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The Process of Developing Model Research for the Technology of Obtaining Energy Resources

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Abstract: The current problems associated with the maintenance of hard coal longwall mining depend on the application or use of extraction technologies. In order to make the best use of these technologies, a new approach based on simulation studies is necessary. This paper aims to develop a mathematical model for the powered roof support's operation. The three groups of professionals involved in the testing of the roof support were involved in the work on changing the hydraulic system of the powered roof support stand. These professionals were powered roof support's designers, researchers and users. The research subject was the development of a mathematical model as a starting point for conducting simulations. The model is based on d'Alembert's principle and the equation of the balance of flow rates. Based on the developed model, it is possible to determine the pressure in the space under the piston of the hydraulic prop. The results obtained in the simulations are the basic assumptions for the development of a prototype that would solve the current problems in the hydraulic systems of powered roof supports. The adopted research methodology assumed the development of a mathematical model, simulation in the MATLAB environment and verification of the model on a test stand. The obtained results of simulation tests based on the developed mathematical model were confirmed in bench tests. Simulation and bench tests determined the correctness of the assumptions made for the development of the prototype model. Based on the analysis of the results, the nature of the work of the future prototype has been predetermined. The next stage will be the testing of the prototype, which is to be included in the hydraulic system of the prop of powered roof support in the future. The model mentioned before is the baseline model, and it will be modified depending on the application of the future design in real conditions. Simulation studies of powered roof support will allow the structure that is used currently to be optimised, so as to adapt it to increasingly difficult working conditions.

Keywords: powered roof support; hydraulic prop; mathematical model of the prop; numerical simulation; longwall mining

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1. Introduction

One factor determining a company's future success is its continuous development and following and leading with environmental changes. This also applies to the mining industry. The current trends of development in mining companies mostly consider improved safety [1], increasing mining productivity, optimisation of the used machine fleet [2] and reduction in the energy consumption of machines [3]. The mining industry also seeks to automate the extraction process [4–7]. In order to achieve these goals, innovative solutions are still being sought. New technologies, intelligent systems and algorithms based on data analysis are being introduced into mining [8]. More and more emphasis is put on the quality, endurance and diagnostics of machines [9]. From an economic point of view, it is also essential to make optimal use of the machine fleet.

The need for continuous development is also dictated by a stricter environment and safety constraints and increasingly difficult mining and geological conditions. This is especially true in underground coal mining. Exploiting increasingly low-lying decks generates new problems in mining [10,11]. It is necessary to constantly adapt to changing mining and geological conditions [12–14]. This requires the introduction of new solutions in the process of exploitation [15–17] and improvements in maintaining the stability of the workings [18,19]. There is also a need to combat natural hazards more effectively [20].

Mathematical analysis and numerical simulations are more often used for this kind of development [21,22]. They complement laboratory tests and in-situ tests [23]. Numerical simulations have the advantage that they do not require the construction of specialised research stations or access to real conditions. Current computer programs make it possible to simulate almost all phenomena and systems. Simulation of flows [24], stability analysis of workings [25], modelling in the field of natural hazards [26] and strength analysis of machines and their components [27] are used in the mining industry, among many others. Numerical studies and simulations also include powered roof support [28–35], which the authors of this work have focused on.

Powered roof support is the essential longwall excavation protection system under which the operation process is carried out. The powered roof support protects the wall excavation, the workers and other machines from loose roof rocks. It is the excavation's primary protection against the rock mass's adverse effects. It also supports other wall complex machines (i.e., mining harvester, coal planer and scraper conveyor). The tasks of the powered roof support also include moving the entire wall complex along the progress of the wall.

A set of powered roof support for a typical longwall consists of about 100–150 individual units—depending on the length of the wall. Each section of the powered roof support is connected to the wall conveyor by means of a sliding system. The sections of the powered roof support consist of the essential parts: the structure, the power hydraulics and the control system. During the excavation process, the sections perform repetitive work cycles. These work cycles include drawing off, moving in the excavation and expanding between the roof and the footwall. In a harvester wall system, the sections perform this work cycle after each time the harvester passes. Drawing off is the sliding of hydraulic props, thus the powered roof support's cap piece is lowered from the excavation's roof. After this operation, shifting the powered roof support section towards the advancing coal face is possible by means of a displacement cylinder. After displacement, the section is expanded in the excavation. Then, the pistons of the hydraulic props are extended so that the cap piece rests directly against the roof of the excavation. After expansion, the section secures the roof of the excavation [34–36].

To effectively secure the excavation, it is necessary to expand the longwall shield sections correctly. The required pressure value in the subpiston space of the prop must be obtained to correctly expand the powered roof support. The expansion determines the load-carrying capacity, which is the force of the powered roof support acting on the excavation's roof. There are three types of load-carrying capacity for powered roof support: initial, working and nominal. Immediately after the expansion, the powered roof support section acquires initial load capacity. After taking over the pressure of the roof rocks, the powered roof support operates at working load capacity. Nominal load capacity, on the other hand, is the maximum value of load-carrying capacity that the powered roof support can obtain. The nominal load capacity value depends on the setting of the safety valves.

This research aimed to develop a mathematical model for simulating powered roof support's expansion. The authors focused on the expansion because this is the most crucial phase of work. Correct expansion of the section significantly impacts the load-carrying capacity. The model concerns only the hydraulic prop because it is central to expanding the powered roof support section. The mathematical model presented in the article is the baseline model. It will be modified for the needs of future constructions. Computer simulations should be the first step in producing powered roof support. The simulations allow the powered roof support section to be optimised to achieve the best operating parameters.

The first chapter of this article contains an overview of the current development directions in world of mining and discusses the powered roof support. It describes its general construction, application and operation scheme. The second chapter provides the theoretical basis for modelling dynamic systems, on which the mathematical model was developed. This model, together with the derivation of formulas, is presented in chapter three. Based on the developed mathematical model, several simulations were carried out for the expansion of the powered roof support. The results of these simulations are presented and discussed in chapter four. Chapter five summarises the work carried out and the conclusions.

2. Materials and Methods

Mathematical modelling is one of the research tools used more and more often in engineering and mining. It allows us to describe reality in the language of mathematics. Resulting from the modelling, it is possible to analyse the processes and behaviours of various systems. Mathematical models can conduct simulations instead of research in real conditions. It makes it possible to simulate phenomena that may be too difficult, expensive, time-consuming or impossible to perform in empirical research. Mathematical modelling and simulation of processes allow for their better understanding and introduction of valuable conclusions [37].

2.1. Modelling Dynamical Systems

Systems can be characterised based on the relationship between input and output parameters. In static systems, the output parameters depend only on the input parameters. A mechanical example of such a system is a massless spring. The length of the spring depends only on the force acting on it (input parameter). The system becomes dynamic when the mass is attached to the spring (Figure 1). Then, the mass's position (and the spring's length) no longer directly depends on the input force. They are also associated with the acceleration of mass, which depends on all the forces acting on it. The property where mass acceleration depends on its position relates to a dynamic system [37]

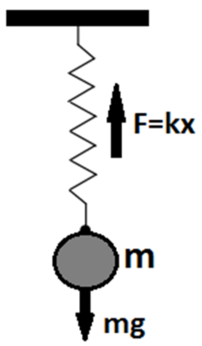

Figure 1. Dynamical system—mass spring system, where: f—force, k—constant related to the stiffness of the spring, x—the position of the mass, m—mass, g—gravitational constant.

Most natural systems are dynamic systems. Differential equations can characterise dynamic systems. For example, the equation shown in Figure 1 will take the following form [37]:

$$m\ddot{x} = -kx + mg, \tag{1}$$

where:

x—the position of the mass m (the length of the spring);
$\ddot{x}$—the acceleration of the mass;
k—constant related to the stiffness of the spring;
g—gravitational constant.

Dynamic systems can be characterised by the relationship between state variables and their derivatives (temporary). For example, the state variable for our system shown in Figure 1 is x. According to Hooke's law of elasticity, the elongation of a spring is directly and linearly proportional to the applied load [34].

$$F = -kx \tag{2}$$

According to Newton's law of dynamics, the resultant force on a body is equal to the product of its mass and acceleration [37].

$$F = m\ddot{x} \tag{3}$$

Two forces act on the system: the force of the spring and the force of gravity. Thus, the equation characterising the resultant forces acting on the mass has the form.

$$m\ddot{x} = -kx + mg \tag{4}$$

This equation is a second-order differential equation because the highest derivative is the second derivative. The equation defines the relationship between state variables and their derivatives. An equation of this type can be solved using numerical solvers in MATLAB [37]. The solution is to integrate the differential equation in time, which makes it possible to simulate the system's operation.

2.2. Procedure for Modelling the Work of a Hydraulic Prop of Powered Roof Support

Mathematical modelling is a tool used to solve problems in various fields of science. It is often assumed that the model represents the object under study. The representation is deliberately simplified and lacks many details, irrelevant from the point of view of modelling purposes. The entry point to the model is the actual object to be examined. For the selected real object, you need to formulate a problem that needs to be solved. The modelling process is started after defining the problem and goal.

In this paper, an interdisciplinary team of authors researched powered roof support. In the work of powered roof support, a significant problem is the correct expansion of the sections and ensuring the required pressure value in the under-piston space of the prop. Therefore, the goal was to develop a model for simulating the expansion operation of powered roof support to optimise the process. The authors adopted a procedure to develop a mathematical model of the hydraulic prop's operation. The modelling process is divided into the steps shown in Figure 2.

The beginning of the modelling process required the adoption of technical parameters for the hydraulic prop of the powered roof support. After defining these parameters, adopting certain objectives and simplifications was necessary. The objectives and boundary conditions are shown in Figure 3. The input phase is the prop (Figure 3a). This means that the height of the powered roof support is reduced by inserting the piston of the hydraulic prop. This way, the headpiece loses contact with the excavation roof, and the pressure in the subpiston space of the prop is close to zero. The liquid supply to the prop is closed. The prop expansion phase begins in Figure 3b. It consists of sliding out the piston of the hydraulic prop until the headpiece comes into contact with the roof of the excavation. Next, the prop's liquid supply is opened, and the pressure in the subpiston space increases. As a result of the pressure increase, the piston begins to move, and the prop is expanded (Figure 3c). The prop's liquid supply is closed when the piston outlet limit ($x = x_{gr}$) is reached (Figure 3d). This limit is the moment of contact of the headpiece of the powered roof support with the excavation's roof. The pressure of the liquid enclosed under the piston determines the value of the initial load-carrying capacity of the powered roof support.

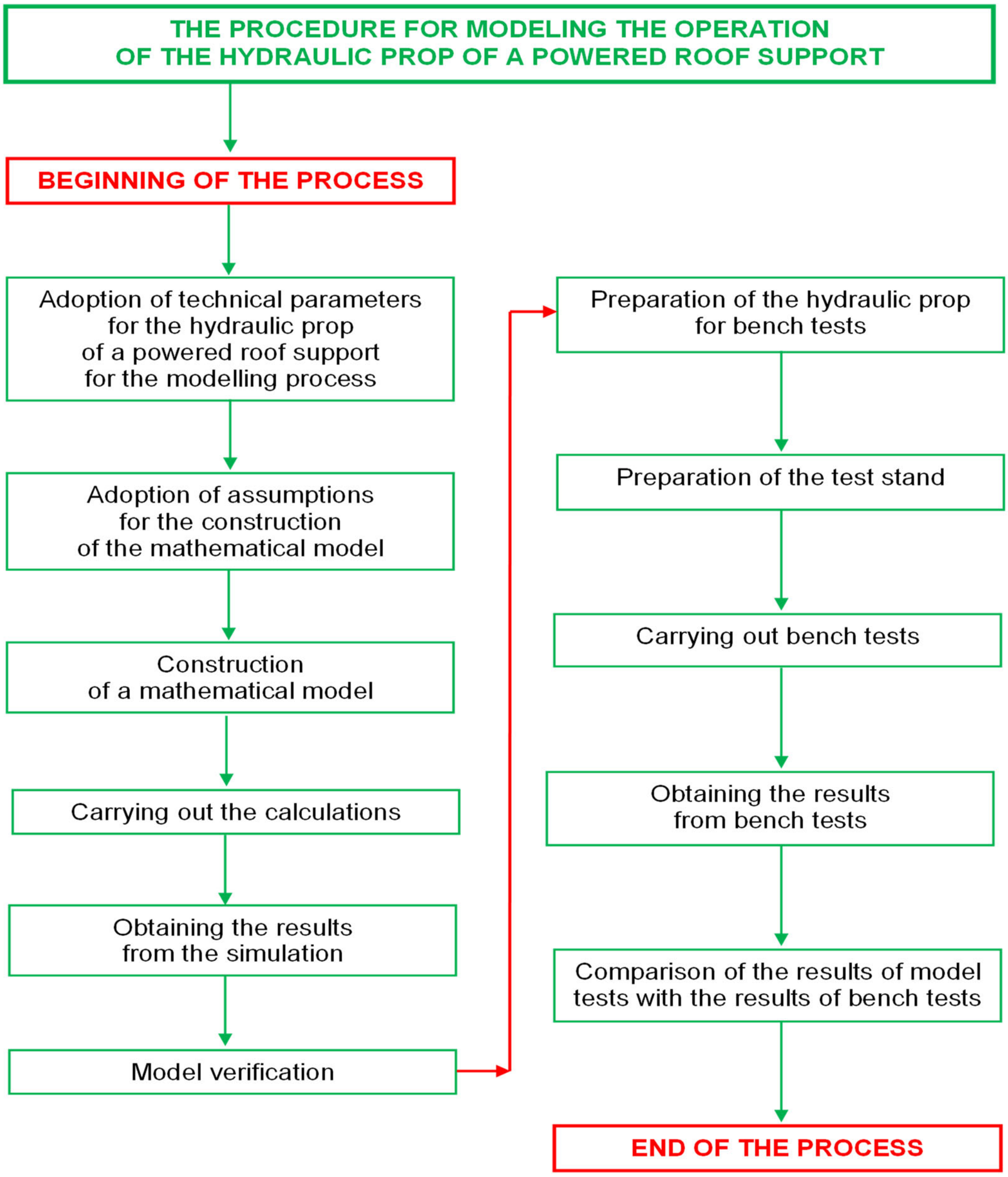

Figure 2. Diagram showing the development of a mathematical model.

The construction of the mathematical model also required the adoption of certain simplifications. The mathematical model is based on the following objectives [38]:

- the module of elasticity, density and viscosity of the liquid does not change during the system's operation;
- the effect of gravity on the operation of the system is omitted;
- deformations of hydraulic components are omitted;
- it is assumed that there is no cavitation in the system;
- it is assumed that there is no dry friction between the moving elements;

- the propagation effect of the finite velocity propagation of disturbances in the system is omitted.

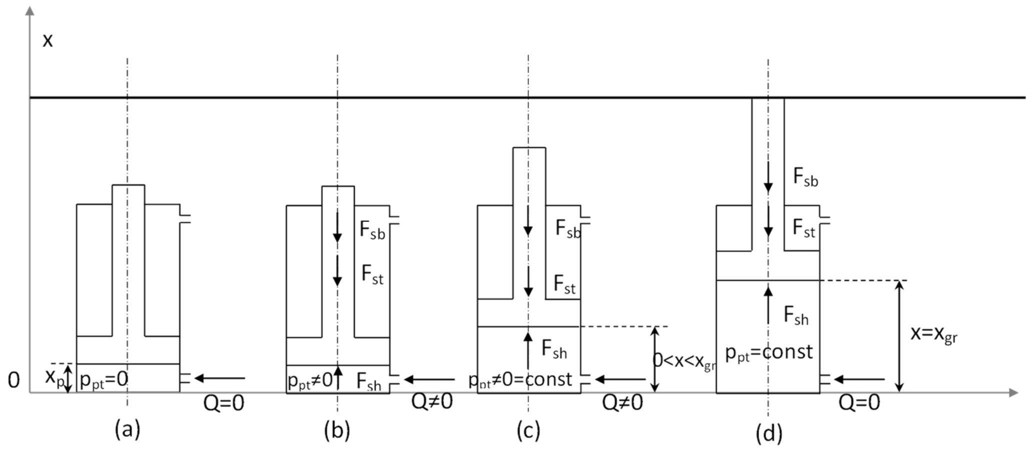

Figure 3. The scheme of the prop's expansion operation of the powered roof support, where (**a**) the input state, (**b**) the start of the expansion operation—opening the liquid supply to the hydraulic prop, (**c**) the movement of the piston of the hydraulic prop, (**d**) the end of the expansion operation—reaching the boundary point, where: x_p—the beginning position of the piston, x—the displacement of the piston, x_{gr}—the limit position, p_{pt}—the pressure in the subpiston space of the prop, Q—the flow rate of the liquid that flows into the cylinder, F_{sb}—the force of inertia, F_{st}—the friction force and F_{sh}—the force acting on the piston.

After defining the prop and the objectives, one can construct the model. The construction of a mathematical model consists of determining the dependencies occurring in the studied object. These dependencies are written in the form of mathematical equations. In addition to the equations, the boundary conditions must also be defined. Thus, a system of equations is formed, which is the basis of the mathematical model. Simulation studies are conducted on the model. The research is carried out using software. The model still needs verification, that is, evaluation of its correctness. The results obtained from the simulation shall be verified. Empirical knowledge based on experience and observations of reality can be used to verify the model. For this purpose, it is best to conduct bench testing. This requires the preparation of a hydraulic prop with specified technical parameters and the construction of a research station. The bench testing and the results obtained will allow us to verify the mathematical model. The results of the model studies shall be compared with the bench testing results. The convergence of the results will allow the modelling process to be completed. The verified model, which is the baseline model, can already be used to conduct simulation studies.

3. Results

The mathematical model of the powered roof support's hydraulic prop was based on two equations—the forces and the flows equations [38,39]. In order to record the work of the prop mathematically, the forces acting on it are taken into account. These forces are then noted as a mathematical equation using d'Alembert's principle. After introducing the inertia force (d'Alembert) into the system, the question of dynamics is treated as the question of statics. According to d'Alembert's principle, the sum of the forces acting on a point mass must be zero. A balance of fluid flow rates supplements this equation. The balance of flow rates is important because it allows for determining the characteristics of pressure changes in the subpiston space of the prop. This parameter is essential from the point of view of the operation of the powered roof support. It determines the value of the load-carrying capacity of the powered roof support. Thus, a system of equations is formed, which is the basis of the mathematical model. Computer simulations were performed for the resulting system of equations and boundary conditions.

3.1. Mathematical Model of the Hydraulic Prop

The relationship between the forces acting on the prop of powered roof support was determined by the d'Alembert principle. It takes the following form:

$$-F_{sb} - F_{st} + F_{sh} = 0, \tag{5}$$

where:

F_{sb}—the force of inertia;
F_{st}—the friction force;
F_{sh}—the force acting on the piston.

The following relationships can determine these forces:

$$F_{sb} = m_{tl} \cdot \frac{d^2x}{dt^2}, \tag{6}$$

$$F_{st} = f_s \cdot \frac{dx}{dt}, \tag{7}$$

$$F_{sh} = p_{pt}(t) \cdot A, \tag{8}$$

where:

m_{tl}—the mass of the piston;
x—the displacement of the piston;
f_s—the coefficient of friction;
$p_{pt}(t)$—the pressure in the subpiston space of the prop in time;
A—the surface area of the piston.

Considering the dependencies (6)–(8), Equation (5) can be written in the form:

$$-m_{tl} \cdot \frac{d^2x}{dt^2} - f_s \cdot \frac{dx}{dt} + p_{pt}(t) \cdot A = 0, \tag{9}$$

3.2. Equation of Flow Rates

The equation of the liquid flow rate to the prop during the expansion operation of the powered roof support takes the form of:

$$Q = Q_s + Q_c, \tag{10}$$

where:

Q—the flow rate of the liquid that flows into the cylinder;
Q_s—the flow rate associated with the movements of the piston;
Q_c—the flow rate associated with the compressibility of the liquid.

The following dependencies determine the flow rates Q_s and Q_c:

$$Q_s = A \cdot \frac{dx}{dt}, \tag{11}$$

$$Q_c = \frac{A \cdot (x_p + x(t))}{B} \cdot \frac{dp_{pt}}{dt}, \tag{12}$$

where:

A—the surface area of the piston;
x(t)—the displacement of the piston in time;
x_p—the beginning position of the piston;
B—the bulk modulus of hydraulic fluid;
p_{pt}—the pressure in the subpiston space of the prop.

Considering the dependencies (11) and (12), the Formula (10) takes the following form:

$$Q = A \cdot \frac{dx}{dt} + \frac{A \cdot \left(x_p + x(t)\right)}{B} \cdot \frac{dp_{pt}}{dt}, \tag{13}$$

Thus, considering the dependencies (9) and (13), the mathematical model adopted for conducting the simulation takes the following form:

$$\begin{cases} -m_{tl} \cdot \frac{d^2x}{dt} - f_s \cdot \frac{dx}{dt} + p_{pt}(t) \cdot A = 0 \\ \frac{dp_{pt}}{dt} = \frac{B \cdot \left(Q - A \cdot \frac{dx}{dt}\right)}{A \cdot \left(x_p + x(t)\right)} \end{cases}. \tag{14}$$

3.3. Numerical Solution and Implementation

To solve the proposed problem numerically, we adopt the Euler method [40]. At first, the system of second-order ODE (14) is transformed to the system of first-order ODE by introducing the substitution $y(t) = \frac{dx(t)}{dt}$. The new equivalent system is given by:

$$\begin{cases} \frac{dx}{dt} = y(t), \\ \frac{dy}{dt} = \frac{p_{pt}(t) \cdot A - f_s \cdot y(t) - m_{tl} \cdot g}{m_{tl}}, \\ \frac{dp_{pt}}{dt} = \frac{B \cdot (Q - A \cdot y(t))}{A \cdot \left(x_p + x(t)\right)}. \end{cases} \tag{15}$$

We discretize the time domain of interest into an equidistant grid with constant difference h. According to this discretisation, the derivatives in (15) are approximated by finite difference:

$$\frac{dx}{dt} \approx \frac{x_{t+1} - x_t}{h}, \ \frac{dy}{dt} \approx \frac{y_{t+1} - y_t}{h}, \ \frac{dp}{dt} \approx \frac{p_{t+1} - p_t}{h}, \tag{16}$$

where x_t, y_t, p_t approximate the values of unknown function in time step $t = 1, \ldots, T$. Additionally, if we denote the vector function of right-hand sides of (15) by $F(x_t, y_t, p_t)$, then the Euler method performs an iterative procedure defined as

$$\left[x_{t+1}, y_{t+1}, p_{t+1}\right] = [x_t, y_t, p_t] + h \cdot F(x_t, y_t, p_t). \tag{17}$$

During the iterations, we check constraints and in the case of violation, the values are corrected to satisfy boundary conditions, i.e., non-negative piston displacement and maximum piston displacement. Let [xˆ_(t + 1), yˆ_(t + 1), pˆ_(t + 1)] be values computed by Equation (15). Then:

- if xˆ_(t + 1) ≤ 0, then we set x_(t + 1) = 0 and y_(t + 1) = {0, yˆ_(t + 1)};
- if xˆ_(t + 1) ≥ x_gr, then we set x_(t + 1) = x_gr and y_(t + 1) = {0, yˆ_(t + 1)}.

Additionally, we keep the pressure non-negative and correct the inflow into the piston in the case of achieving the maximum possible pressure.

We implemented the approach in the MATLAB environment and simulated the piston movement for several values of input parameters.

3.4. Results from Numerical Simulations

The mathematical model was developed following the accepted procedure. The object of the calculations was to determine the time of pressure flow in the subpiston space of the hydraulic prop during the expansion of the powered roof support. In addition, the developed model determines the displacement of the piston of the hydraulic prop and its speed. The desired characteristics were obtained by solving Equation (14) with the help of MATLAB R2020b software. The basic parameters of the hydraulic prop and fluid that were considered in the calculations are summarised in Table 1.

Table 1. Parameters of the hydraulic prop and fluid in the hydraulic system.

Parameter	Parameter Designation	Parameter Value
mass of the piston	$m_{tł}$	637 kg
coefficient of friction	f_s	0.026 Ns/m
surface area of the piston	A	0.07 m^2
bulk modulus of hydraulic fluid	B	$2{\cdot}10^9$ Pa

For the adopted parameters, simulation studies started. The preliminary results are shown in Figure 4. After a visual assessment of the results, it can be concluded that the intensity of the fluid supply to the cylinder was incorrectly modelled, which increases linearly without restrictions—this increased pressure above the permissible value. The flow rate is regulated primarily by the parameters of the pump used. The maximum flow rate is determined for the given system, resulting from the elements used. Thus, the model required correction after the first visual assessment of the results.

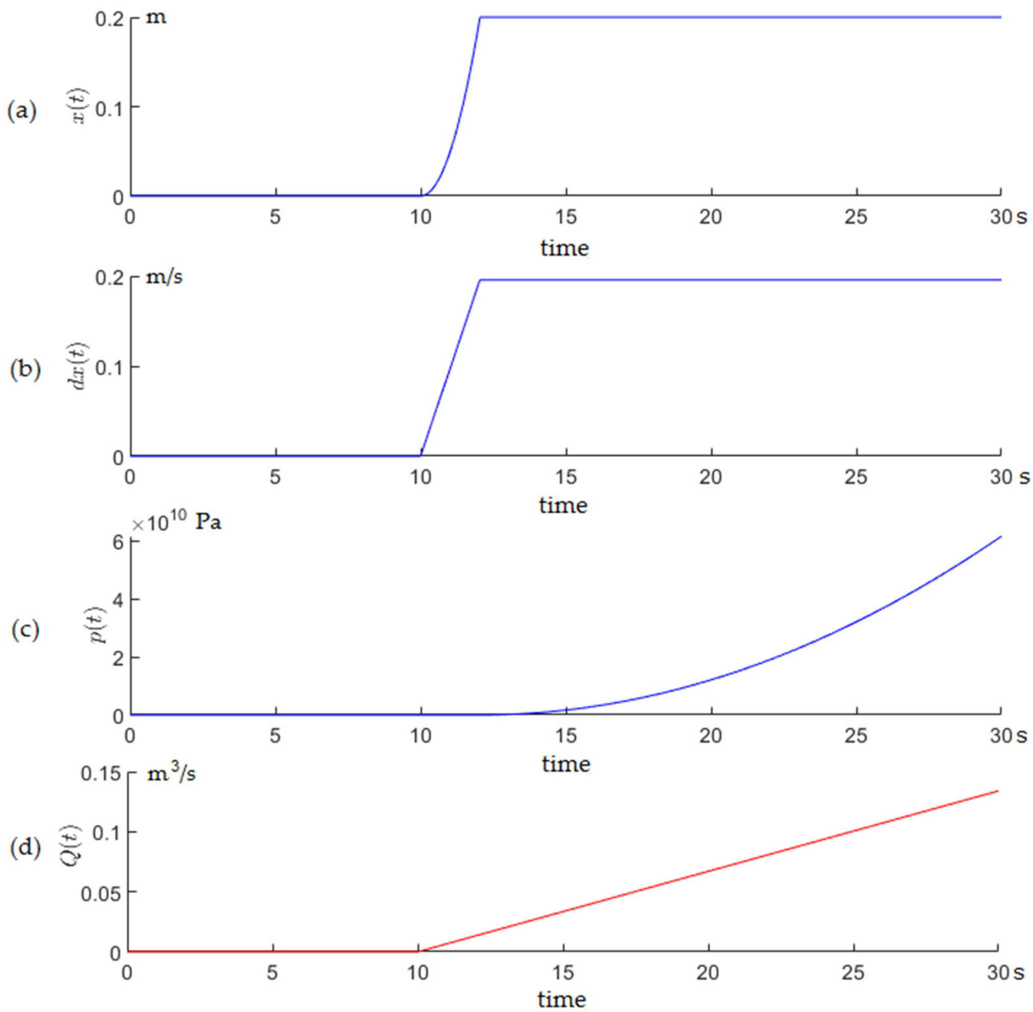

Figure 4. Results of the preliminary test computer simulation for the adopted model showing: (**a**) x(t)—the displacement of the piston of the prop over time, (**b**) dx(t)—the speed of the piston of the prop, (**c**) p(t)—the pressure flow in the subpiston space of the prop over time and (**d**) Q(t)—the flow rate of liquid into prop over time.

The above problem was solved by the Euler's method. The second-order ODE system was rewritten to the first-order ODE system. Then, the derivatives were approximated (in time) by differences. A limit value has been assumed for pressure with boundary conditions. In reality, special valves limit the pressure increase above the permissible value in the cylinder. After the changes were implemented, further simulations were performed, and their results are shown in Figure 5.

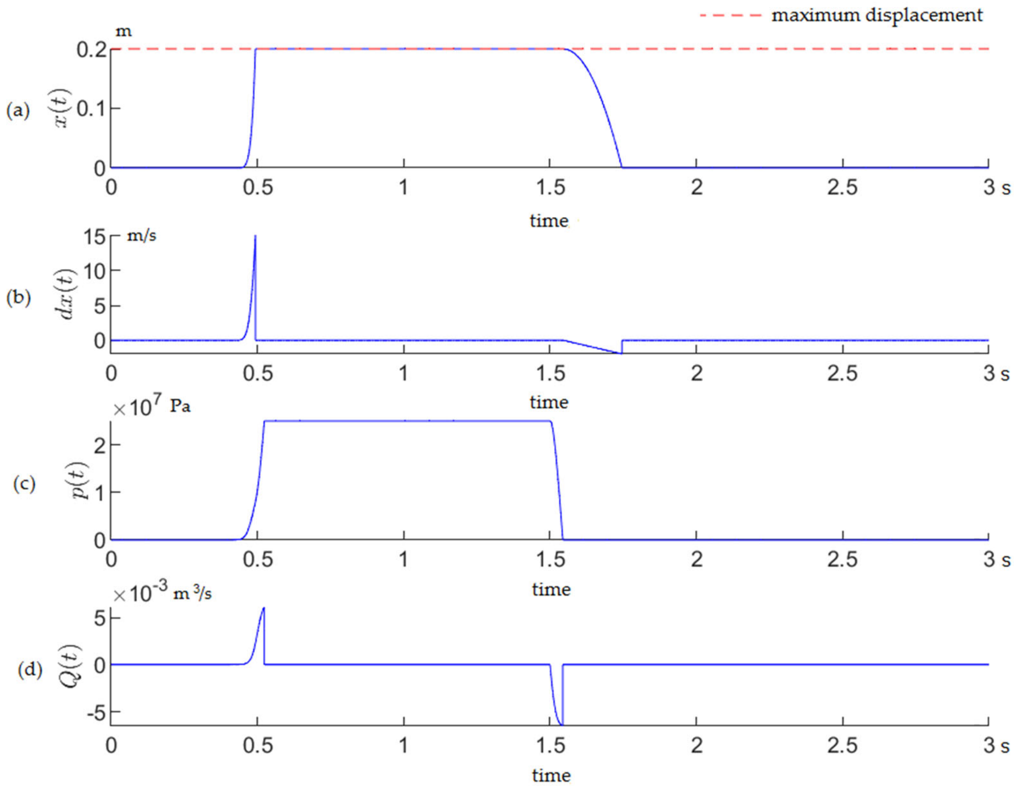

Figure 5. Results of the preliminary test computer simulation for the adopted model showing: (**a**) x(t)—the displacement of the piston of the prop over time, (**b**) dx(t)—the speed of the piston of the prop, (**c**) p(t)—the pressure flow in the subpiston space of the prop over time and (**d**) Q(t)—the flow rate of liquid into prop over time.

The changes made it possible to obtain a constant pressure value in the prop's subpiston space after its expansion. However, the modelled liquid flow rate features indicated a linear increase. In reality, when the distributor is adequately controlled, the liquid supply to the prop is opened. The flow of this fluid is constant. Thus, in the next step, the characteristics of the liquid flow rate to the cylinder were refined with its constant value. In addition, the value of the liquid flow rate has been reduced from its maximum value resulting from the system parameters to the optimal value. The results of the simulation are shown in Figure 6.

After obtaining the assumed characteristics of the liquid flow rate to the prop, the simulation was executed. Computer simulations were performed for five fluid flow rate values (Q). These parameters are summarised in Table 2, and the simulation results are shown in Figure 7.

The resulting pressure flow in the prop's subpiston space during its expansion can be divided into two characteristic phases. A very rapid increase in pressure distinguishes the first phase. The piston of the prop does not move, and as a result of the compressibility of the liquid, the pressure quickly increases. When a specific pressure limit is exceeded, the force acting on the piston sets it in motion. Thus, in the second phase, the pressure increase in the subpiston space of the prop is much milder and depends on the value of the liquid flow rate.

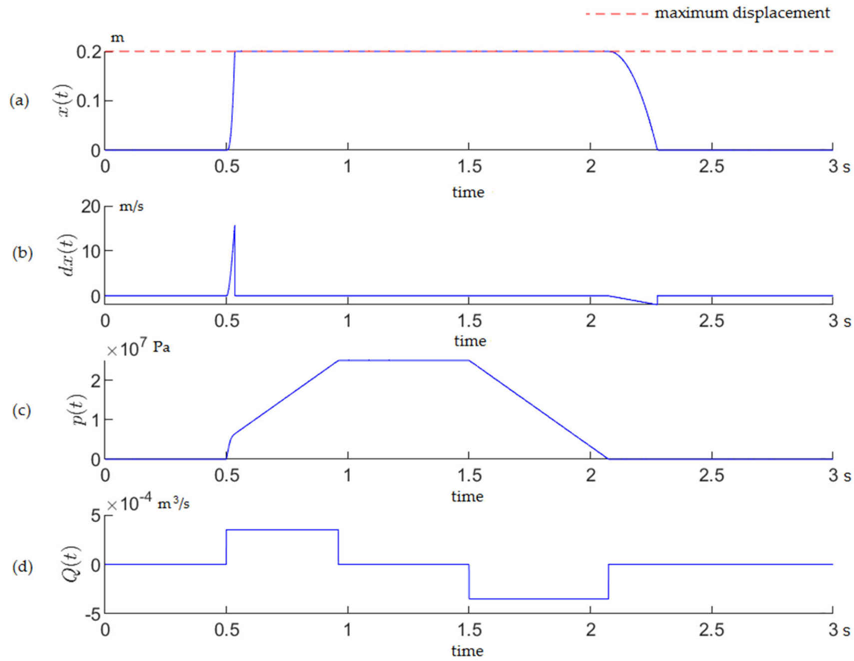

Figure 6. Results of the preliminary test computer simulation for the model with a constant characteristic of the liquid inflow: (**a**) x(t)—the displacement of the piston of the prop over time, (**b**) dx(t)—the speed of the piston of the prop, (**c**) p(t)—the pressure flow in the subpiston space of the prop over time and (**d**) Q(t)—the flow rate of liquid into the prop over time.

Table 2. Variable parameters for the computer simulations.

Parameter	Parameter Designation	Parameter Value
Fluid flow rate value	Q	0.00067 m^3/s 0.00058 m^3/s 0.00050 m^3/s 0.00042 m^3/s 0.00033 m^3/s

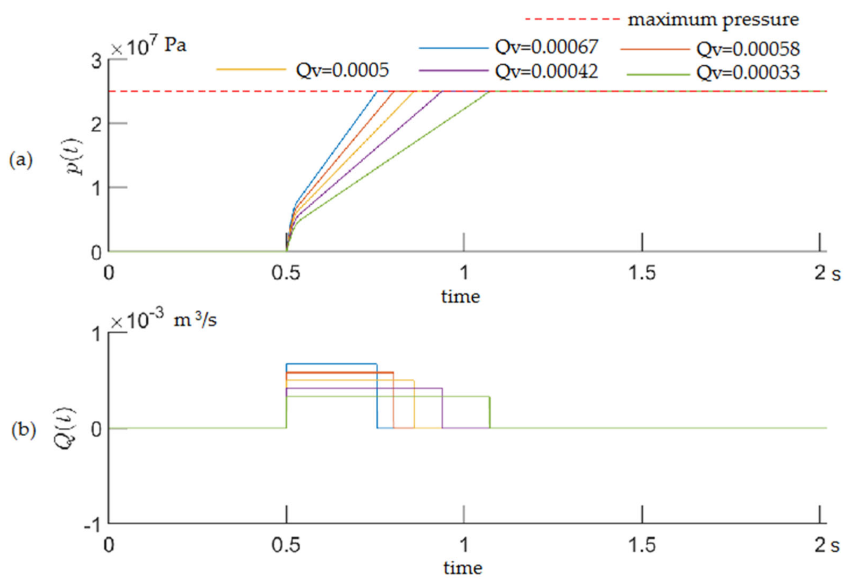

Figure 7. The results of the preliminary test computer simulation of the prop spreading for five different values of flow rate of liquid, where: (**a**) p(t)—the pressure flow in the subpiston space of the prop over time, (**b**) Q(t)—the flow rate of liquid to the prop over time and Q_v—the value of the maximum liquid inflow rate for a given test.

4. Discussion

The last step in mathematical modelling is its verification. For this purpose, bench tests were carried out, and their results were used to verify the correctness of the model. The bench tests required the preparation of a special test stand, which is shown in Figure 8. The prop was expanded in the frame of the test stand. The expansion was performed by supplying hydraulic fluid from the pump station. The research allowed us to obtain pressure changes in the subpiston space of the hydraulic prop during its expansion. DROPS-01 wireless pressure sensors from DOH were used to measure the pressure. The range of sensors was up to 60 MPa. The sensors measured the pressure at a frequency of 100 measurements per second. The results of the research allowed us to verify the mathematical model.

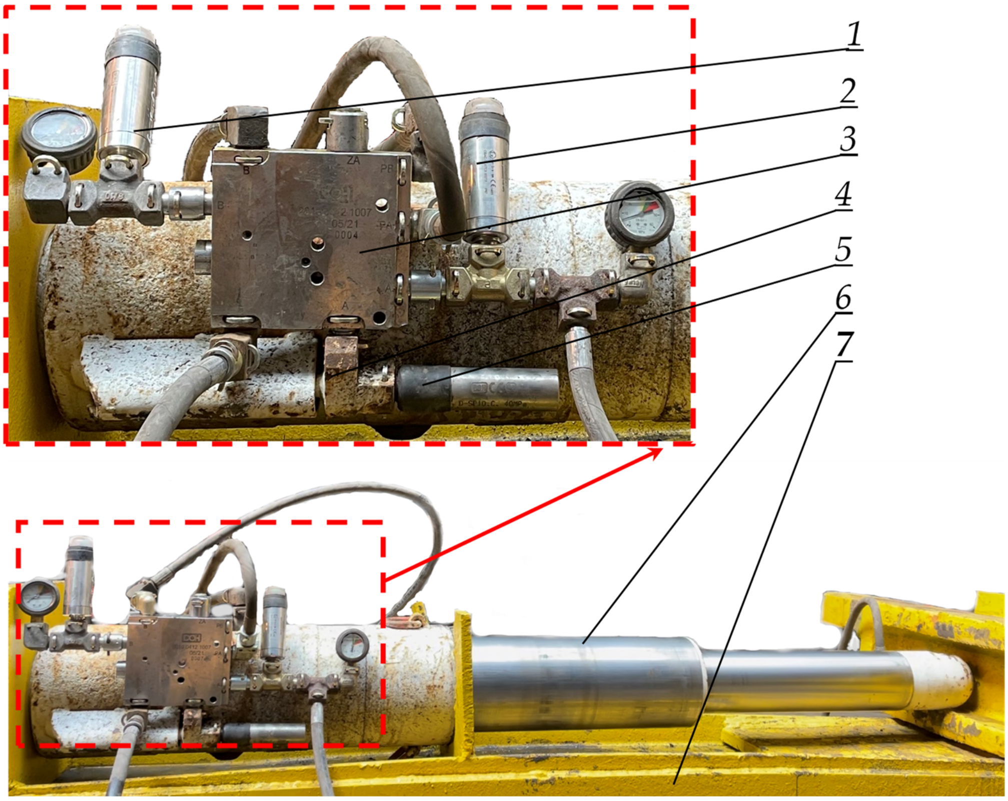

Figure 8. View of a specially prepared test stand for the verification of the mathematical model, where 1, 2—pressure sensor, 3—valve block, 4—connection from under-piston space, 5—safety valve, 6—hydraulic prop and 7—frame of the site.

Based on the bench tests performed, the pressure changes in the subpiston space of the prop during its expansion were defined. An example of the resulting waveform is shown in Figure 9. As in the model studies, the graph shows two characteristic phases of pressure increase. A very rapid rise in pressure characterises the first phase. However, after exceeding 5 MPa, the pressure increase is much milder.

The results of the bench testing were compared with the results of the model studies (Figure 10). As shown in the graph, there is a significant convergence of results. There are very similar characteristics of pressure changes in the under-piston space of the prop. The maximum pressure obtained in the bench tests is about 23 MPa, which is slightly lower than the value obtained in the model tests. This is probably due to the pump operation during bench testing. The convergence of the results obtained will allow the completion of the modelling process. The model prepared in this way can be thus used for simulation studies.

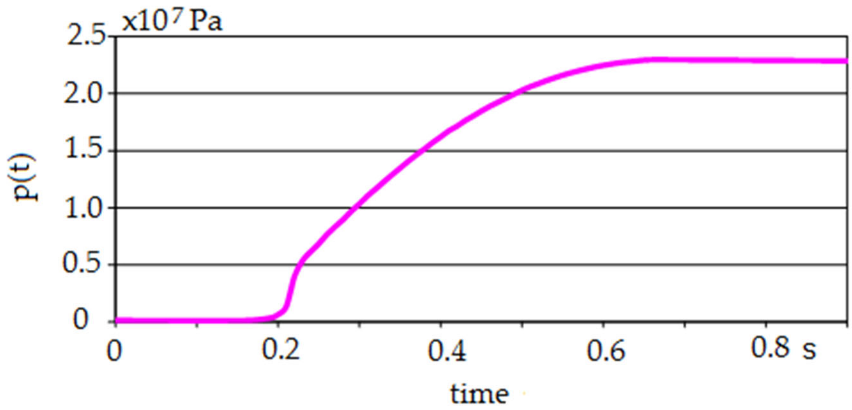

Figure 9. Results of bench tests—pressure in the subpiston space of the prop.

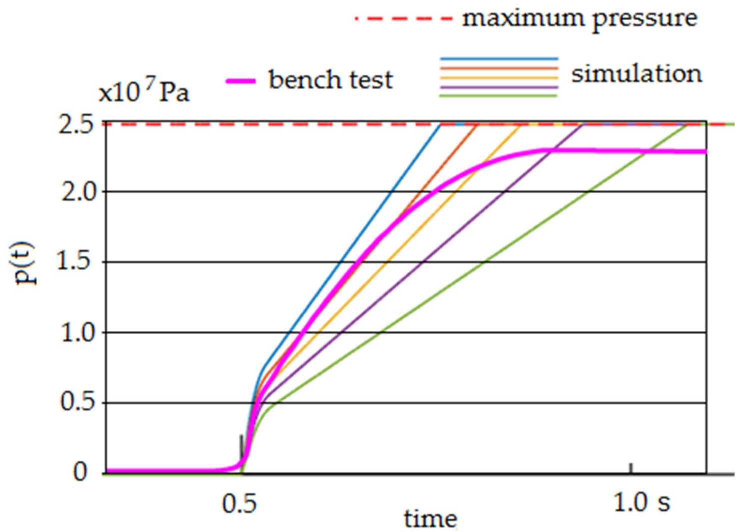

Figure 10. Verification of the mathematical model—comparison of the results of simulation and bench tests of pressure changes in the subpiston space of the prop during the expansion.

5. Conclusions

To conduct simulation studies of the work of powered roof support, the authors developed a mathematical model of a hydraulic prop. The development of the model required a multicriteria approach. The powered roof support was analysed in terms of construction, use and research. The interdisciplinary approach determined the need for cooperation between three groups of researchers. The first step in preparing the mathematical model was adopting the procedure (Figure 2).

The necessary objectives, simplifications and interdependencies have been identified following the adopted procedure. As a result, a preliminary model was created. The model has been modified several times to obtain the required characteristics of the liquid flow rate into the prop—in line with reality. Finally, the adopted model still needed verification. For this purpose, the authors conducted bench testing. The results of bench and model tests showed a significant convergence. Verifying the model confirmed that it is correct, and at the same time, completed the modelling procedure. This model is the beginning working model. It can be used to conduct simulation studies. The model can be used by constructors, producers and users of powered roof supports. It can be used to develop and verify future prototypes. It can also be used for research on the currently used powered roof support—for a better understanding of the phenomena occurring during its operation. This will make it possible to optimize the powered roof support, especially in terms of ensuring pressure in the subpiston space of the prop and maintaining the load-carrying capacity. This is extremely important from the point of view of improving safety in the longwall. In the future, this model can also be used to develop an automatic system for spreading the powered roof support section.

The developed model allowed conclusions of a cognitive nature to be drawn:

(1) Based on the design objectives adopted for the simulation, the work profile can be determined at the stage of creating a new prototype of the powered roof support.
(2) The simulations defined the change in the piston's position, the piston's speed and the pressure change in the prop's subpiston space.
(3) The mathematical model and the simulation quickly assessed whether the accepted objectives for the powered roof support were confirmed.
(4) The mathematical model developed is interdisciplinary; the three groups working on a new powered roof support design drew essential conclusions, which were helpful to one another.
(5) Mathematical modelling and conducting simulation research in an interdisciplinary team increases the chance of prototype success based on verifying accepted objectives.

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References

1. Wang, X.; Xu, J.; Zhu, W.; Li, Y. Roof pre-blasting to prevent support crushing and water inrush accidents. *Int. J. Min. Sci. Technol.* **2012**, *22*, 379–384. [CrossRef]
2. Bajda, M.; Błażej, R.; Hardygóra, M. Optimizing splice geometry in multiply conveyor belts with respect to stress in adhesive bonds. *Min. Sci.* **2018**, *25*, 195–206. [CrossRef]
3. Gładysiewicz, L.; Król, R.; Kisielewski, W.; Kaszuba, D. Experimental determination of belt conveyors artificial friction coefficient. *Acta Montan. Slovaca* **2017**, *22*, 206–214.
4. Peng, S.S.; Feng, D.; Cheng, J.; Yang, L. Automation in U.S. longwall coal mining: A state-of-the-art review. *Int. J. Min. Sci. Technol.* **2019**, *29*, 151–159. [CrossRef]
5. Ralston, J.C.; Reid, D.C.; Dunn, M.T.; Hainsworth, D.W. Longwall automation: Delivering enabling technology to achieve safer and more productive underground mining. *Int. J. Min. Sci. Technol.* **2015**, *25*, 865–876. [CrossRef]
6. Hu, S.; Ma, L.; Guo, J.; Yang, P. Support-surrounding rock relationship and top-coal movement laws in large dip angle fully-mechanized caving face. *Int. J. Min. Sci. Technol.* **2018**, *28*, 533–539.
7. Ralston, J.C.; Hargrave, C.O.; Dunn, M.T. Longwall automation: Trends, challenges and opportunities. *Int. J. Min. Sci. Technol.* **2017**, *27*, 733–739. [CrossRef]
8. Oggeri, C.; Oreste, P. Tunnel Static Behavior Assessed by a Probabilistic Approach to the Back-Analysis. *Am. J. Appl. Sci.* **2012**, *9*, 1137–1144.
9. Buyalich, G.; Buyalich, K.; Byakov, M. Factors Determining the Size of Sealing Clearance in Hydraulic Legs of Powered Supports. *E3S Web Conf.* **2017**, *21*, 3018. [CrossRef]
10. Kumar, R.; Singh, A.K.; Mishra, A.K.; Singh, R. Underground mining of thick coal seams. *Int. J. Min. Sci. Technol.* **2015**, *25*, 885–896. [CrossRef]
11. Jixiong, Z.; Spearing, A.J.S.; Xiexing, M.; Shuai, G.; Qiang, S. Green coal mining technique integrating mining-dressing-gas draining-backfilling-mining. *Int. J. Min. Sci. Technol.* **2017**, *27*, 17–27.
12. Babyr, N.V.; Korolev, A.I.; Neupokoeva, T.V. Enhancement of powered cleaning equipment with the view of mining and geological conditions. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *194*, 032004. [CrossRef]
13. Buevich, V.V.; Gabov, V.V.; Zadkov, D.A.; Vasileva, P.A. Adaptation of the mechanized roof support to changeable rock pressure. *Eurasia Min.* **2015**, *2*, 11–14. [CrossRef]
14. Gabov, V.V.; Zadkov, D.A.; Stebnev, A.V. Evaluation of structure and variables within performance rating of hydraulically powered roof support legs with smooth roof control. *Eurasia Min.* **2016**, *2*, 37–40. [CrossRef]
15. Klishin, V.I.; Klishin, S.V. Coal Extraction from Thick Flat and Steep Beds. *J. Min. Sci.* **2010**, *46*, 149–159. [CrossRef]

16. Zhu, Z.; Wu, Y.; Liang, Z. Mining-Induced Stress and Ground Pressure Behavior Characteristics in Mining a Thick Coal Seam With Hard Roofs. *Front. Earth Sci.* **2022**, *10*, 843191. [CrossRef]
17. Wang, J.; Wang, Z. Systematic principles of surrounding rock control in longwall mining within thick coal seams. *Int. J. Min. Sci. Technol.* **2019**, *29*, 591–598. [CrossRef]
18. Ji, Y.; Zhang, Y.; Huang, Z.; Shao, Z.; Gao, Y. Theoretical analysis of support stability in large dip angle coal seam mined with fully-mechanized top coal caving. *Min. Sci.* **2020**, *27*, 73–87.
19. Babyr, N.; Babyr, K. To improve the contact adaptability of mechanical roof support. In *E3S Web of Conferences*; EDP Sciences: Les Ulis, France, 2021; Volume 266, p. 03015.
20. Ji, Y.; Ren, T.; Wynne, P.; Wan, Z.; Zhaoyang, M.; Wang, Z. A comparative study of dust control practices in Chinese and Australian longwall coal mines. *Int. J. Min. Sci. Technol.* **2016**, *25*, 687–706. [CrossRef]
21. Baiul, K.; Khudyakov, A.; Vashchenko, S.; Krot, P.V.; Solodka, N. The experimental study of compaction parameters and elastic after-effect of fine fraction raw materials. *Min. Sci.* **2020**, *27*, 7–18. [CrossRef]
22. Khayrutdinov, M.M.; Golik, V.I.; Aleksakhin, A.V.; Trushina, E.V.; Lazareva, N.V.; Aleksakhina, Y.V. Proposal of an Algorithm for Choice of a Development System for Operational and Environmental Safety in Mining. *Resources* **2022**, *11*, 88. [CrossRef]
23. Gabov, V.V.; Zadkov, D.A.; Babyr, N.V.; Xie, F. Nonimpact rock pressure regulation with energy recovery into the hydraulic system of the longwall powered support. *Eurasia Min.* **2021**, *36*, 55–59. [CrossRef]
24. Juganda, A.; Strebinger, C.; Brune, J.F.; Bogin, G.E. Discrete modeling of a longwall coal mine gob for CFD simulation. *Int. J. Min. Sci. Technol.* **2020**, *30*, 463–469. [CrossRef]
25. Jayanthu, S. Strata control problems of underground coal mining vis-à-vis geotechnical instrumentation and numerical model studies. *J. Eng. Geol.* **2014**, *39*, 2.
26. Hebda-Sobkowicz, J.; Gola, S.; Zimroz, R.; Wyłomańska, A. Identification and Statistical Analysis of Impulse-Like Patterns of Carbon Monoxide Variation in Deep Underground Mines Associated with the Blasting Procedure. *Sensors* **2019**, *19*, 2757. [CrossRef] [PubMed]
27. Qiao, S.; Zhang, Z.; Zhu, Z.; Zhang, K. Influence of cutting angle on mechanical properties of rock cutting by conical pick based on finite element analysis. *J. Min. Sci.* **2021**, *28*, 161–173. [CrossRef]
28. He, T.; Yu, C.; Wu, X.; Deng, H. Modeling and Analysis of Single Hydraulic Props in Coal Mines. *Key Eng. Mater.* **2016**, *693*, 364–372. [CrossRef]
29. Ren, H.; Zhang, D.; Gong, S.; Zhou, K.; Xi, C.; He, M.; Li, T. Dynamic impact experiment and response characteristics analysis for 1:2 reduced-scale model of hydraulic support. *Int. J. Min. Sci. Technol.* **2021**, *31*, 347–356. [CrossRef]
30. Świątek, J.; Janoszek, T.; Cichy, T.; Stoiński, K. Computational Fluid Dynamics Simulations for Investigation of the Damage Causes in Safety Elements of Powered Roof Supports—A Case Study. *Energies* **2021**, *14*, 1027. [CrossRef]
31. Buyalich, G.; Byakov, M.; Buyalich, K.; Shtenin, E. Development of Powered Support Hydraulic Legs with Improved Performance. *E3S Web Conf.* **2019**, *105*, 3025. [CrossRef]
32. Frith, R.C. A holistic examination of the load rating design of longwall shields after more than half a century of mechanised longwall mining. *Int. J. Min. Sci. Technol.* **2015**, *26*, 199–208. [CrossRef]
33. Zhao, X.; Li, F.; Li, Y.; Fan, Y. Fatigue Behavior of a Box-Type Welded Structure of Hydraulic Support Used in Coal Mine. *Materials* **2015**, *8*, 6609–6622. [CrossRef] [PubMed]
34. Zhang, Y.; Zhang, H.; Gao, K.; Zeng, Q.; Meng, F.; Cheng, J. Research on Intelligent Control System of Hydraulic Support Based on Position and Posture Detection. *Machines* **2023**, *11*, 33. [CrossRef]
35. Zeng, Q.; Xu, P.; Meng, Z.; Ma, C.; Lei, X. Posture and Dynamics Analysis of Hydraulic Support with Joint Clearance under Impact Load. *Machines* **2023**, *11*, 159. [CrossRef]
36. Byakov, M.A.; Buyalich, G.D.; Buyalich, K.G.; Uvakin, S.V. Radial strains in two-stage hydraulic extension legs. *MIAB. Mining Inf. Anal. Bull.* **2020**, *1*, 133–140. [CrossRef]
37. Gribble, P. Integrating ODEs & Simulating Dynamical Systems; Scientific Computing Fall. 2019. Available online: https://gribblelab.org (accessed on 29 June 2023).
38. Domagała, Z.; Kędzia, K. Analysis, modelling and verification of the phenomena occurring in a hydraulic prop during dynamic load. *Tech. Trans.* **2017**, *114*, 139–153. [CrossRef]
39. Gabov, V.V.; Babyr, N.V.; Zadkov, D.A. Mathematical modelling of operation of the hydraulic support system of the powered support sections with impulse-free continuous regulation of its resistance to the roof rock lowering. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2021; Volume 1064, p. 012045. [CrossRef]
40. Atkinson, K.; Han, W.; Stewart, D.E. *Numerical Solution of Ordinary Differential Equations*; John Wiley & Sons: Hoboken, NJ, USA, 2009.