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In situ Verification of Numerical Model of Water Hammer in Slurries

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ABSTRACT

This paper presents a numerical model of transient flow in a pressure slurry pipeline network with verification based on in situ measurements. The model, primarily verified in laboratory conditions, has been extended and applied to the case of a large and complex slurry pipeline network in Poland. In the model, the equivalent density concept was applied. In situ experiments were performed for various unsteady flow episodes, caused by different pump operation strategies in the industrial pipeline network. Based on the measurements of slurry concentration and pressure variations, the numerical model was tested and verified. A satisfactory coincidence between the

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calculated and the observed pressure characteristics was achieved. Additional numerical tests led to important conclusions concerning safe pump and valve operation and system security threats.

INTRODUCTION

Slurry pumping has become a widely used, preferred method of transporting solid particles. The materials that are transported in the form of slurry through pipelines can vary widely [1]. As in other pressure systems, in order to calculate values of head loss, a model of quasi-steady motion is used. However, due to the valve maneuvering and possible power system failures etc., transient flow can occur and should be taken into consideration [2]. The presence of solid particles in slurries causes them to not have the same properties as clean water. For this reason, the traditional mathematical models describing transient flow have to be modified.

This paper is part of a more in-depth analysis of transient flow in slurries. The analysis was carried out for the needs of KGHM – the largest Polish enterprise dealing in the mining and processing of copper. KGHM uses a flotation process to recover copper ore from native rock. Water is used to transport crushed rocks in the form of slurry. The hydrotransport system consists of a series of pressure pipelines and a few pumping stations. Transient flow very often occurs in that system due to unsteady flow and pressure conditions. That was the most important reason for developing an in-depth analysis of the phenomenon. The whole project consisted of a literature search, experiments of water hammer in the laboratory and numerical modelling of transient flow, in situ measurements, verification of the numerical model used, conclusions and recommendations for the KGHM authority. This article focusses on the verification of a numerical model on the basis of in situ measurements. The laboratory experiments and numerical model details are described in [3]. In this paper, a simplified method of describing water hammer phenomenon in slurries was developed. On this basis, software was created that numerically solves the transient flow equations. It allows prediction of the pressure changes caused by pipeline system operation, such as valve opening, closing etc. The main problem was determining pressure wave celerity, which is crucial when describing the phenomenon. In situ measurements, described in [4], were important in finding values of pressure celerity in a real working system. It should be mentioned that, during laboratory tests, a simple water hammer was conducted. Real hydrotransport systems have their own limitations. First of all, the volume of liquid in pipes is much larger than in chambers in pumping stations. Also the distances and elevations are more complex. As a result, a varied depth of benthic layer of dragged solid particles is expected. These problems led to different experimental methods. A small pressure impulse was determined by sudden changes of pump parameters. In situ measurements focused on detecting the time of pressure increase which occurred in two cross-sections [4]. The aim of this study is to verify a numerical model for transients in slurries, which was developed on the basis of laboratory testing and the results of field tests, carried out in a pipeline system at the "Żelazny Most" copper tailings sump reservoir.

Basic equations

The unsteady flow of compressible liquid is described by the hyperbolic system of partial differential equations which consists of : (e.g. [5])

Continuity equation:

$$\frac{\partial p}{\partial t} + v\frac{\partial p}{\partial x} + \rho a^2 \frac{\partial v}{\partial x} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \Delta h_f = 0, \tag{2}$$

where: x – space coordinate, t – time, v – flow velocity, p – pressure, g – gravity acceleration, a – pressure wave celerity.

The term Δh_f in Eq. (2) is a friction factor, which is a sum of the quasi-steady part and unsteady part [6]:

$$\Delta h_f = \Delta h_s + \Delta h_u \, , \tag{3}$$

where Δh_s is the quasi-steady friction factor, which involves updating the Reynolds number variable in time, and Δh_u is a component which considers the unsteady effect.

Equations Eq. (1) and Eq. (2) describe the elastic model. Viscoelastic materials have different reaction to the applied stress [7, 8]. This material not only responds instantaneously to the applied stress, but the additional retarded reaction to the applied load can be observed. After taking into account the linear viscous behavior of the pipe material described by the Kelvin-Voigt model [9 5-9,18], the continuity equation (1) is transformed into:

$$\frac{\partial p}{\partial t} + v\frac{\partial p}{\partial x} + \rho a^2 \frac{\partial v}{\partial x} + 2\rho a^2 \sum_{i=1}^{N} \frac{d\varepsilon_i}{dt} = 0 \, , \tag{4}$$

where ε_i are the components of the retarded strain ε_r,

$$\varepsilon_r = \sum_{i=1}^{N} \varepsilon_i \tag{5}$$

In the N-element Kelvin-Voigt model.

For small Mach numbers ($v/a \langle\langle 1$), the convective terms in Eq. (4) can be neglected and one finally obtains [7, 9-13]:

$$\frac{\partial p}{\partial t} + \rho a^2 \frac{\partial v}{\partial x} + 2\rho a^2 \sum_{i=1}^{N} \frac{\partial \varepsilon_i}{\partial t} = 0 \, . \tag{6}$$

The second problem is introducing the characteristic parameters of the slurry into the equations. Solid-liquid flow can be described in two ways: homogenous or heterogeneous. In the case of homogenous flow, the mean density of the slurry can be easily calculated. In the case of non-homogenous slurries, the density of the mixture depends on the geometrical parameters of the pipeline and the flow velocity. Furthermore, due to differences in their velocity, the liquid phase and solid phase should be described by different friction factors. Two approaches can be applied to solve this problem, a single-phase Newtonian mixture formula [14] or non-Newtonian liquid formulas with an additional component for calculating the friction factor [15]. The Durand equation can be used to calculate the total steady or quasi-steady head losses [14]. Some authors [16] also propose to determine pressure losses separately for homogenous and heterogeneous flow and then calculate head losses as the sum of both parts.

The practical implementation of the above-mentioned methods of slurry hammer simulation requires additional parameters that should be properly identified. Some of the parameters, due to their spatial diversity and time-variability and the number of additional factors affecting their values, are very difficult to recognize in real industrial systems. For this reason, simplified approach to the mathematical description of the transient phenomena was proposed [3], in which an equivalent density was introduced into equations to represent the combined effect of the real mixture density and bottom layer existence.

IN SITU TESTS

Analyzed pressure networks

The slurry pipeline network of the “Żelazny Most” Reservoir is one of the largest slurry systems in Europe. This is a waste reservoir for the flotation of copper, which is transmitted in the form of a highly hydrated hydromixture. The slurry is taken from three stations (ZWR Polkowice, ZWR Rudna and ZWR Lubin) and transported by a pumping system to the crest of the landfill. ‘ZWR’ is a place where rock is crushed, flotation processes are carried out (copper and other metals are recovered), and the by-products of flotation are removed in the form of highly diluted slurry. They are located close to copper mining shafts.

The schema of the main pipe network is shown in Fig.1. The geometrical dimensions of the network are evidence of the scale of the object; the entire sludge transport system consists of over 150 km of pipelines with a diameter of more than 800 mm. From the pumping station of each ZWR, the slurry can be led through at least three parallel pipelines to the main reservoir. Three strips surround the storage tank, on three levels: lower, intermediate and crest. The pipeline located on the crest is used to discharge sludge in the form of a single point discharge of large diameter or a series of discharges at smaller diameters.

Copper recovery waste in the form of slurry is typically transported to the sludge tank via a pressure pipeline. In each ZWR station, a set of pumps is used to transport slurry in a single pipeline. A model consists of a set of pumps, a single pipeline and a point outlet or an evenly dispersed pipe. In other words, the slurries from different ZWR stations are transported separately (in different pipelines) from pumping station to the tank.

The ZWR Polkowice has three pump units (P1, P3 and P4) and one back-up system. Working units consist of two connected, Warman type ST 450-L Series pumps, with a nominal flow of 55 m^3/min and a height of 60 m H_2O. Both pumps in each of the teams are equipped with engines powered by a frequency converter, which allows for a smooth adjustment of flow and pressure. Sludge is pumped through the pipelines to the arterial chamber (RG-PG) with a length of 3.45 km each. From the chamber, RG-PG slurry can be pumped in the direction of the OUOW node H, to the arterial pipelines R6, R5, R3, R2 and R1 with a length of 4.45 km.

ZWR Rudna consists of two pumping stations: A and B. A pumping station consists of five teams of Warman 14/12 AH pumps, connected in two series. In each of the assemblies, one of the pumps is driven by an electric motor, fed by a frequency converter which allows for the continuous adjustment of the operating parameters, such as rotational speed of the rotor. The nominal capacity of each unit is equal to 33 m^3/min, with a lifting height (depending on the scheme of work)from 44.5 m to 85 m H_2O.

ZWR Lubin consists of three Warman 14/12 AH pumps, connected in series. The slurry pumping station is connected to chamber 'LG' and to deposit chamber 'L' through pipelines with a length of 4.80 km. A schema of the pipeline profile is presented in Fig. 2.

Such a complex system has to be investigated in detail, so that the hydraulic conditions can be properly described. Transportation of slurries needs to provide high flow velocities. For small suction chambers and when pumping directly to a pipeline without any pressure tank, a significant difference in elevation is an important and negative factor. The system is equipped with a high number of valves, which are used to direct the sludge to the appropriate pipelines. These conditions are conducive to creating a transient flow.

Two reasons are the most probable: the quick closing valves in the nodes by the service or by valve failure and the sudden shutdown of the working pump / pump unit by the service or accidentally. Therefore transient flow analysis can be used to protect the system against enormous pressure increase. There are many factors that can affect the phenomenon. The density of the slurry and concentration distribution may vary with time and over the length of a pipeline. The mathematical description, involving all aspects of the slurry's transient flow, would be very complex. A large number of values should be measured. For a practical solution, a complicated description would lead to unrealistic results, so a more universal and simpler solution is needed. The previous analysis, which was carried out on the results of laboratory tests [3, 4] was used to solve this problem for a real pressure system.

An implementation of the numerical model should be preceded by field measurements, which will allow the collection of data for model verification.

In situ measurements

Experimental tests were conducted in four cross-sections on two separate pipelines (two cross-sections per pipeline). The location of the cross-sections, along with the pipeline lengths and their elevations, are shown in Fig. 1 and Fig. 2.

Pressure sensors with a range from -0.1 to 2.0 MPa and a sensitivity of 0.1% were installed in each of the measuring sections. Uncertainty in the pressure measurement was a result of the pressure sensors' class and the accuracy of elevation measurement. The total pressure uncertainty was less than 0.00225 MPa. Time sampling for each sensor was equal to 0.002 s. The time shift between pressure transient changes in two cross-sections was in the range of 6 to 15 seconds. Because of the very high sampling frequency, the uncertainty of time measurement was negligibly small. The data from the pressure sensors were recorded on the hard drive of a measuring device. Both recorders were equipped with a clock with the same setting, which allowed comparison of the measurement results and an assessment of the course of the phenomenon in both sections. The measurements were performed in the real pressure network. This was the main reason for the most important limitation of the measurement series. The aim was to check the probability of the occurrence of a transient flow under ordinary service conditions. The second part of the experiment was to determine wave celerity, as one of the most important parameters of a transient flow.

The experiments were undertaken according to the following steps:

1. Installation of pressure sensors in both measuring sections. Atmospheric pressure measurements were recorded during the installation. After that, venting was carried out (each measurement point was equipped with a vent valve) and test measurements were made.
2. Notifying the service department of the ZWR of the commencement of measurements.
3. Recording data: the service staff of ZWR turned off one of the three pumps during the operation (it is called the phenomenon of negative sludge hammer). After filling the sump, the service staff of ZWR switched on the third pump (the positive sludge hammer). This procedure was performed several times during the day. As a result, a shock wave was created in the pipelines. During the experiments, a shifting shock wave front transition was measured in two cross-sections. That value was crucial to wave celerity calculation, which was later used in the numerical model. For the slurry from ZWR Rudna, measurements of 15 shock wave transitions were performed. For slurry from ZWR Lubin, 10 series were carried out and, for ZWR Polkowice, 5 series. The lower number of measurements for the last case was a result of the geometry effect, and slurry from ZWR Rudna and ZWR Polkowice is transported through the same pipelines.
4. Completion of tests and dismantling the measuring devices.

It should be mentioned that, due to the volumetric limitation of chambers in pumping stations, the time of flow reduction has to be limited. For various scenarios, the time ranged from 5 to 12 minutes. As a result, only the first phase of transient flow can be stored and analyzed.

Experimental results

The main aim of the in situ experiments was to collect pressure characteristics during an unsteady flow (Fig. 3). The stored pressure characteristics were used as a basis for a numerical model simulation. They can also be used to determine a value of pressure wave celerity, which is crucial when simulating a proper phenomenon run.

During in situ testing, different values of average wave celerity were observed for each pumping station. The minimum value of wave celerity was reached for the slurry transported via ZWR Rudna (269.4 m/s). For ZWR Lubin, an average value of wave celerity was equal to 374.8 m/s and for ZWR Polkowice it was 461.8 m/s. Such values are the result of the complexity of the flow of the sludge; the physical differences of the grains and the process of particle deposition caused a change in the cross-sectional area of the flow and influenced the dissipation of energy. As a result, the values of the wave velocity determined during field studies were adopted for the numerical simulation of the transient flow.

NUMERICAL CALCULATIONS

Numerical model description

The next stage of analysis concerned the development of a mathematical model that would provide correct and effective simulations of time-varying pressure characteristics occurring during unsteady flow in the slurry network being studied. The main purposes of such calculations are the evaluation and prognosis of the network operation in various conditions in order to specify critical localizations, analyze acceptable operating ranges for devices and theoretically assess the consequences of possible failures. Efforts focused on the optimal simplification of the phenomenon in order to enable satisfactory pressure reproduction as well as increase the speed of calculation and reduce the number of model parameters (especially those that are immeasurable, characterized by high temporal and spatial variability in a real system or otherwise very difficult to identify in the correct way).

In the study, the model of unsteady slurry flow [3] applied was successfully verified in laboratory conditions. The model was extended due to the needs of a complex network of pressure pipes with different geometric characteristics and pipe materials. For clarity, the main features of the general model [3] and the new assumptions made at this stage of development are presented below:

1. A full cross-section flow, without the bottom layer or air pockets, is considered;
2. The slurry mixture is considered as a quasi-homogeneous liquid with a fixed (constant in time and space) density and viscosity;
3. The transient flow of the slurry is described by the system of one-dimensional, partial differential equations for a compressible fluid in a pipeline network consisting of elastic (e.g. steel) and/or viscoelastic (polymer) pipes. Continuity and momentum equations for a single conduit are defined by Eq. (1), Eq. (2) and Eq. (6).
4. Viscoelasticity of the pipeline material in the presented model is described using a one-element Kelvin-Voigt model (N = 1). [9-11, 17-19]

5. A concept of equivalent density [3] is applied. The value of the equivalent density ρ_e is a parameter that must be identified for each case individually;
6. The flow conditions in pipeline junctions are described by additional mass and energy balance equations. When balancing energy in network nodes, the local energy losses were neglected due to their negligible values and the inability to identify time-varying values of resistance coefficients.
7. As an initial condition for the calculations, the steady flow conditions were applied. The initial condition is calculated based on steady flow equations in a pipeline network.
8. The boundary conditions for unsteady flow were defined according to the specific episode. Boundary nodes are either the pump cross-sections, valve cross-sections or free-flow pipe ends. The boundary conditions were thus defined by the functions of flow variation $Q(t)$ during pump or valve operation and the constant value of pressure in the outflow ends of the pipeline.

The solution of the set of partial differential equations was performed using the four-point finite difference method (more precisely – its particular variant, called Preissmann difference scheme [e.g. 17]. The scheme has favorable numerical properties, including relatively high accuracy and absolute stability, independent of the Courant number (e.g. [17]). More precisely, the stability is independent of the size of the numerical grid and the wave celerity, which in general case may vary during the unsteady flow. In this aspect, the scheme has favorable numerical features, compared to commonly used method of characteristics. The values of the numerical parameters in the analyzed approach were adopted to ensure absolute stability and maximal accuracy of the scheme (maximal possible reduction of the numerical errors). As the result of the approximation according to the Preissmann scheme, the partial differential equations were replaced with their differential equivalents, which together with boundary conditions, constituted the system of nonlinear algebraic equations, that was finally solved with the efficient Newton method.

Numerical tests

Model verification

Although simplified, the model still has a relatively large number of parameters that must be identified. The parameters related to the geometry and structure of the pipeline network are relatively easily determined based on documentation and in-situ verification. The parameters related to viscoelasticity of polymer pipes were estimated based on a procedure published in [9]. More details concerning the problems arising in the case of viscoelastic parameter identification were described in [10, 18-19].

The values of slurry density (for individual slurries from Rudna, Polkowice and Lubin) and pressure wave celerity (for each individual episode) were determined based on measurements. The proper values of equivalent density were determined by model calibration during unsteady flow simulations. Although the value of ρ_e may be estimated theoretically [3] in practice, such an approach appears to be ineffective due to the complexity of the flow (mainly time and space variability of the concentration and bottom layer depth and the complexity of the geometrical characteristics of the pipeline system). Therefore, the equivalent density may be treated as a conceptual parameter that results from model simplifications and represents the combined effect of different mechanisms not considered in mathematical descriptions. Its identification may be based on a trial and error method, in which the optimal value of the parameter is that which best matches computational results to the estimated measurements.

To verify the suitability of the applied numerical model, the calculations of transient slurry flow scenarios measured during in-situ tests were carried out. As an example, the measurements obtained in Rudna pipeline on the 30th June 2015 (slurry density 1100 kg/m^3) were considered (Fig.3). In the first step, the steady flow calculations which define the initial condition in the pipeline system were carried out. The initial values of discharge in the pump cross-sections were based on known operating parameters recorded in the pump stations. In the next stage, calculations of unsteady flow were carried out, with boundary conditions reproducing the different shutdown scenarios in pump operation being applied during in-situ measurements. The calculations of each analyzed scenario were carried out with different values of equivalent density. In each case, the pressure characteristics were calculated and compared to observations. The example of the pressure values obtained for “Chamber RG” and H cross-sections (for the episode at Rudna on 30th June 2015) are presented in Fig.4.

As can be seen, the computational results are strongly dependent on the applied value of equivalent density. To determine the optimal value of ρ_e , the numerical simulations were compared to the measurements and the case with the highest consistency between calculations and observations was considered optimal in each analyzed episode. In the analyzed example, the best results were obtained for the value of ρ_e equal to 1800 kg/m^3 (Fig.5). A similar approach was applied to other cases. For all of the types of slurry analyzed (from Rudna, Polkowice and Lubin), the appropriate values of equivalent densities were determined. Finally, the calculations were carried out for various episodes recorded during in-situ measurements. The proposed model satisfactorily reproduced the rate and magnitude of pressure changes during unsteady flow in the analyzed pipeline network.

From practical point of view, the crucial questions are the proper reproduction of extremal pressure values, referred to both – time and place of the occurrence. From that point of view the model meets expectations. Comparison of the calculations and the measurements, however, shows some discrepancies (Fig.5). The pressure characteristics in both cases are similar but not the same, what proves that the complex phenomena are not fully reproduced by the model. That conclusion should not come as a surprise, taking into account the level of simplifications in mathematical description of the processes. One of the most important reasons is the assumption of the lack of bottom layer formulation and quasi-homogeneous nature of the mixture. The second reason is introduction of equivalent density, which from mathematical point of view creates inconsistency between steady and unsteady flow conditions. That may be the explanation of the local unphysical oscillation in simulated values of pressure during the stabilization of the unsteady flow after the pressure impulse passes. Such discrepancies are the 'costs' of the simplifications in flow description, both with inability to reproduce some flow effects, e.g. variable concentration and velocity distribution in the cross-sections and in longitudinal profile of the pipeline, bottom layer existence and space- and time variability, air pockets occurrence etc. On the other hand, the benefits of the simplified approach are relatively small number of parameters requiring identification and effectiveness of calculations (satisfactory accuracy of pressure reproduction combined with short calculation time).

Numerical simulations of selected operating scenarios

Once the model was verified, based on the in-situ measurements, it could be applied to the analysis of working systems in different operating scenarios (both real and hypothetical).

Calculations were carried out for the following cases:

- normal operation of the system (switching the pumps on and off, according to typical scenarios);
- rapid incidental exclusion of pumps (e.g. due to electrical failure);
- incidental rapid closing of the valve.

For each of the scenarios, the extreme pressure values were calculated, the critical pipeline cross-sections were determined (particularly those exceeding the permissible values of the flow parameters) and the minimum possible durations of the switching on/off maneuver providing system safety were estimated. The analysis was carried out for various slurry flow paths in the pipeline network, especially for the critical routes from the pump station to the reservoir (the shortest and the longest). In the study, the selected results for the critical route from Rudna to the reservoir are presented.

Pump operation. Changes in pump operation are introduced into the model via boundary conditions, representing the discharge variations in time $Q(t)$ in pump cross-sections. By imposing different boundary conditions, one can simulate any real or hypothetical scenario of typical or incidental pump operation. From a practical point of view, the most important conclusions from such calculations can be based on extreme pressure value analysis. An example of the results obtained is shown in Fig. 6.

The diagrams present the distribution of maximal and minimal values of pressure [MPa] and pressure head [m above the datum] along the slurry flow path. The results shown in Fig.6a refer to the unsteady flow episode caused by a consecutive switching on and off of one of the pumps (each maneuver duration T = 100 s) with a relatively small change in the flow rate. Fig.7b presents the results for the hypothetical rapid failure of all the pumps in the system.

Based on the results of the calculations, it is possible to identify the location of critical sections in which the highest/lowest pressure will occur, as well as to assess the impact of the duration and intensity of discharge changes during switching maneuvers on pressure distribution in the pipelines.

Valve operation. A similar analysis of extreme pressure values can be carried out regarding valve maneuvering (intentional opening/closing of valves and valve failures, defined here as rapid decreases of flow discharge to zero). Fig. 7. presents an example of pressure distribution caused by the failure of a valve located approximately 4900 m below the pumping station. After the rapid closure of a valve, the pressure increase in the cross-sections, located up the valve, and pressure decrease, down the valve, are observed. Obviously, the most dangerous situation arises nearest to the valve. The duration of valve closing is essential to the magnitude and nature of the pressure changes. If the valve closure is rapid enough, the unsteady slurry flow may take the form of a slurry hammer, both in up and down-the-valve pipeline sections. The influence of closure time on pressure changes in the first 50 seconds after the failure is presented in Fig.8. Based on similar analyses, it is possible to estimate limit values for maneuvering times of different devices that will not exceed permissible flow parameters in the pipeline.

CONCLUSIONS

In this study, a simplified model of 1D unsteady slurry flow and its application to a real system of slurry transportation was presented. The analysis showed that the proposed model may be successfully applied to pressure characteristics simulations in various scenarios of pipeline network exploitation. Although a detailed analysis of flow phenomena (such as bottom layer formation, time and space variations of homogeneous solid phase concentration etc.), could not be carried out due to the applied model simplifications, essential conclusions concerning the rate and propagation of pressure changes in the system were obtained. The resulting pressure characteristics provide important information concerning the pressure ranges occurring in the system, the risk of exceeding the limit values of the flow parameters, localization of critical cross-sections, and recommended durations of pump and valve maneuvers etc. The analyzes showed that the consequences of unsteady flow (including slurry hammer) in slurry systems are very strongly dependent on such factors as:

- the slurry flow route (length, pipe dimensions and materials, pipeline elevations);
- properties of the slurry;
- initial flow conditions;
- the type, localization and intensity of the factors causing unsteady flow in the system.

The simplified numerical model of transient slurry flow described, resulted in a very good convergence of calculation and measurement results. However this method has its own limitations. The most crucial parameter of water hammer, wave celerity, was introduced into the numerical model on the basis of experiments. However a new approach, equivalent density, led to very good results [3], although there was a problem measuring the depth of the bottom layer in a real installation. During experiments in the laboratory, the method allowed us to determine the depth of solid particles due to the horizontal geometry of the pipeline. In real installations, the depth of the bottom layer may vary in length and time, due to different longitudinal profiles of the pipelines. That was the main reason for the measured real values of wave celerity in the existing network. Moreover, the analysis proved that the empirical value of pressure wave celerity is different from the value calculated based on theoretical formulas for wave celerity, even if the depth of the bottom layer is taken into account. Due to these facts, experimental determination of the real value of wave celerity in existing network is required, instead of theoretical values obtained from calculations. In conclusion, the proposed numerical description of transient flow in a real system led to very good results. However, it requires real values of wave celerity.

Finally, it should be noticed, that the presented model was developed for the specific slurry transportation system, that is also for certain specific conditions of flow and slurry characteristics (specific granulometric size of particles and volumetric concentration – it the considered case relatively low). The model is more universal, what means that it may be applied for other transportation systems as well, as long as the simplifications concerning quasi-homogeneous nature of the slurry can be accepted, and as long as the detailed description of flow phenomena (e.g. space and time distribution of concentration and velocity, bottom layer variability, air pockets etc) is not required. In all such cases, however, the values of crucial parameters - wave celerity and equivalent density should be individually identified.

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NOMENCLATURE

a	wave propagation celerity (m/s)
g	gravity acceleration (m/s^2)
p	pressure (Pa)
T_R	return time of the reflected pressure wave (s)
v	velocity (m/s)
x	space co-ordinate (m)
Δh_f	head losses (m)
ε	strain, $\varepsilon = \mathrm{d}D/D$ (-)

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Figure Captions List

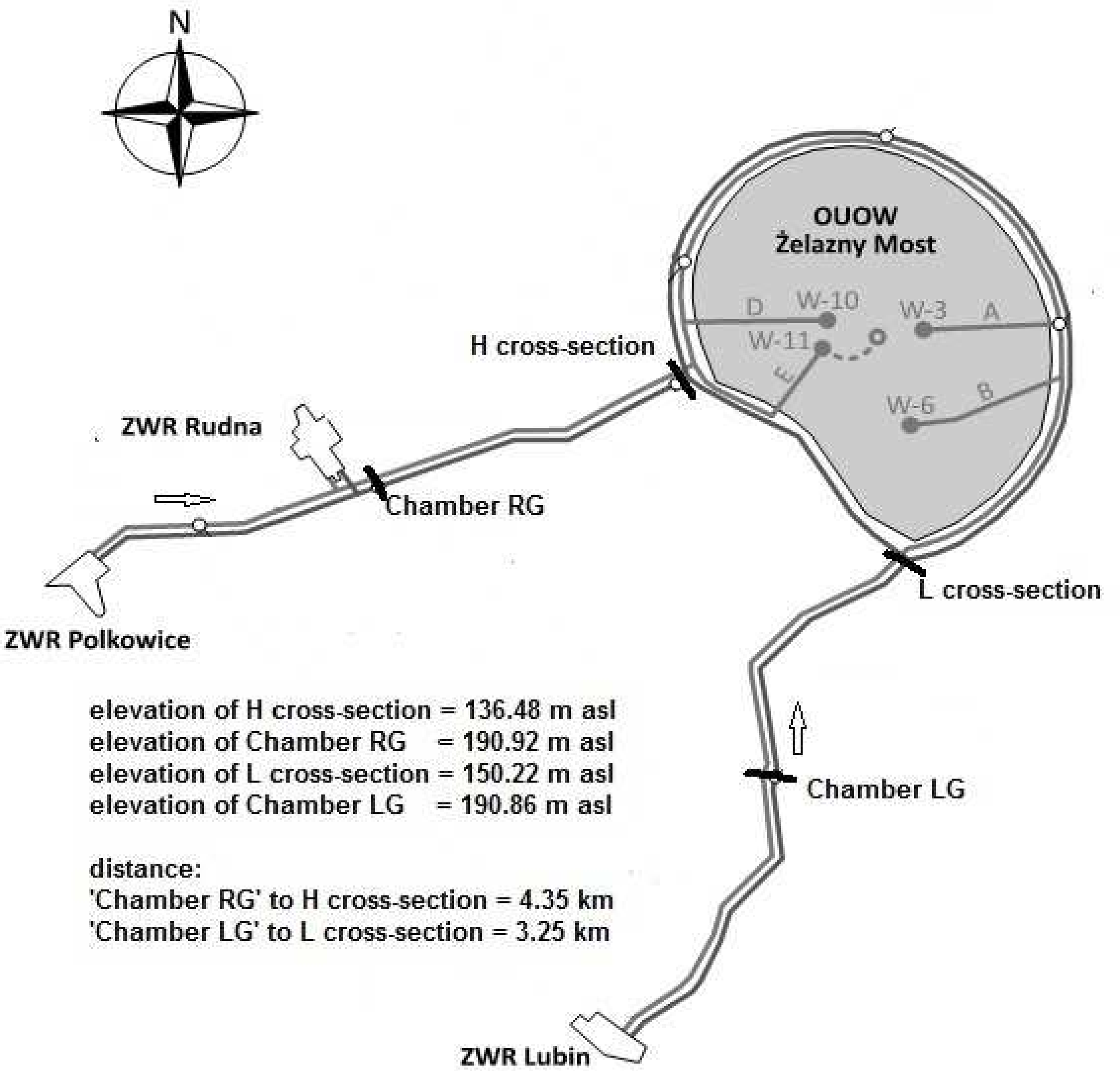

Fig. 1. Location of measurement cross-sections in the network

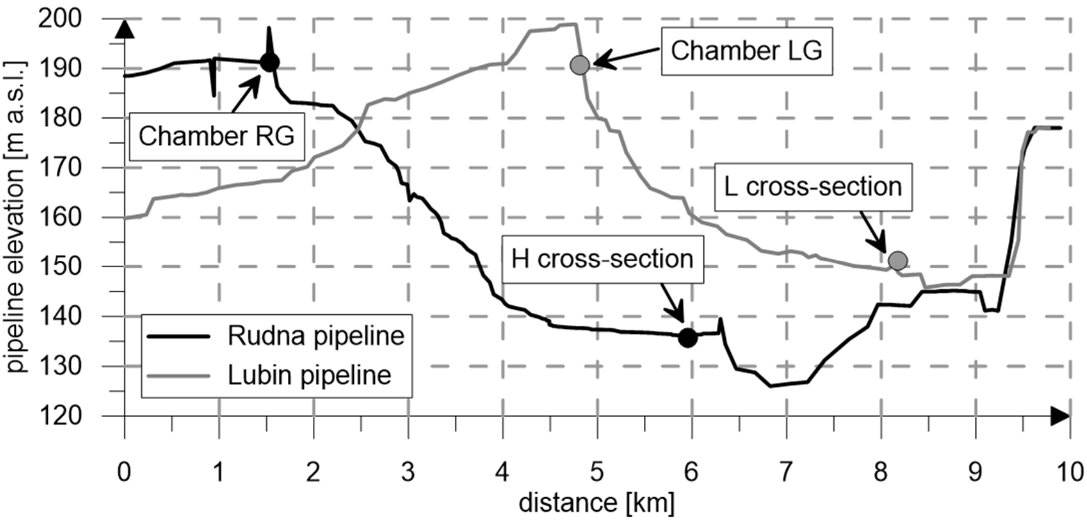

Fig. 2. A longitudinal profile of pipelines.

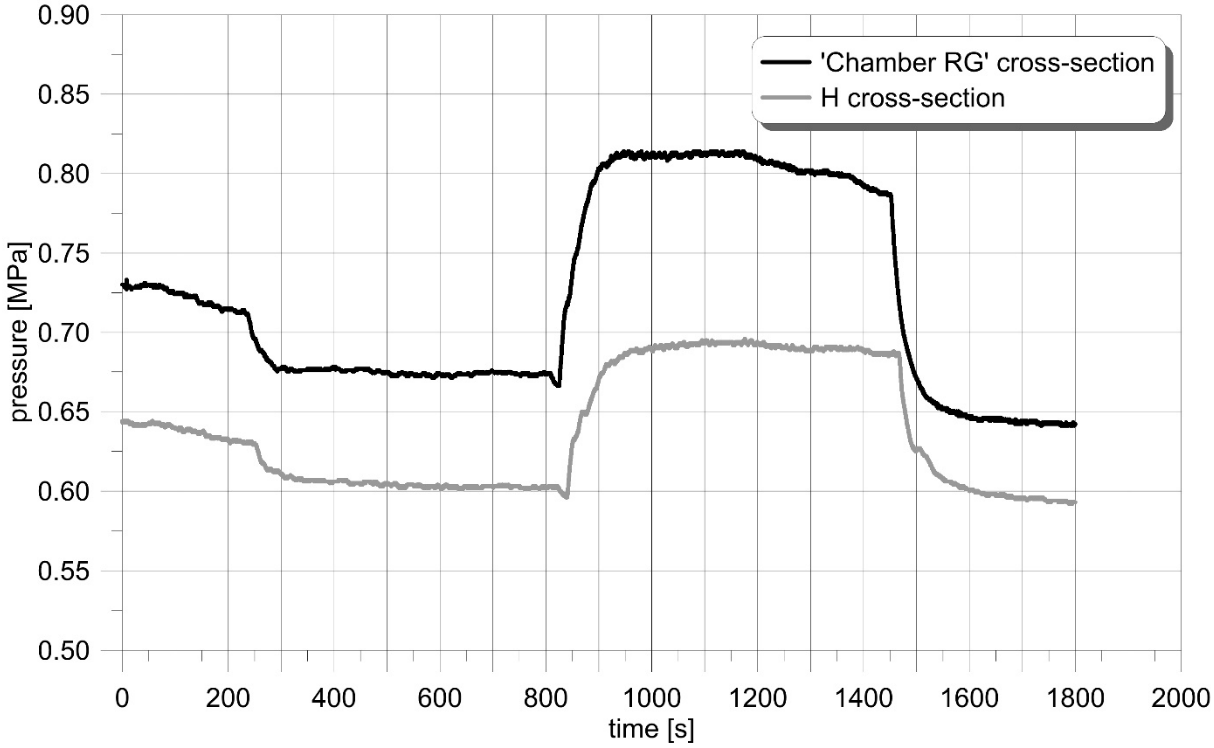

Fig. 3. Pressure characteristics measured during the flow of sludge on June 30, 2015 at 9.59 a.m., 'Chamber RG' cross-section (the elevation 190.92 m asl), H cross-section (the elevation 136.38 m asl)

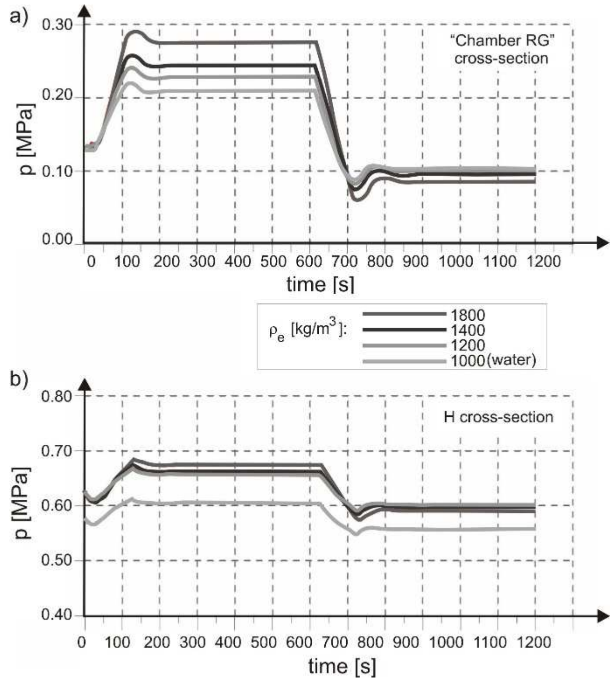

Fig. 4. Pressure characteristics for sudden shutdown of pumps for different values of equivalent density: a) "Chamber G" cross-section; b) H cross-section.

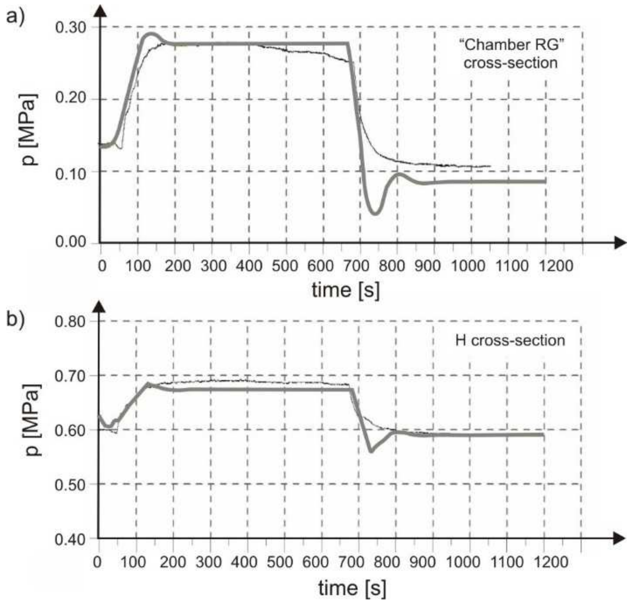

Fig. 5. Comparison of the results of in-situ measurements (black line) with the results of calculations (gray line): a) "Chamber RG" cross-section; b) H cross-section.

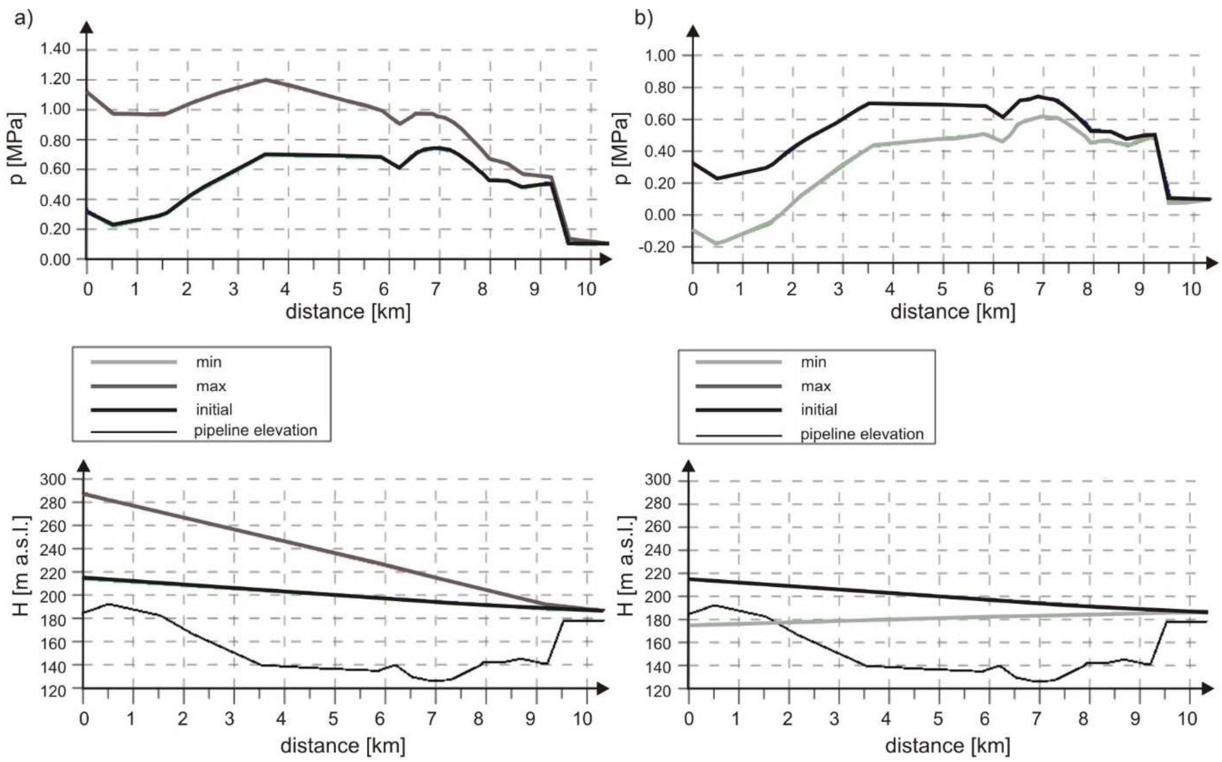

Fig 6. Extreme pressure distribution along Rudna pipeline: a) switching on/off the additional pump, T=100 s; b) rapid failure of all pumps, T=200 s.

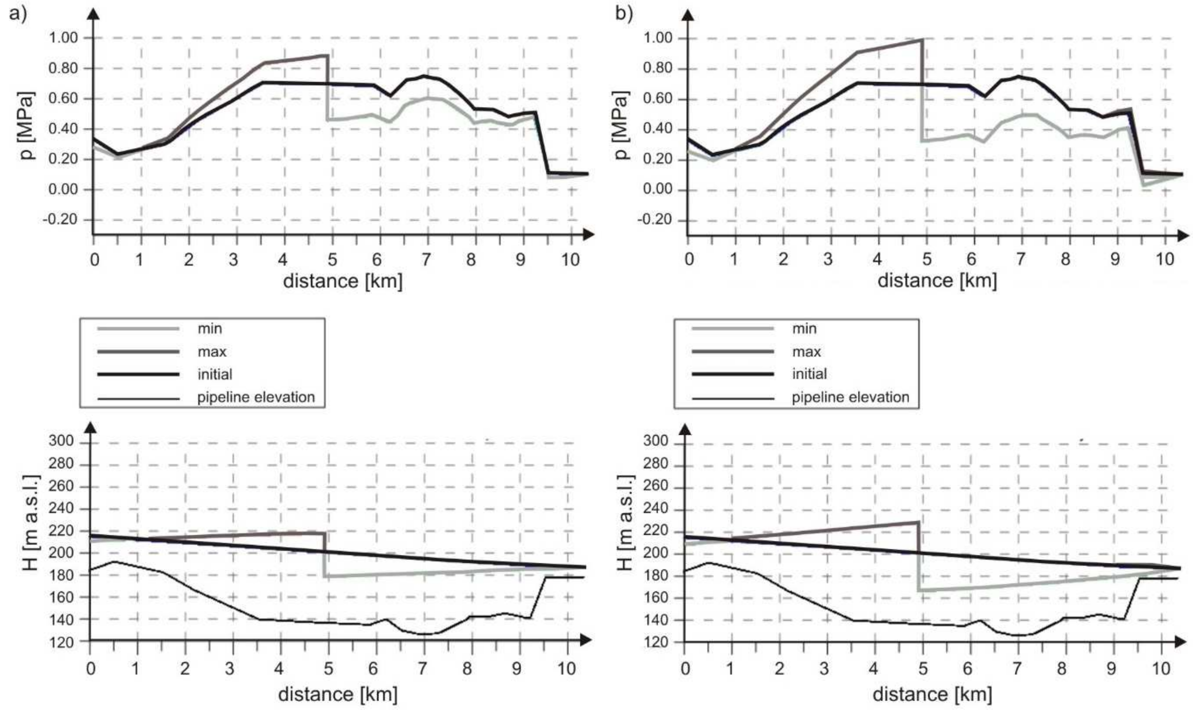

Fig. 7. Extreme pressure distribution during valve failure: a) T=100 s; b) T=30 s.

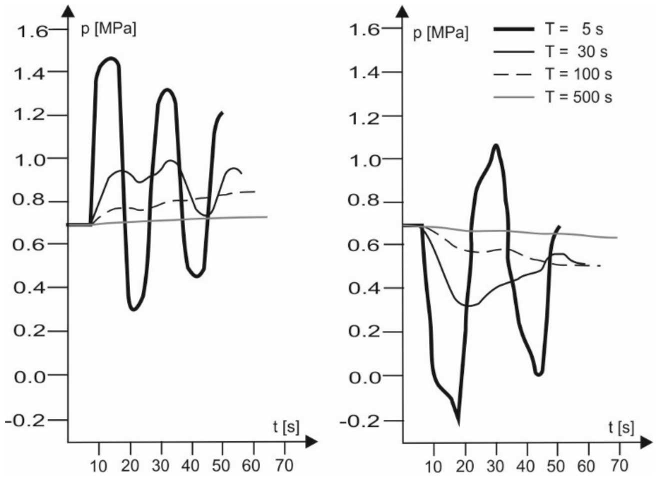

Fig. 8. Pressure variations due to valve failure: a) up-the-valve section, b) down-the-valve section of a pipeline.