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Virtual prototyping of the suspended monorail in the aspect of increasing the permissible travel speed in hard coal mines

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Highlights

- Parameters of the computational model of the suspended monorail was identified.
- The emergency braking method has a direct impact on the overload values affecting on the crew.
- Increasing the speed of the suspended monorail requires the identification of emergency braking parameters.
- The value of the safe crew transport speed has an impact on the extraction process efficiency.

Abstract

Due to the longer distance of moving the crew to the workplace in hard coal mines, the possibility of increasing the maximum permissible speed of suspended monorails was considered. To ensure an adequate level of safety, decelerations affecting the crew in the case of emergency braking in various travelling conditions were analysed. The computational model was verified based on the results of the bench tests on a dedicated test track. The article presents a comparison of results of numerical calculations with measurements at the test stand, and results of numerical simulations in relation to the critical states that could not be checked at the test stand as well as the analysis of overloads that affect the crew during the emergency braking. These overloads have a significant impact on safety of the operator and passengers, and their determination and analysis may be the basis for assessing the degree of safety as well as for the development of guidelines for designing the additional equipment for the operator's cabs and passenger cars, i.e. components increasing their safety.

Keywords

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mining industry, numerical simulations, suspended monorails, travel speed.

1. Introduction

For the proper functioning of underground hard coal mines, it is necessary to design properly not only the longwall panels and machines working there, but also the proper transportation routes and the auxiliary mine transport. The auxiliary transport is used to supply consumables, the materials used to protect workings as well as to move the crew to the workplaces. The proper design and maintenance of transportation routes in a proper technical condition has a significant impact on the functioning of the mine and ensuring the operational safety of the working people and the machines as well as on the work effectiveness. Transportation routes are protected by using the yielding roadway support. This support protects against falling rocks and it also plays a role of the system, to which rails being the route of the suspended railway, which is one of the auxiliary transportation means, are fixed. The organisation of the auxiliary transport determines the time needed for the crew to reach the workplace, and thus determines the time of miner effective work, what in consequence affects the production efficiency and mine economy. Therefore, the auxiliary transport should be designed in such a way as to ensure that the crew will reach the workplace in a safe way and in the shortest possible time. So, the safety and the efficiency are two very important features of the auxiliary transport [5, 24].

Along with the changes in the hard coal mining industry, caused, among others, by winning the deeper and deeper coal deposits as well as opening the new mining regions and merger of mines, the distances from the shaft to mining faces and other places of miners' work are increasing. Suspended monorails are one of the main means of transportation intended for moving the crew to the workplaces. In the light of the legal regulations being in force in Poland, in accordance with the Regulation of the Minister of Energy of November 23, 2016 on detailed requirements for underground mining plant operations, the maximum permissible speed of a suspended monorail set during crew movement is 2 ms^{-1} [15]. Therefore, if the suspended monorail needs to cover several kilometres, the journey time forth and back from the workplace becomes significantly longer. This results in a decrease in the effective worktime and the efficiency of the coal production, which in turn translates into the mine economy [5, 14, 21]. That is why there is a need to search for a method to shorten the time of the crew travel to the workplace. In [27], the authors report that at the İmbat Mining Co. Manisa, located in the city of Eynez in Turkey, by using a conveyor belt to convey people, the time required to reach their workplace was reduced. According to the authors of the cited work, the possibility of moving miners on conveyor belts, in relation to their walking, enabled to save 15 minutes on reaching the longwall

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panel and 30 minutes on the way back. With three working shifts, 135 minutes per day were saved, which was converted into an additional 1,606.95 tons of a coal extracted per day. The maximum speed of the conveyor used in the example was 2.5 ms^{-1} , however, but when moving the people it had to be limited to 1 ms^{-1} . In addition, during the transportation of the crew on the conveyor belt, the run-of-mine transportation was suspended. The crew using this means of the transportation had to undergo a special training. However, the presented solution will not be justified in the mines, where it is possible to use suspended monorails with the permissible speed, according to the Polish law, equal to 2 ms^{-1} .

Therefore, increasing the permissible speed of suspended railways seems to be justified, due to the criteria for reducing the time of the crew travel to the workplace, what can increase the efficiency of the coal production. However, the transportation safety should be taken into account. The first suspended monorail had a rope drive. The further development of this type of the transportation resulted in the development of self-powered suspended monorails by a diesel engine, and more recently by battery powered electric motors. The intensive work on the development of suspended monorails in the mining industry still continues, what has been confirmed by many projects undertaken by manufacturers of these devices as well as by many R&D organisations [1, 3, 6, 9, 10, 16, 18, 21]. Manufacturers of suspended monorails declare the possibility of increasing the monorails speed to the values higher than those permitted by law [2, 14, 28]. Increasing the maximum permissible speed on the selected sections of the route allows a significant reduction in the travel time. However, to increase the permissible speed, it is necessary to carry out many analyses and tests that allow designing and verifying a new means of the transportation ensuring an adequate level of the safety for the transported persons. This is mainly related to the analysis of emergency situations, such as, in particular, emergency braking. During such braking at a higher speed, overloads may be much higher than those permitted by law, affecting the operator or people being carried. In [13], the author cites the possibility of overloads of up to 3 g. In addition, the loads transmitted by suspensions to the arches of the yielding roadway support should be analysed [1, 5, 13, 20, 28]. Such analyses can be carried out in test stands or by using the virtual prototyping technology.

The construction and the validation of the suspended monorail model enabled carrying out a series of numerical simulations aiming at the identification of the impact of travel speed of the suspended monorail on the operator and passengers safety. The computational model of the suspended monorail with cars, adapted to travel with a higher speed, is an example [6]. This model was developed as a part of the project [7]. The main project objective was to increase the efficiency and the safety on transportation routes in underground workings and the development of suspended monorails with a possibility of increasing the travel speed in the case of moving people. The test stand for analysing the modified suspended monorail which could run with a higher speed, was constructed within the project. After completion of the stand tests, the numerical model was validated and then used in numerical simulations in the criterial states that were not possible to be realised on the test stand. This work was aimed at comparing the decelerations affecting the monorail operator, as well as at estimating the impact of the changing monorail travel speed on the route suspended to the roadway support and the load to its suspensions. The highest dynamic overload was observed in emergency situations, that is why the overloads affecting people in the monorail were determined during the emergency braking. Use of new rails, longer than current ones, with a length of 4 m, was the innovation both in the test stand and in the computational model. The use of these rails in the monorail route improves the route stability and improves the passenger comfort at the increased speed. The results of simulations using the developed computational model enable assessing the impact of the increased travel speed both on the load to the yielding roadway support, as well as on the safety of the operator and the transported crew. The results of forces loading each suspension, were the bound-

ary values for the analyses of the stability of arches of the yielding roadway support [5, 13]. Analysis of overloads acting on the operator and passengers during the emergency braking, as well as the possibility of estimating the exposure to vibrations of people traveling by train are another aspects for applying the simulation results. For the purpose of the analysis of the safety, the obtained accelerations acting on the operator or passengers can be used as boundary conditions for analysis using the DUMMY HYBRYD III virtual dummy, used for analysis of a driver and the passengers safety in the automotive industry [11, 12, 25, 29]. Analyses using the model of this dummy of the selected centile size enables estimating the risk of severe or fatal head injuries analysis (HIC - Head Injury Criterion) taking into account the human size, the identification of the dangerous phenomena such as operator falling out from the cab while cornering, or the estimation of the need to use seat belts in the operator's cabin or the passenger cabin when traveling at a higher speed [10, 20, 21, 22].

2. The stand for testing the track for suspended monorail travelling with a higher speed

The test stand of the suspended monorail track included 24 supporting frames on which the 90-meter-long monorail track was suspended, along with a drivetrain adapted to travel at a higher speed (Fig. 1). This track consisted of 23 rails, each 4 m long. These rails were specially designed to enable the train to travel faster. Each of the rail joints was equipped with a traverse, suspended to the supporting structure, using two suspensions. The suspended monorail on the track is presented in Fig. 2.



Fig. 1. View of the 90 m long test track, on the test stand [7]

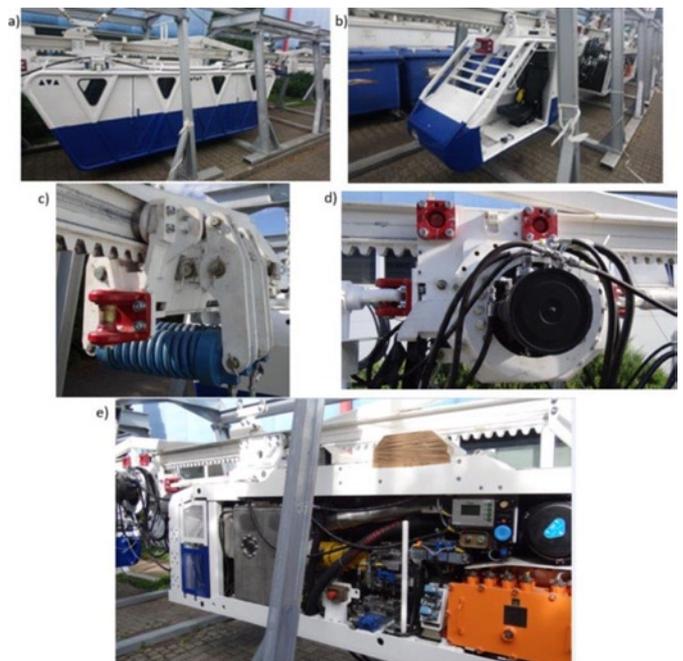


Fig. 2. Components of the suspended monorail on the testing track: a) personnel cabin, b) operator's cabin, c) breaking trolley, d) gear drive with built-in multi-disk brake, e) machinery part [7]

The tests were conducted with the train speeds 3 ms^{-1} and 5 ms^{-1} . The emergency braking test at speed of 3 ms^{-1} and 5 ms^{-1} was the next stage of stand tests. A braking trolley was used on the test stand to brake with the activation of one or two pairs of brake shoes. Due to limitations resulting from the test stand design, the multi-disk brakes were not used. During each of the tests, decelerations of the train were recorded.

3. A design of the computational model of the test stand

The computational model of the test stand was created for the extended tests and analyses related to the movement and braking of the suspended monorail at the increased speed. Preparation and validation of the computational model enabled carrying out complementary virtual tests, including those with use of multi-disk brakes, which could not be realised on the test stand. Emergency downward braking tests with a large inclination angle as well as the emergency braking at the increased braking force were performed. The computational model consisted of the dynamic model of the suspended monorail prepared using the software for kinematic and dynamic analysis of multi body systems (MSC Adams), as well as the module controlling the dynamic model developed in MatLab Simulink software. The structure of the computational model is shown in Fig. 3.

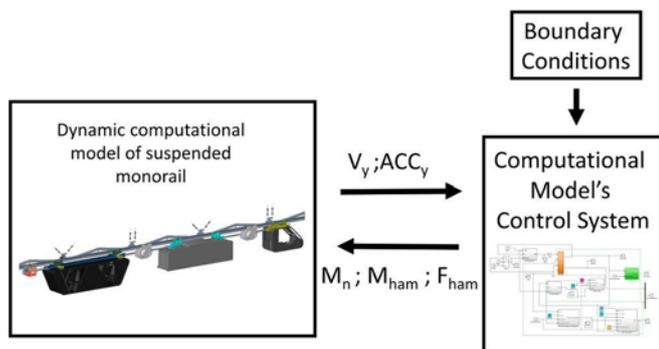


Fig. 3. The structure of the computational model of the suspended monorail [7]

Signals between the two parts of the model to control the computational model and conduct parallel simulations were defined [8, 17, 19, 23]. Parameters such as: a drive torque, braking forces, braking torque, as well as activation and deactivation signals for each force vector and torque vector were calculated on the basis of the measured speed and the acceleration of the suspended monorail in the dynamic model, and boundary conditions. Boundary conditions include the maximum speed at which the emergency braking is activated, time required for reaching the maximum braking force as well as decisions regarding activation or not, in relation to each vector. The force vectors and braking torques, as well as the time delay from the moment, when the full force of the brake shoes pressing the rail web is achieved, till the activation of the braking torque of multi-disk brakes in gear drives were also defined as the boundary conditions. A dynamic model of the suspended monorail, along with a route section, is shown in Fig. 4. This model consisted of an operator's cabin, two gear drives, a machinery part, a cabin for moving people, and a braking trolley with two pairs of braking shoes. The train was suspended on a straight section of the route, consisting of 23 rails, each 4 m long, fixed with traverses and suspensions just like on the test stand.

The computational model included 383 rigid bodies, 13 cylindrical constraints, 111 rotational constraints, 298 spherical constraints, and 15 restraint constraints. The model had 720 degrees of freedom.

A drive torque (M_n) was applied to the gear wheels in the model. The activation of this vector of the required value, set the monorail into motion and allowed accelerating it to the set speed (Fig. 5).

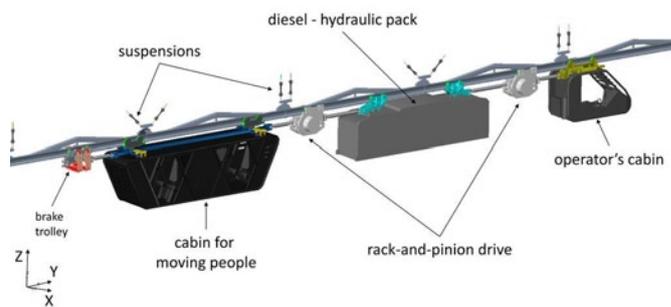


Fig. 4. Computational model of the KP-95 suspended monorail on a route, prepared in the MSC Adams software [7]

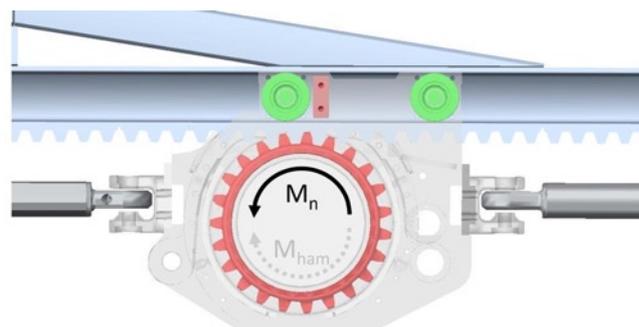


Fig. 5. Suspended monorail gear drive model, equipped with multi-disc brake [7]

The suspended monorail is braked by activating the forces (F_{ham}) pressing one or two pairs of brake pads against the rail web (Fig. 6), with the activation of the multi-disc breaking torque (M_{ham}). This vector was applied to the gear in the drive (Fig. 5).

In the computational model of the suspended monorail, a model of contacts of brake pads, rollers and drive gears with the route rails was defined. The contacts model was used in the MSC Adams software. In this model, the virtual spring and damper systems between the selected solids were defined. When the solids come into the contact, the spring is deflected and the contact force is created.

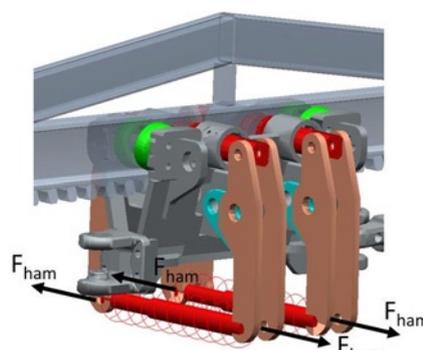


Fig. 6. Braking trolley model [7]

At the beginning, the spring length was " x_1 " (Fig. 7). When one solid hits the other, the virtual spring is deflected and its momentary length is " x ". The interacting solids deflect, so " x " is smaller than " x_1 ". In such a case, the contact force is proportional to the spring deflection. If the solids do not interact, the " x " is greater than the " x_1 " and the contact force is equal to zero.

The contact force can be described by the following relationship (1) [26]:

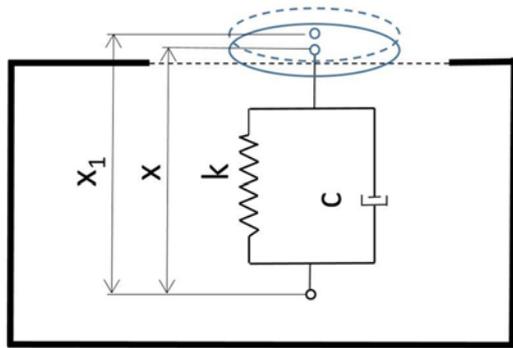


Fig. 7. Contact model implemented in the MSC Adams software [26]

$$F = \begin{cases} \max(k(x_1 - x)^e - c\dot{x}, 0) & \text{when } x \leq x_1 \\ 0 & \text{when } x > x_1 \end{cases} \quad (1)$$

where:

- F – contact force,
- k – rigidity of the virtual spring,
- x_1 – length of the virtual spring at the moment of the bodies contact,
- x – instantaneous length of the virtual spring,
- e – virtual spring linearity coefficient;
- e = 1 means a linear relationship,
- c – damping coefficient of the virtual damper,
- \dot{x} – relative speed of interacting bodies.

The damping coefficient “c” takes into account the energy dissipation during the bodies collision. The damping force is proportional to the relative speed of the bodies which come into contact. For the numerical calculations reasons, it is not advisable that the damping coefficient change stepwise. This coefficient is described by the following equation (2) [26]:

$$c(p) = \begin{cases} 0 & \text{when } p \leq 0 \\ c_{\max} \left(\frac{3}{h^2} p^2 - \frac{2}{h^3} p^3 \right) & \text{when } 0 < p \leq h \\ c_{\max} & \text{when } p > h \end{cases} \quad (2)$$

where:

- c – damping coefficient,
- c_{\max} – maximum damping coefficient,
- h – penetration depth of one solid into another,
- p – function describing dependence of the damping factor c on the depth of the solid penetration.

During preparation of the computational model, based on the literature analysis [11], the following initial contact parameters were assumed:

- virtual spring rigidity coefficient $k = 1 \cdot 10^8 \text{ Nm}^{-1}$,
- damping coefficient $c_{\max} = 5 \cdot 10^4 \text{ Nsm}^{-1}$,
- maximum penetration depth $h_{\max} = 1 \cdot 10^{-4} \text{ m}$,
- virtual spring linearity coefficient $e = 1,5$.

The contact model also defines the static and dynamic friction coefficients. These coefficients were as follows:

- static friction coefficient, in relation to the contact places of rollers and gears with rails, $\mu_s = 0,3$,
- dynamic friction coefficient, in relation to the contact places of rollers and gears with rails, $\mu_d = 0,1$,
- static friction coefficient, in relation to the contact places of brake pads with rails, $\mu_s = 0,5$,

- dynamic friction coefficient, in relation to the contact places of brake pads with rails, $\mu_d = 0,45$,
- the rate of the increase of the friction force was assumed as $1 \cdot 10^{-2} \text{ ms}^{-1}$ in each case.

With the assumed dynamic friction coefficient and the force (F_{ham}) pressing the brake pads against the rail web, equal to 12.5 kN, a suspended monorail braking force of 52 kN is generated when two pairs of brake shoes are activated. It is a force equal to the static braking force declared by the manufacturer of the braking trolley.

Then, in the process of adjustment and validation of the monorail computational model, the adopted contact parameters were modified, reaching the following values:

- in relation to the contact place of rollers and gears with the rails:
 - virtual spring rigidity coefficient $k = 7 \cdot 10^9 \text{ Nm}^{-1}$,
 - damping coefficient $c_{\max} = 7 \cdot 10^4 \text{ Nsm}^{-1}$,
 - maximum penetration depth $h_{\max} = 1 \cdot 10^{-4} \text{ m}$,
 - virtual spring linear coefficient $e = 2,2$,
- in relation to the contact place of brake pads with the rails:
 - virtual spring rigidity coefficient $k = 9,5 \cdot 10^8 \text{ Nm}^{-1}$,
 - damping coefficient $c_{\max} = 1 \cdot 10^5 \text{ Nsm}^{-1}$,
 - maximum penetration depth $h_{\max} = 1 \cdot 10^{-4} \text{ m}$,
 - virtual spring linear coefficient $e = 2,2$.

The results of verification and adjustment of the computational model to the real object in relation to the three criterial states listed in point 4, are presented. In addition, the results of the parameter modification in the contact model are presented in Table 1.

4. Stand tests – verification of the computational model

The following stand tests were conducted for the model validation:

- emergency braking with one pair of shoes in the braking trolley, at the speed 3 ms^{-1} ,
- emergency braking with one pair of shoes in the braking trolley, at the speed 5 ms^{-1} ,
- emergency braking with two pairs of shoes in the braking trolley, at the speed 5 ms^{-1} .

During the tests, the operator accelerated the suspended monorail to the set speed, and then, in the place set on the route, the emergency braking of the monorail was activated. During braking, the monorail accelerations were recorded. All tests were repeated three times. In the same way the numerical simulations, in which the monorail was accelerated to the set speed, and then the driving torque (M_n) was deactivated, and the force vectors (F_{ham}), responsible for braking the train, were activated, were carried out. The suspended monorail accelerations read in the operator’s cab, both on the test stand and during numerical simulations were compared to verify and adjust the computational model. Parameters defining contacts between the selected solids in the model were modified to better fit the model to the real object. Table 1 presents the maximum decelerations during bench tests and those calculated by numerical simulations, with initial and modified contact parameters.

Fig. 8 presents acceleration curves recorded at the test stand (test 1 - test 3), and those determined by numerical simulations during the emergency braking with one pair of brake shoes, at a speed of 3 ms^{-1} .

The maximum decelerations recorded in each tests and calculated in the simulations during the emergency braking with one pair of shoes, at an initial speed of 3 ms^{-1} , are presented in Table 2. In addition, Table 2 presents the average maximum deceleration on the test stand, and the difference between this value and the value calculated in numerical simulations.

Table 1. Maximum decelerations and the results of the adjustment of the computational model to the real object [7]

	Maximum deceleration at initial contact parameters (ms^{-2})/ difference referring to the stand tests (%)	Maximum deceleration at modified contact parameters (ms^{-2})/ difference referring to the stand tests (%)	Average maximum deceleration recorded on the test stand	Difference in adjustment of the model after changing the contact parameters
Speed 3 ms^{-1} , braking with one pair of shoes	3.7 / -20.0	4.3 / -5.2	4.6	14.8 %
Speed 5 ms^{-1} , braking with one pair of shoes	4.1 / -19.4	5.6 / +9.8	5.1	9.6 %
Speed 5 ms^{-1} , braking with two pairs of shoes	5.6 / -20.1	7.4 / +4.9	7.0	15.2 %

Table 2. Maximum decelerations during the emergency braking with one pair of shoes, at an initial speed of 3 ms^{-1} [7]

	measured value [ms^{-2}]	average value [ms^{-2}]	difference in relation to the average value [%]
test 1	4.47	4.57	X
test 2	4.54		
test 3	4.71		
numerical simulation	4.34		-5.0

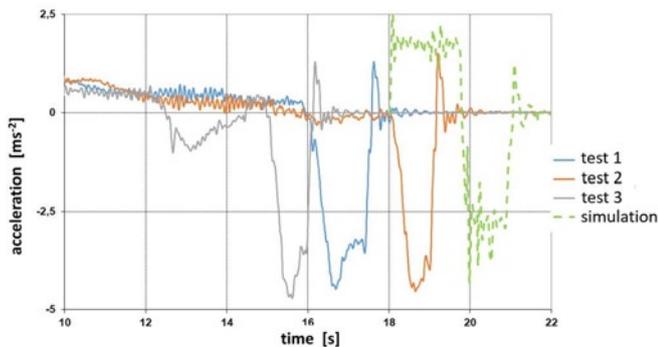


Fig. 8. Accelerations of the suspended monorail during stand tests and during simulations when braking with one pair of shoes at speed of 3 ms^{-1} [7]

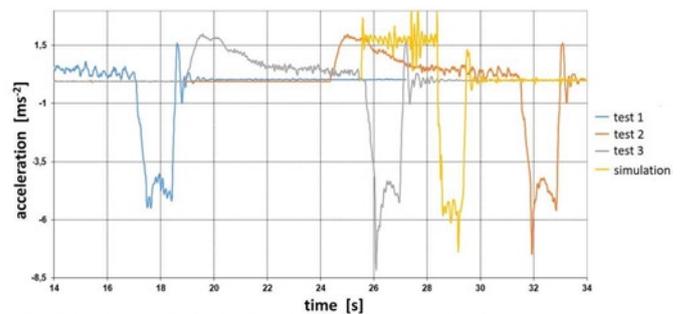


Fig. 10. Accelerations of the suspended monorail during stand tests and during simulations when braking with two pairs of shoes at speed of 5 ms^{-1} [7]

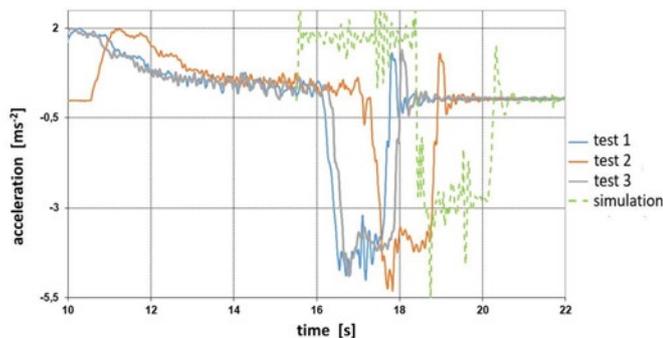


Fig. 9. Accelerations of the suspended monorail during stand tests and during simulations when braking with one pair of shoes at speed of 5 ms^{-1} [7]

Fig. 9 presents acceleration curves recorded at the test stand (test 1 - test 3), and those determined by numerical simulations during the emergency braking with one pair of brake shoes, at a speed of 5 ms^{-1} .

The maximum decelerations recorded in each tests and calculated in the simulation, during the emergency braking with one pair of shoes, at an initial speed of 5 ms^{-1} , are presented in Table 3. In addition, Table 3 presents the average maximum deceleration on the test stand, and the difference between this value and the value calculated in numerical simulations.

Fig. 10 presents acceleration curves recorded at the test stand (test 1 - test 3), and those determined by numerical simulations during the emergency braking with two pairs of brake shoes, at a speed of 5 ms^{-1} .

The maximum decelerations recorded in each tests and calculated in the simulation, during the emergency braking with two pairs of

Table 3. Maximum decelerations during the emergency braking with one pair of shoes, at an initial speed of 5 ms^{-1} [7]

	measured value [ms^{-2}]	average value [ms^{-2}]	difference in relation to the average value [%]
test 1	5.02	5.08	X
test 2	5.32		
test 3	4.90		
numerical simulation	5.57	X	+9.6%

Table 4. Maximum decelerations during emergency braking with two pairs of shoes, at an initial speed of 5 ms^{-1} [7]

	measured value [ms^{-2}]	average value [ms^{-2}]	difference in relation to the average value [%]
test 1	5.49	7.05	X
test 2	7.48		
test 3	8.17		
numerical simulation	7.39	X	+4.8%

shoes, at an initial speed of 5 ms^{-1} , are presented in Table 4. In addition, Table 4 presents the average maximum deceleration on the test stand, and the difference between this value and the value calculated in numerical simulations.

The maximum decelerations of the monorail, calculated in numerical simulations, differed from the average values of three stand tests by 4.8% to 9.6%.

Based on the presented comparisons of the suspended monorail decelerations, it was found that the computational model can be used in the next braking tests aimed at analysing the maximum suspended monorail decelerations in the criterial states, which it is difficult or dangerous for the monorail operator to be carried out on the test stand.

5. Results of numerical simulations for the selected criterial states

Development and verification of the suspended monorail computational model enabled many tests to be carried out at various criterion states. The following tests were carried out:

- the emergency downward braking of the suspended monorail with an inclination angle of 30° , at an initial speed of 3 ms^{-1} ,
- the emergency downward braking of the suspended monorail with an inclination angle of 30° , at an initial speed of 5 ms^{-1} ,
- the emergency braking on not inclined route by two pairs of brake shoes and two multi-disk brakes at initial speed 5 ms^{-1} .

Based on the numerical simulations, it was concluded that with the analysed suspended monorail travelling downward with a large angle of inclination of 30° , it is necessary to activate two pairs of brake shoes and at least one multi-disk brake to stop the train. Development of a two-stage emergency braking algorithm is one of the directions for further research work. In this algorithm, the activation of the second brake stage (multi-disk brake) will depend on the suspended monorail deceleration resulting from the operation of the first stage (brake shoes). It has been assumed that activation of the second stage will be delayed compared to the first stage. In the analyses, the delay time of the activation of the second braking stage was assumed to be 0.1 s and 0.3 s after reaching the maximum pressure force of the brake pads against the rail web.

The first simulation concerned emergency braking with two pairs of brake shoes and one multi-disk brake, at a speed of 3 ms^{-1} downward with inclination of 30° . The graph of braking forces (F_{ham}) and the braking torque (M_{ham}) during braking from a speed of 3 ms^{-1} , in the case of a torque activation delays of 0.1 s and 0.3 s, is shown in Fig. 11.

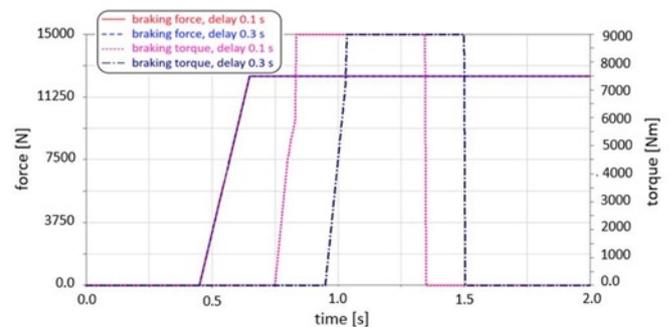


Fig. 11. Curves of forces and braking torques during the downward braking with inclination 30° from a speed 3 ms^{-1} at delay in the activation of the braking torque 0.1 s and 0.3 s [7]

Time process of the speed in the operator's cabin, recorded during the simulation, is presented in Fig. 12.

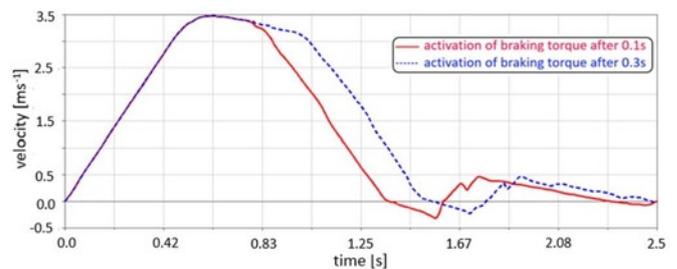


Fig. 12. Speed of the suspended monorail during the emergency braking simulation at 3 ms^{-1} on a 30° downward inclination with a delayed activation of the braking torque of 0.1 s and 0.3 s [7]

The acceleration time process, recorded during the simulation of the emergency braking of the suspended monorail on a 30° downward inclination at an initial speed of 3 ms^{-1} , with two pairs of brake shoes and a multi-disk brake activated with a delay of 0.1 s and 0.3 s is presented in Fig. 13.

The second simulation concerned the emergency braking with two pairs of brake shoes and a multi-disk brake at a speed of 5 ms^{-1} on a 30° downward inclination. The graph of braking forces (F_{ham}) and

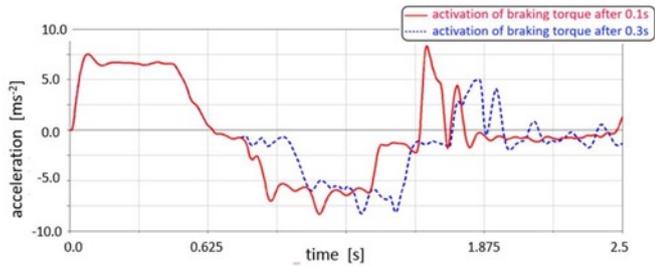


Fig. 13. Acceleration time process recorded during the simulation of the emergency braking with two pairs of brake shoes and a multi-disc brake, on a 30° downward inclination, at the initial speed of 3 m/s [7]

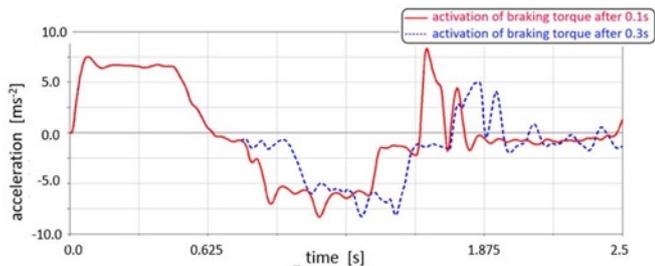


Fig. 14. Time process of the braking force and the torque during braking from the speed of 5 m/s, on a 30° downward inclination, with a delay in the braking torque activation of 0.1 s and 0.3 s [7]

the braking torque (M_{ham}) during braking from speed of 5 m/s, in the case of a delay in the braking torque activation of 0.1 s and 0.3 s, is shown in Fig. 14.

The time process of speed changes, recorded during the simulation in the operator's cabin is shown in Fig. 15.

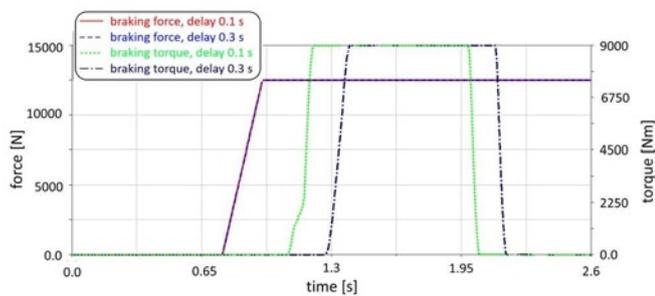


Fig. 15. Suspended monorail speed during emergency braking simulation, at an initial speed of 5 m/s, on a 30° downward inclination, with a delay of the braking torque activation of 0.1 s and 0.3 s [7]

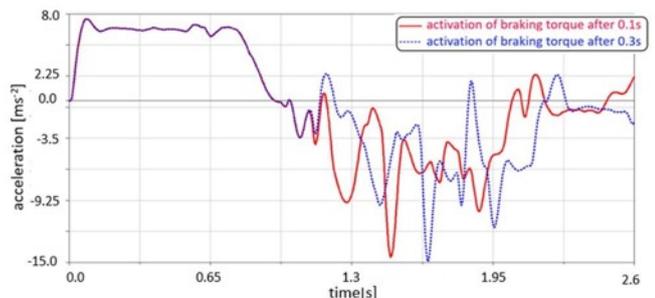


Fig. 16. The acceleration time process recorded during the simulation of the emergency braking with two pairs of brake shoes and a multi-disc brake, on a 30° downward inclination, at the initial speed of 5 m/s [7]

The acceleration time process recorded during the simulation of the emergency braking of a monorail, on a 30° downward inclination, at the initial speed of 5 m/s, with two pairs of brake shoes and a multi-disc brake activated, and a delay of 0.1 s and 0.3 s is presented in Fig. 16.

During the simulation of the emergency downward braking, the forces (F_{ham}) pressing the brake pads against the rail web were activated, then after a defined time delay, the braking torque (M_{ham}), corresponding to the operation of the multi-disc brake, was activated after reaching the set maximum speed. It is worth mentioning that in such a situation, the time necessary to reach the maximum braking force and the delay in the activation of the multi-disc brake, can result in exceeding the set maximum permissible speed, depending on the inclination and the transported mass. If it is assumed that the emergency braking starts at the speed of 3 m/s, on a downward route, the maximum speed of the monorail was 3.5 m/s; similarly, assuming the emergency braking at the speed 5 m/s, its maximum recorded speed was 5.5 m/s.

Then, the emergency braking with two pairs of brake shoes and two multi-disc brakes at an initial speed of 5 m/s on not inclined route was simulated. This simulation enabled determining the maximum braking deceleration, when activating all braking systems installed in the analysed suspended monorail. The graph of monorail speed changes during the tests is shown in Fig. 17.

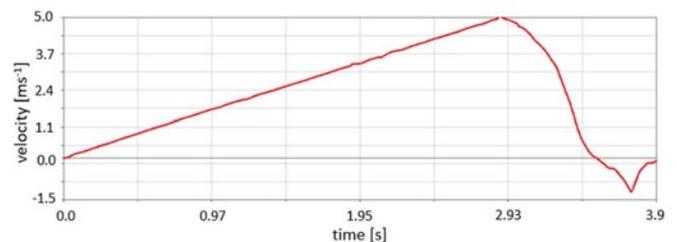


Fig. 17. Suspended monorail speed recorded during the simulation of the emergency braking with two pairs of brake shoes and two multi-disc brakes, on a not inclined route [7]

The graphs of activating the braking force and torque in the simulation of the emergency braking with two pairs of brake shoes and two multi-disc brakes, from an initial speed of 5 m/s, on a not inclined route, are shown in Fig. 18.

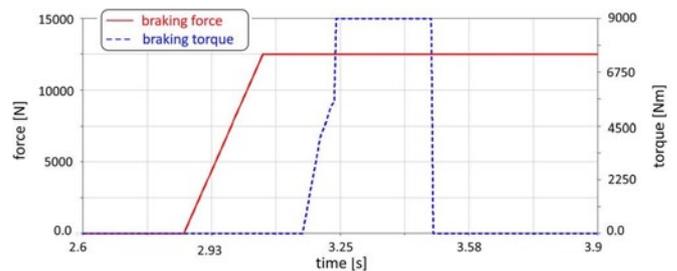


Fig. 18. Graphs of braking forces and torques, when braking from a speed of 5 m/s, on a not inclined route, with the activation of two pairs of brake shoes and two multi-disc brakes [7]

The graph of the acceleration during the emergency braking of a monorail on not inclined route, with two pairs of brake shoes and two multi-disc brakes and a delay of 0.1 second at an initial speed of 5 m/s is shown in Fig. 19.

The maximum monorail deceleration, the braking time and the braking distance calculated during the simulation are presented in Table 5. The results were listed with reference to the simulation of braking on not inclined and downward route, with the inclination angle of

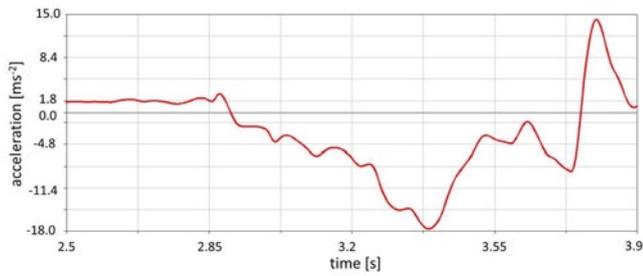


Fig. 19. Acceleration during the emergency braking on a horizontal route, with two pairs of brake shoes and two multi-disc brakes [7]

initial speed of 3 ms⁻¹ and 5 ms⁻¹, downward as well as without the inclination is shown in Fig. 20.

When analysing the presented results, it can be observed that during a significant increase in the braking force (two pairs of brake shoes and two multi-disc brakes), and during the braking on a steep inclination, the displacement of the monorail's route increases significantly. Therefore, it is necessary to consider the use of an appropriate method to stabilise the route on inclinations, as well as to optimise the braking method, through the extended sequence of activating the braking force and the torque. The selection and maintaining of the proper braking sequence depending on the system condition, is also important with regard to the impact of braking decelerations on the operator and passengers and for protecting them against excessive and unaccepted overloads.

Table 5. Results of numerical simulations during suspended monorail emergency braking [7]

Boundary conditions				Results of numerical simulations			
Assumed speed at which emergency braking starts [ms ⁻¹]	Route inclination [°]	Number of activated brake shoes	Number of activated multi-disc brakes / delay in activation [s]	Maximum deceleration during braking [ms ⁻²]	Maximum speed of the suspended monorail [ms ⁻¹]	Braking time [s]	Braking distance [m]
3	0	1	0	4.3	3.0	1.2	1.90
5	0	1	0	5.6	5.0	1.8	4.58
5	0	2	0	8.6	5.0	1.1	3.54
5	0	2	2/0.1	17.6	5.0	0.7	2.05
3	30	2	1/0.3	8.3	3.5	1.1	2.68
3	30	2	1/0.1	8.3	3.5	0.9	2.14
5	30	2	1/0.3	16.8	5.6	1.8	5.58
5	30	2	1/0.1	13.5	5.5	1.6	4.29

30°, at initial speeds of 3 ms⁻¹ and 5 ms⁻¹ and in different configurations of the force (F_{ham}) and the braking torque (M_{ham}). In addition, in the case of the downward braking, two situations were considered in which the activation of the braking torque (multi-disc brake) took place with a delay of 0.3 s and 0.1 s from reaching the maximum braking force.

Numerical simulations allowed to record the displacement of the route on which the suspended monorail was moving. The displacement of the route's first rail during the simulation of the braking at the

5. Conclusions

Within the design work, a computational model of the suspended monorail was developed, then it was verified, based on the results of measurements taken on the test stand. The computer simulation enabled realisation of many numerical experiments at the selected criterial states. Regarding the increase of the maximum permissible speed of the monorail during personnel movement, it is especially important to ensure the safety of traveling people. For this purpose, the maximum monorail decelerations during the emergency braking were analysed.

Based on these results, it was possible to assess the impact of the increased speed of the monorail on the safety of transported people. According to the applicable law, the suspended monorail operator cannot be affected by the deceleration over 10 ms⁻² [15]. This limitation minimises the risk of injuries to the crew in emergency situations. The second important issue is to ensure the safety of the entire monorail route (track stability) as well as the stability of the yielding roadway support. Based on the analysis, it was found that when applying too much of the braking force on a downward route, the permissible decelerations may be significantly exceeded. Such trends were also reported in the publication [13]. At the same time, the reduction in braking force results in smaller overloads during the emergency braking, however, it does not provide the ability to stop the monorail on a steep downward route. In order to ensure an adequate level of the safety for people traveling in suspended monorails, the

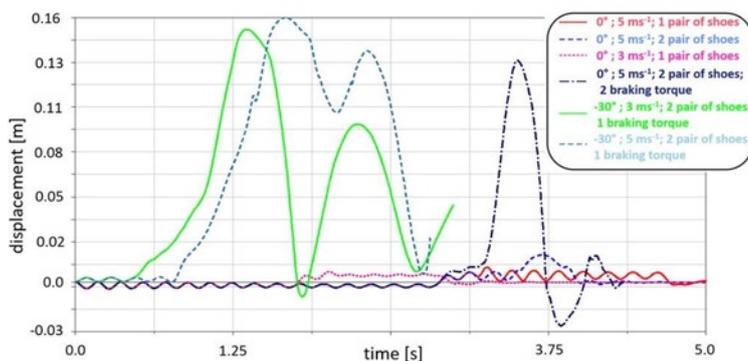


Fig. 20. The displacement of the monorail's first rail during the emergency braking [7]

authors developed the innovative emergency braking algorithm. This algorithm enables adjusting the braking force to the conditions of the monorail movement. Such approach ensures the required braking efficiency without exceeding the maximum safe deceleration [6].

Defining the system ensuring the stability of the monorail route is another aspect that improves both the driving comfort and the miners safety. The problem of excessive swinging of the train from side to side while driving was reported in [4]. Use of a new type of 4 m long rails, tested in this work is one of the innovations improving the route stabilisation. Transverse movements were observed while travelling and braking, both on the test stand and in numerical simulations. The amplitude of these movements was not dangerous and did not reduce the level of the safety. However, as demonstrated in the simulations, the route built using the presented rails requires the use of a guy-rope system, preventing it from moving excessively in the direction of the monorail travelling axis. Such stabilisation is especially important to ensure the safety of the operator and passengers during the travel and the emergency downward braking of the high inclination.

The results of the simulations, especially the maximum deceleration of the monorail will be used in the next stages of the simulation verifying the safety of people and the mine infrastructure. The virtual dummy DUMMY HYBRID is employed for the analyses of the human safety during numerical simulations. Based on the results of such

analyses, the solutions increasing the safety of both the operator and the people travelling in a monorail can be introduced. The use of seat belts in the operator's cabin and in the passenger cabins [10, 20, 21] is one of such solutions. Numerical analyses aimed at testing the safety of the mine infrastructure include analyses of the load-bearing capacity and the stability of the yielding roadway support [2, 5, 13, 20, 28]. It can therefore be concluded that numerical simulations of the emergency braking is the first and the vital step to start comprehensive analyses aimed at ensuring the safety during the suspended monorail travelling and the braking when moving at a higher speed. Increasing the speed is a method to increase the productivity and improvement of the work efficiency in underground mining plants.

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