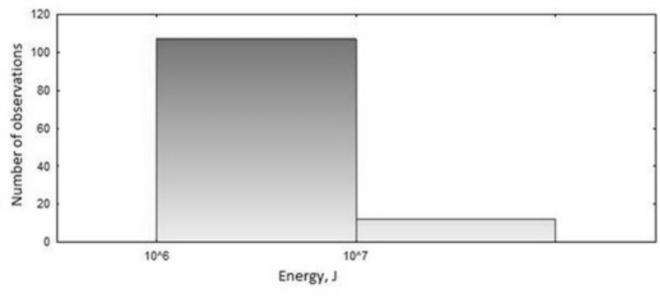

Fig. 5. Histogram of tremors energy occurred in the years 2010 - 2014.

Fig. 6 presents the values of the horizontal velocity component of the vibrations, recorded at measurement stations. The range of recorded values is from 0.0002 to 0.3150 m/s, while the median for all stations is similar and amounts to approximately. 0.0030 m/s. The highest value of ground vibration velocity was registered on 16.02.2013 at the 6th measurement station, while the smallest values at stations 5 and 2.

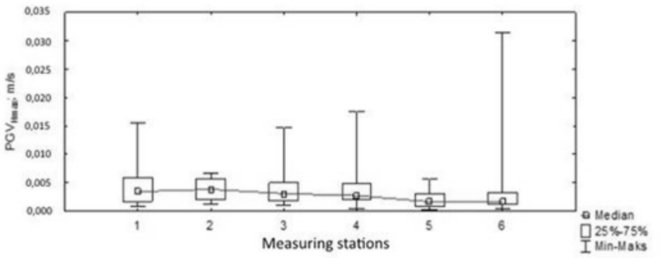

Fig. 6. Distribution of the medians of the horizontal component value of peak ground vibrations velocity for measurement stations for tremors with energy E ≥ 106 J occurred in 2010 - 2014.

3. Local attenuation relation

The estimation of the regression equation parameters was carried out using the least squares method. The model eliminated independent variables, which were characterized by the smallest value of the explained to unexplained variance. Finally, the local attenuation relation for logPGVHmax, for the significance level λ = 0.05, took the following form:

$$logPGV_{Hmax} = 0{,}44937 \cdot logE - 1{,}49304 \cdot logR + 0{,}07623 \cdot S_i - 0{,}88661 \quad (8)$$

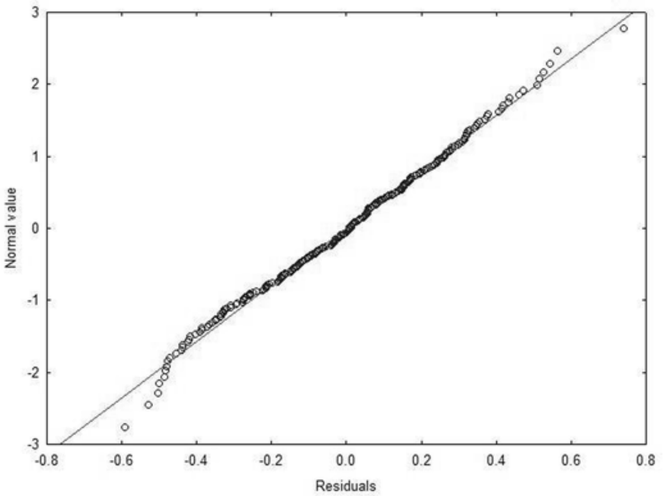

Fig. 7. Normal probability plot of residuals for a prediction model of logPGV$_{Hmax}$

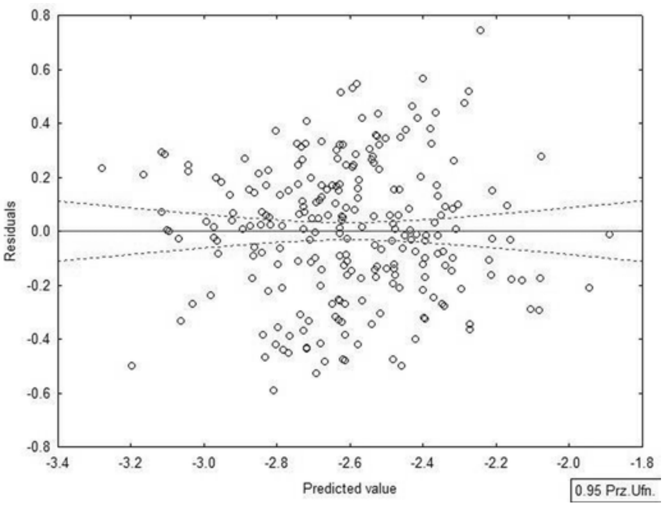

Fig. 8. Scatter plot of residuals for a prediction model of logPGV$_{Hmax}$

where:

PGVHmax – horizontal component of Peak Ground Velocity ; [m/s],
E – tremor energy, [J],
R – the distance from the source of the tremor for pseudo depth h = 1022m for which the value of the standard estimation error according to equation (3) assumes the smallest value, [m],
Si – quality variable taking value Si = 0 for a ground type B and Si = 1 for a ground type C, [-].

The correlation coefficient for the developed model is 0.68840. The value of the coefficient of determination R^2 = 0.47390 means a moderate fit of the model to the analyzed data. The value of coefficient of determination depends on: inaccuracy determination of energy and source of tremors [2], do not take into account the differentiation of the energy radiation from the source [2], not fully recognized geological structure [2], measurement errors of the accelerometers, regression model errors. In most of the seismic wave propagation models found in the literature [2,6,10,26,27], the coefficient of determination assumes similar values. Accordingly, it was decided to continue the analysis based on the obtained regression model.

The standard error of the estimate is Se = 0.25344 and means that the estimated values of the logPGVHmax variable differ from the empirical values by an average of 0.25344.

The construction of the multiple regression model was completed by residual analysis, which confirmed that the model meets the assumptions of the classic least squares method (Fig. 7, Fig. 8).

4. The influence of selected factors on the failure intensity of the water distribution subsystem

The results of the failure intensity analysis of all water supply network and groups of steel and gray cast iron pipes are presented in Tab. 3.

In the case of a groups of: all pipes and steel pipes, the obtained values of coefficients of determination indicate a good fitting of the models to the data. The PGV_{Hmax} parameter informing about the impact of mining tremors is an important variable for these models and has a positively affects on the dependent variables. The most significant influence on the dependent variable in the model for all pipes exerts successively: DN and M, Tp and PGV_{Hmax}, and in the case of steel pipes: DN and PGV_{Hmax}. For instance, for a model built for steel pipes if PGV_{Hmax} increase of 0.01 m/s, the dependent variable logλspvs will increase of 0.72906 (the damage intensity will increase of 5.35797 damage/(km·4 year)).

For a gray cast iron pipes, a weaker relationship was obtained (R^2 = 0.47845) and the variable informing about the impact of mining tremors on the water pipes turned out to be irrelevant.

In the whole range of analyzed pipe diameters (DN20 - DN600), only for DN80, DN100 and DN150 statistical relations between selected factors and the failure intensity of pipelines were obtained. For the remaining variables, either there was a lack of sufficient data or independent variables turned out to be irrelevant, or the correlation and determination coefficients were zero. A comparison of the obtained multiple regression models is contained in Tab. 3.

Only in the model built for a pipes with a diameter DN100, the variable describing the impact of mining tremors turned out to be significant. The model explains about 40% of the variability of the dependent variable. The correlation coefficient is close to 0.65. The following influence on the dependent variable has the following effects: Tp, PGV_{Hmax} and W. The models built for DN80 and DN150 have low values of coefficient of determination.

In the case of the analysis of failure intensity, taking into account diameters and materials from which the pipes were made, it was possible to build regression models only for pipes: DN100 made of steel, DN100 made of gray cast iron and DN150 made of steel. The results of the analyzes carried out are summarized in Tab. 4.

Only in the model for pipes made of steel with a diameter DN100, the variable describing the impact of mining tremors (PGV_{Hmax}) turned out to be an important variable. The variable has a positive effect on the failure intensity. In the model, also Tp and the intercept parameter have a significant impact on the dependent variable. The model explains about 47% of the variability of the logλsv100s.

For pipes made of gray cast iron with a diameter DN100 and for pipes made of steel with a diameter DN150, only Tp and the intercept parameter are an important variables. The dependence obtained for grey cast iron pipes DN100 is very weak, the value of the coefficient of determination is only 25% and indicates the lack of dependence. A better model was obtained for steel pipes DN150, in which the coefficient of determination is approximately. 55%.

Due to the fact, that in the research water pipelines at the age of even 129 were analized, it seems justified to perform analysis of failure rates of pipes made at particular time intervals (Tab. 6).

The obtained regression models are characterized by a very good fit to the observation, the coefficient of determination is in most cases in the range of 74 to 83%. Only the model for pipes built in 1922 - 1938 has a coefficient of determination around 53%. The variable characterizing mining tremors is significant only for the model did for pipes built in 1885 - 1920. According to the above, it can be concluded that the oldest analyzed pipelines may be least resistant to occurring mining tremors. In the presented model, an important variable was also the pressure in the place of pipe failure, which may also indicate that only the oldest pipes are less resistant to this factor. For pipes built in 1922 - 1938 and 1979 - 1994, only diameter with a intercept parameter had a significant impact on the failure intensity of the water pipes, which is most likely the result of significant differences in the way the pipes with each diameters were built.

For the remaining groups of pipes, analyzed due to the time of their construction, the parameters important in the created models were: diameter and

Table 3. Regression models for the failure intensity of water pipelines.

Type of pipelines	Regression model	R, R^2, Se
All pipes	$\log\lambda spv = -0{,}03547\cdot DN + 0{,}68996\cdot M + 73{,}53762\cdot PGV_{Hmax} + 0{,}00085\cdot Tp + {,}62527$	R= 0,84113 R^2= 0,70750 Se = 1,11430
Steel pipes	$\log\lambda spvs = -0{,}04067\cdot DN + 72{,}90571\cdot PGV_{Hmax} + 3{,}17737$	R= 0,85774 R^2= 0,73572 Se = 1,03300
Gray cast iron pipes	$\log\lambda spvz = -0{,}00297\cdot DN - 0{,}00068\cdot Tp - 1{,}42276$	R= 0,69170 R^2= 0,47845 Se = 0,26376

Table 4. Regression models for the failure intensity of water pipelines with diameters DN80, DN100 and DN150.

Diameter	Regression models	R, R^2, Se
DN80	$\log\lambda sv80 = -0{,}01010\cdot W - 1{,}20001$	R= 0,53986 R^2= 0,29144 Se = 0,39376
DN100	$\log\lambda sv100 = -0{,}03320\cdot W + 67{,}93168\cdot PGV_{Hmax} - 0{,}00070\cdot Tp - 1{,}60510$	R= 0,64731 R^2= 0,41902 Se = 0,26561
DN150	$\log\lambda sv150 = -0{,}00113\cdot Tp - 1{,}55594$	R= 0,66583 R^2= 0,44333 Se = 0,29573

Table 5. Regression models for the failure intensity for a water pipelines with diameters and materials

Diameter and material	Regression model	R, R^2, Se
DN100 steel	$\log\lambda sv100s = 64{,}44562\cdot PGV_{Hmax} - 0{,}00083\cdot Tp - 1{,}70361$	R= 0,68320 R^2= 0,46677 Se = 0,25054
DN100 grey cast iron	$\log\lambda sv100z = -0{,}00088\cdot Tp - 1{,}63868$	R= 0,49176 R^2= 0,24183 Se = 0,27936
DN150 steel	$\log\lambda sv150s = -0{,}00135\cdot Tp - 1{,}45395$	R= 0,74349 R^2= 0,55278 Se = 0,28652

Table 6. Regression models for the damage intensity of to water supply network pipes and connections built in different time periods.

Group	Year	Regression model	R, R^2, Se
1	1885-1920	$\log\lambda_{spv(1885-1920)} = -0{,}03320\cdot DN + 1{,}34550\cdot M + 216{,}44430\cdot PGV_{Hmax} + 0{,}03000\cdot P$	R= 0,90274 R^2= 0,81494 Se = 1,06430
2	1922-1938	$\log\lambda_{spv(1922-1938)} = -0{,}01687\cdot DN + 1{,}61912$	R= 0,73161 R^2= 0,53525 Se = 1,57350
3	1939-1961	$\log\lambda_{spv(1939-1961)} = -0{,}04136\cdot DN + 1{,}08442\cdot M + 2{,}33101$	R= 0,86648 R^2= 0,75078 Se = 1,09150
4	1962-1978	$\log\lambda_{spv(1962-1978)} = -0{,}03291\cdot DN + 0{,}62525\cdot M + 50{,}00144\cdot Tp + 1{,}28402$	R= 0,86310 R^2= 0,74495 Se = 0,99725
5	1979-1994	$\log\lambda_{spv(1979-1994)} = -0{,}04550\cdot DN + 3{,}65622$	R= 0,87887 R^2= 0,77242 Se = 0,96855
6	1995-2012	$\log\lambda_{spv(1995-2012)} = -0{,}050443\cdot DN - 0{,}645707\cdot M + 4{,}442355$	R= 0,90993 R^2= 0,82797 Se = 0,73568

material of the pipes, operation time without failure and intercept parameter.

The analysis of the residues, for each regression models discussed above, showed that the assumptions of regression analysis in terms of residual normality, model linearity and homoscedasticity for the following variables are fulfilled: logλspvz, logλsv80, logλsv100, logλsv150, logλsv100s, logλsv100z, logλsv150s . In the case of other models, the conditions of the model's linearity with regard to parameters and homoscedasticity were not met. On the scatter plots obtained, two groups of points are visible, due to a large discrepancy between the value of failure of the water supply network and connections. The described situation indicates heterogeneity of the random sample, accepted for analysis and may affect the quality of the models obtained. However, this does not change the fact that the values of coefficient of determination obtained in the models had a good value, due to the greater amount of data taking into account the whole group of pipes. Accordingly, it seems reasonable to conduct a similar analysis individually for the water supply network and connection.

5. Summary and conclusions

The analyzes presented in the article are the first attempt of this type to determine the impact of mining tremors on the failure intensity of the water distribution subsystem.

The research was based only on historical data obtained from the real object, which made it impossible to repeat and eliminate some measurement errors. It should also be emphasized, that the research covered the commune with an area of 69.44 km^2. This results in the possibility of occurrence of many additional factors, not taken into account/unidentified in the conducted research, which could have influenced on the dependent variables, and thus also the quality of the models obtained.

The analyzes presented in the article allowed to formulate the following conclusions:

1. The independent variable (PGV_{Hmax}) informing about the impact of mining tremors on the failure intensity of the water distribution subsystem's pipelines turned out to be significant in the constructed regression models for selected groups of water distribution subsystems. This indicates the existence of a factor, which has not been accounted for so far, affecting the failure rate of water pipes, located in mining areas.
2. The independent variable, which in most of the built regression models had the biggest influence on the dependent variable, was the diameter of the pipes (9 out of 15 models) and sequentially the operation time without failure (7 out of 15 models) and PGV_{Hmax} and the material from which the pipes are made (5 out of 15 models).
3. The methodology of analysis and assessing the impact of mining tremors on the failure intensity of the water distribution subsystems can be applied to each subsystem of water distribution and other pressure - related linear underground facilities, such as: heating, gas, pressure sewerage, located on the impact mining tremors areas, provided that the following data will be available: failure rate of linear objects, the type of ground on which the objects are located, energy values of tremors, coordinates of the tremors epicenter and the local attenuation relations in the considered area or in the absence of such relations - PGV_{Hmax} values, as well as the coordinates of measuring stations and the type of ground on which they are located.
4. The developed regression models can be the basis for the development of a computer program that could be used to forecast the damage of the water distribution subsystem after the mining tremors, with defined parameters for instance, based on a mining tremors forecast, when starting operation in a new mining field.

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