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RESEARCH ON THE IMPACT OF FORCES AND ACCELERATION DURING THE RIDING AND BRAKING OF A SUSPENDED MONORAIL

This article presents the results of experimental studies aimed at identifying the forces and acceleration during the riding and braking action of a suspended monorail. The tests were conducted under in situ conditions, in a dip-heading "B" ZG SILTECH in Zabrze. The paper also discusses a test stand, a metering system, and presents the impact of changes in speed on forces in slings of the suspended route. The measurements of selected parameters were performed for three variants: the route, the emergency haulage braking and the braking trolley set braking. The results include waveforms of forces in route slings, and acceleration values acting on the operator and transported load.

Keywords: underground transportation, suspended monorail, research, load

1. Introduction

Suspended monorails are becoming more and more widely used in Polish mines (Budniok et al., 2014a, 2014b). They are used to transport machinery, equipment, materials and mining staff. Their increasing application is due to a number of advantages, which include: their simple installation, the option to shape the route and apply later modifications, the ability to cover inclinations, as well as the easier loading and unloading of transported items. One unquestionable advantage is also the separation of the track from the floor of the excavation by suspending the arch support of mine workings. This is particularly important in areas characterized by floor upheavals, as it reduces the costs associated with maintenance and reconstruction of the route

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(Rotkegel et al., 2016). A suspended monorail allows loads of considerable mass and dimension to be transported. Their major limitation is their allowable speed – 2 m/s.

Increasing the speed of suspended monorail transport is an extremely important issue as it impacts the operating costs of a mine. Faster delivery of materials to their destination, as well as shorter time required for the mining staff to reach their designated working area can increase the efficiency of underground work. The increase in speed should not reduce the level of security. Any related changes should be preceded by extensive analysis and research on the operation of individual elements of the monorail-route-sling-roof support system. This applies mainly to dynamic forces impacting the roof support and route elements (rails and slings), especially during braking, including emergency braking. Increased route and sling load, resulting from greater speed, may affect the operators, transported people and load (Tokarczyk & Kania, 2016).

A number of tests were carried out underground on selected horizontal tracks, in Zofiówka mine among others, in order to determine the effects of increased speed of transport (Tokarczyk, 2017). This article presents the course and results of research on the impact of a suspended monorail during a ride along a track of a significant incline (~13^{o}). Due to the applicable law and the fact that the research was conducted in an active mine in its normal operation, the maximum speed of the suspended monorail transport unit did not exceed 2 m/s. However, the obtained results enabled the validation process of the MBS computational models of suspended monorail. In this way it is possible to conduct "virtual tests" at higher speeds. The presented scope of the article concerns only the impact of the riding and emergency braking of the monorail on the suspended route. Increasing the driving speed requires a number of other research, e.g. ergonomic and safety assessment of the future monorails (Tokarczyk et al., 2020).

2. Location and subject of the research

The study of the impact of moving transport set on a suspended route, roof support and transported load was carried out in a dip-heading "B" ZG SILTECH Sp. z o.o. The location of the test is shown in Fig. 1. The test stand, marked and equipped with sensors along a section thirty metres long with roof support, was located at a depth of about 250 m, about 900 m away from the inlet to the dip-heading from the surface.

The dip-heading "B" was protected by three-element yielding arch support made of V29 section. The measured width of the working was 4,800 mm and the height was 3,700 mm. The double timber was built with a 1.3 m gauge, reduced to 1.0 m at the section before the intersection. The arches of the support were joined with SDO stirrups (two stirrups per joint). WRG struts (three per element) were used to stabilize the unit. The lagging was made of welded chain-node meshes. The stone lining was covered with ventilation material. A general view of the mine working support is shown in Fig. 2a. The route on the test section was made of 2.6 m rails and suspended on every other double timber using chain slings (Fig. 2b). The sling system and the identification of individual force sensors and markers on the support are shown in Fig. 3.

The load was generated by a transport unit including a drive unit in the form of a suspended diesel locomotive (DLZ110F type-II), manufactured by FERRIT s.r.o. In addition to the locomotive, the unit consisted of two cabs, two sets of hoists together with the load, two braking trolleys, pull rods and carriages. The overview of the components of the transport unit is shown in Fig. 4 and in Table 1.

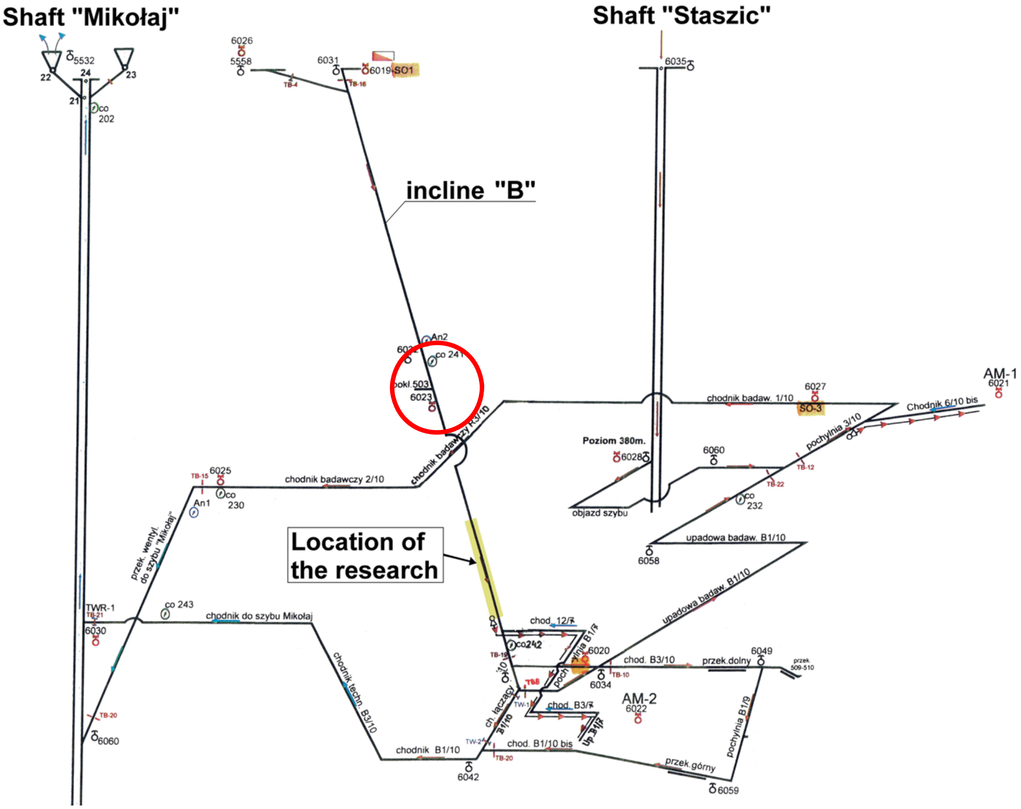
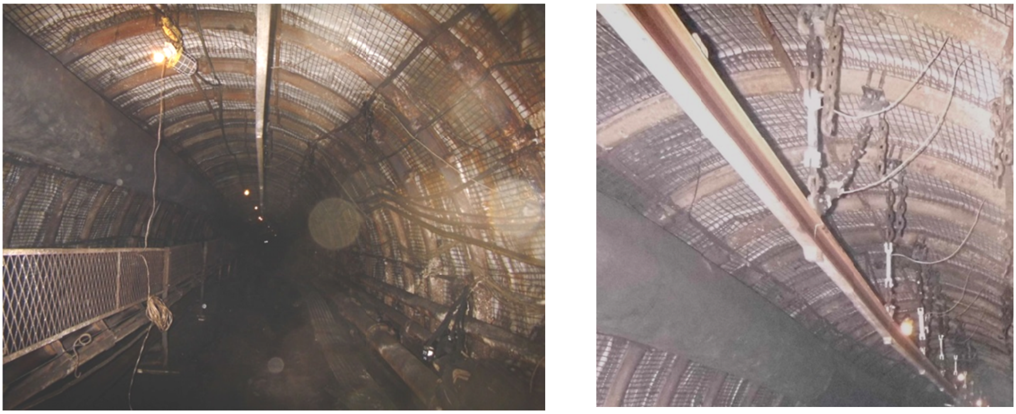


Fig. 1. Location of the research on suspended monorail during driving and braking



a)

b)

Fig. 2. Location of research: a) a general view of pitched roof support B at the test location, b) the route of the suspended monorail at the test location

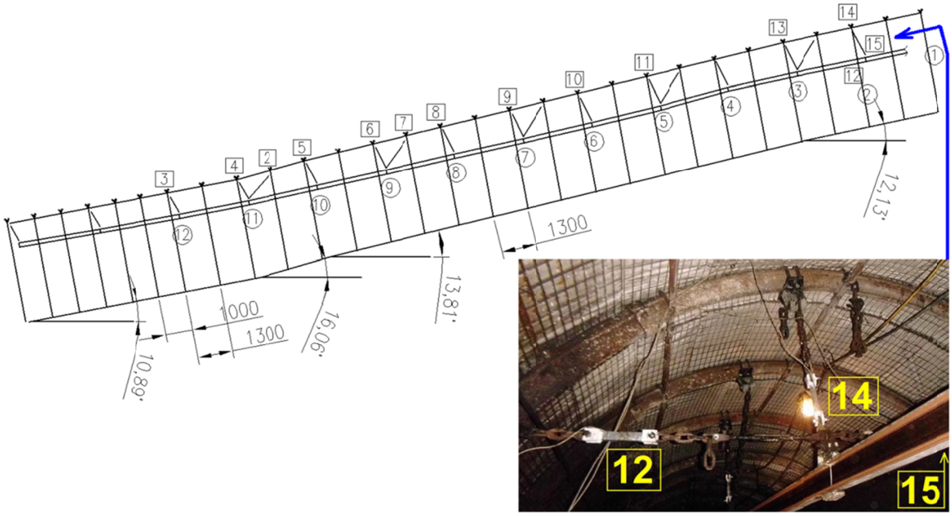


Fig. 3. The route of the suspended monorail at the test location:
□ – force sensor numbers, ○ – marker numbers on the double timber

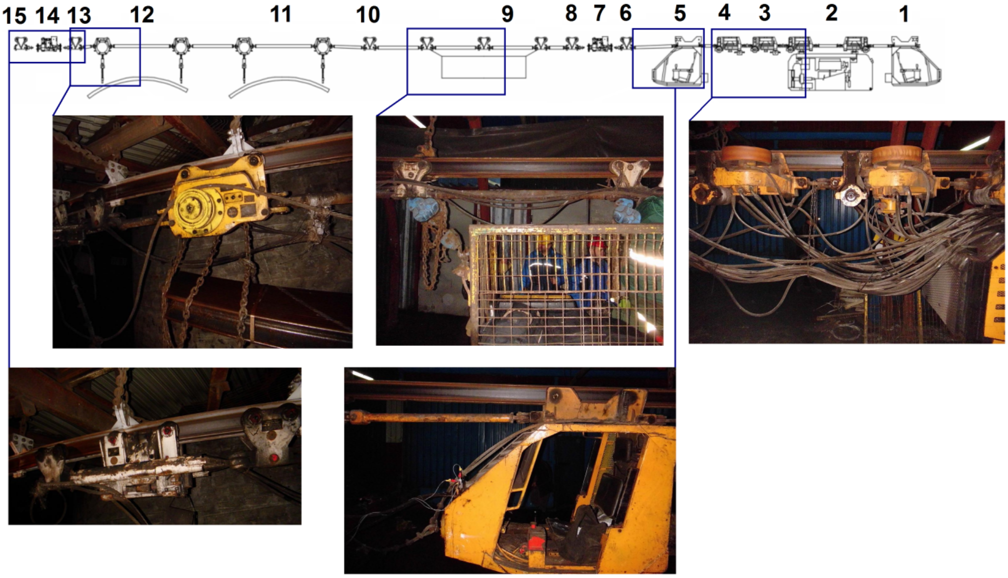


Fig. 4. Transport unit configuration

A ready to run transport unit without load has a mass of 6,866 kg. After taking into account all the additional loads, including 4,050 kg of transported material, the total weight amounted to 11,685 kg. The additional load of a total mass of 4,050 kg included two bundles of steel arches for double timber in yielding arch support for the V29 section, suspended and connected to sets of hoists.

TABLE 1

The components of the transport unit included in the tests

Item No.	Item	Mass [kg]	Remarks
1.	Operator cab	500	—
2.	Machine element	3,000	Two drives, 20 kN each, total braking force of 60 kN
3.	Friction drive	395	Driving force of 20 kN Braking force of 30 kN
4.	Friction drive	395	Driving force of 20 kN Braking force of 30 kN
5.	Operator cab	500 + 100	Operator's weight included
6.	Carriage	45.2 + 36	Additional load of half the weight of the pull rod including braking trolley
7.	Braking trolley	205	Braking force of 52 kN
8.	Carriage	45.2 + 36	Additional load of half the weight of the pull rod
9.	Set of bearing trolley	3×45.2 + 225	Additional load of a container with research equipment
10.	Carriage	45.2	—
11.	Hoists set	2×233 + 2,020	Load – double timber
12.	Hoists set	2×233 + 2,030	Load – double timber
13.	Carriage	45.2 + 36	Additional load of half the weight of the pull rod
14.	Braking trolley	205	Braking force of 52 kN
15.	Carriage	45.2 + 36	Additional load of half the weight of the pull rod including braking trolley
16.	Pull rods joining the elements	373	—

3. The test stand and metering system

The tests were conducted to determine the forces acting on the slings, acceleration in the cab and route displacement. The test stand used to determine the values of forces in the slings of a suspended monorail track comprised of 14 force transducers, numbered 2-15 (Fig. 4), installed on the route section of the suspended monorail with a length of 26 m and an average inclination of 13°. The length of the force transducers was equal to three links in the existing chains (vertical pull rods supporting the route and horizontal pull rods ensuring the stability of the track). Therefore, there was no need to modify the height of the rails and thus the driving profile of the monorail. Fig. 5 shows a geometric model of a force transducer and its mounting in the route slings.

Prior to the test, the transducers were calibrated in the range of 0 to 80 kN, which was in line with the calculated values of the measured forces. Fig. 6 shows an example of the characteristics of force transducer operation.

Force transducers were located in a selected part of the route of the suspended monorail (as in Fig. 3) and connected to metering amplifiers. A flow chart of the metering unit is shown in Fig. 7.

Force transducers, marked as C2-C7, were connected to amplifier 1, and transducers C8-C15 to amplifier 2. Both amplifiers were connected to a digital recorder (PC) via an LPT interface (amplifier 1), and RS232C (amplifier 2). The metering system was configured so that a common time base was generated for both amplifiers. In order to ensure the possibility of registering the dynamic changes of the measured values of metering signals, the sampling rate was set at 150 Hz.

a) b)

Fig. 5. Force transducer – a) geometrical model (Tokarczyk, 2015), b) assembly in route slings

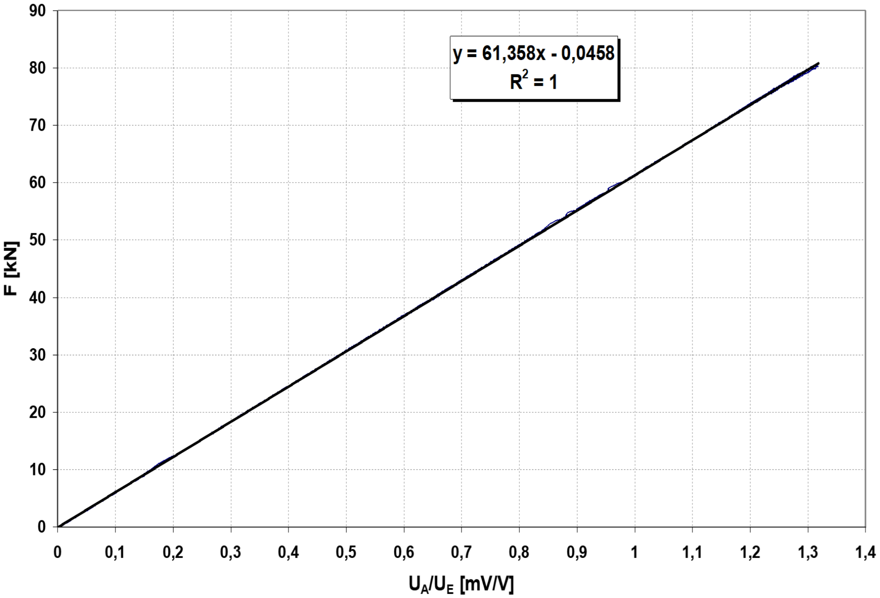


Fig. 6. Characteristic force processing by the transducer included in the tests (Tokarczyk, 2015)

The estimated uncertainty of the results of the measurements of force was set for each of the metering rails (with a 95% confidence level). The maximum value of uncertainty of the force measurement amounted to ±1.48 kN.

Route displacement was measured using a scale attached to the upper part of the I155 beam moving alongside, which screened the stationary line of laser level, mounted on a tripod installed on the floor. The displacements were recorded using a camera. The measuring stand for the suspended route displacement is shown in Fig. 8.

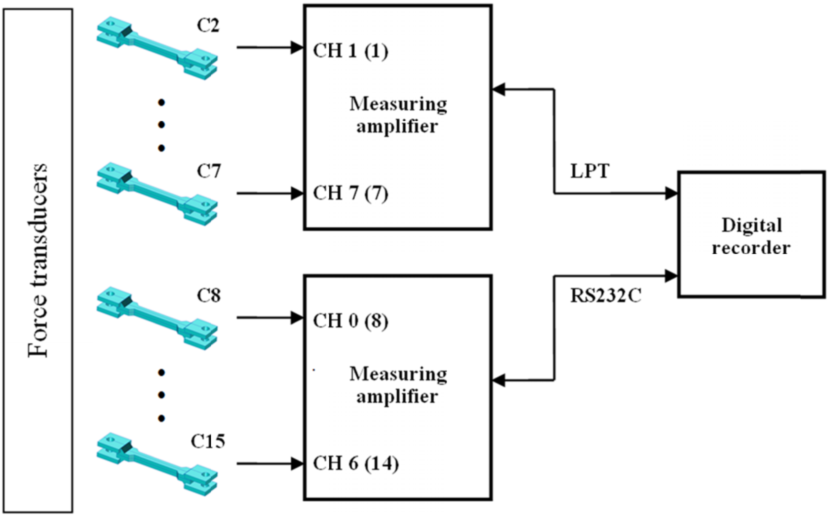


Fig. 7. Flow-chart of the metering system (Tokarczyk, 2017)

a) b)

Fig. 8. The measuring stand for the suspended route displacement: a) scale mounted on the upper part of the I155 beam, b) measuring station

The measurement of acceleration values was conducted by means of acceleration sensors mounted on the operator cabin, Fig. 9. The measurement system was comprised of three sensors, marked with X, Y, Z:

Y – measurement of the cab acceleration in the direction of the cab, dip-heading axis,
X – measurement of the cab acceleration, perpendicular to the dip-heading axis,
X – measurement of the cab acceleration, perpendicular to the dip-heading axis, (sidewall-sidewall).

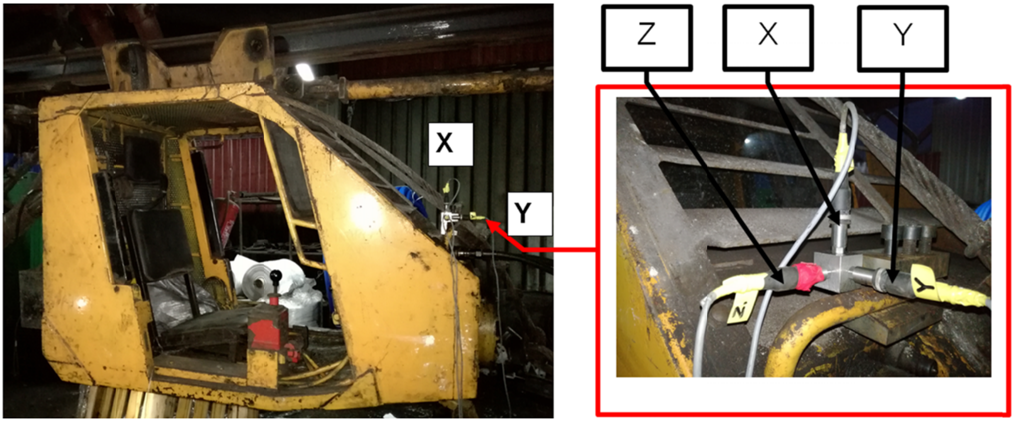


Fig. 9. Accelerometers mounted on the operator cab

Acceleration measurements were performed in a measurement range of 0 to 200 m/s^2. The measurements were recorded at a test frequency of fp = 150 Hz. The movement of the monorail was recorded by a camera synchronized with the measurements of acceleration, which allowed a value of the acceleration to be assigned to specific phases of the monorail movement.

4. Test results

The tests included 17 trials that covered variants of riding and braking of the transport unit at different speeds. The variants and obtained values of route displacement are shown in Table 2. It also includes the location of the operator cab (Component No. 5 acc. to Fig. 4) during the release of the brakes, both while haulage braking and braking trolley braking. The values given in the table are the maximum values recorded in individual measurement tests.

Forces in slings were recorded for each of the runs, and the braking action measurements also included the records of acceleration values. Fig. 10 and 11 illustrate sample force registered in a sling, during downhill ride, via the test section at a rate of 1.0 m/s and 2.0 m/s. Forces recorded in slings stabilizing the route in the direction of movement (transducers 2 and 7) and laterally stabilizing the route (transducers 12 and 15) were not included.

At predetermined states of suspended monorail movement, the forces did not depend on the speed of the transport unit (in terms of testing speed), however, the values of forces in the slings were dependent on the length of the rails, as evidenced by the maximum value of the force recorded in transducer 3 (much greater than on other individual slings – transducers 5, 8, 10, 14). Transducer 3 was built-in on the sling, in the spot where the arch support and rail length scale changes (Fig. 3). The use of two slings (primary and stabilizing), as illustrated in Fig. 3, induced a decrease in forces in the main sling by about 25% (sensors 4, 6, 9, 11, 13). The analysis of force values in stabilizing slings (sensors 2 and 7), not shown in the figures, indicates that the maximum force values were lower than the forces in the main slings (sensors 4 and 6) by about 10% for the suspension route system as shown in Fig. 4. Therefore, it was necessary to analyse the distribution of forces in the slings including their line inclination angle. The use of two slings was not synonymous with a reduction in forces in a single sling by half.

TABLE 2

Variants of riding and braking of the transport unit and route displacement

Measurement No.	Ride speed [m/s]	Route displacement [mm]	Direction/braking spot
Ride			
P01	1.0	2.5	Downhill ride
P02	1.0	2.5	Uphill ride
P03	1.0	3.0	Downhill ride
P04	1.0	2.5	Uphill ride
P05	1.0	3.0	Downhill ride
P06	1.0	3.0	Uphill ride
P07	2.0	5.0	Downhill ride
P08	1.1	4.0	Uphill ride
P09	2.0	5.0	Downhill ride
P10	1.1	3.0	Uphill ride
P11	1.9	4.0	Downhill ride
P12	1.0	3.5	Uphill ride
Haulage emergency braking			
P13	1.0	3.0	Downhill ride – the cab located on a rail between the sensors 9 and 10
P14	1.0	3.0	Downhill ride – the cab located on a rail between the sensors 9 and 10
P15	1.4	3.5	Downhill ride – the cab located on a rail between the sensors 9 and 10
Braking trolley set emergency braking			
P16	1.0	10.0	Downhill ride – the cab located on a rail between the sensors 9 and 10
P17	1.0	10.0	Downhill ride – the cab located on a rail between the sensors 9 and 10

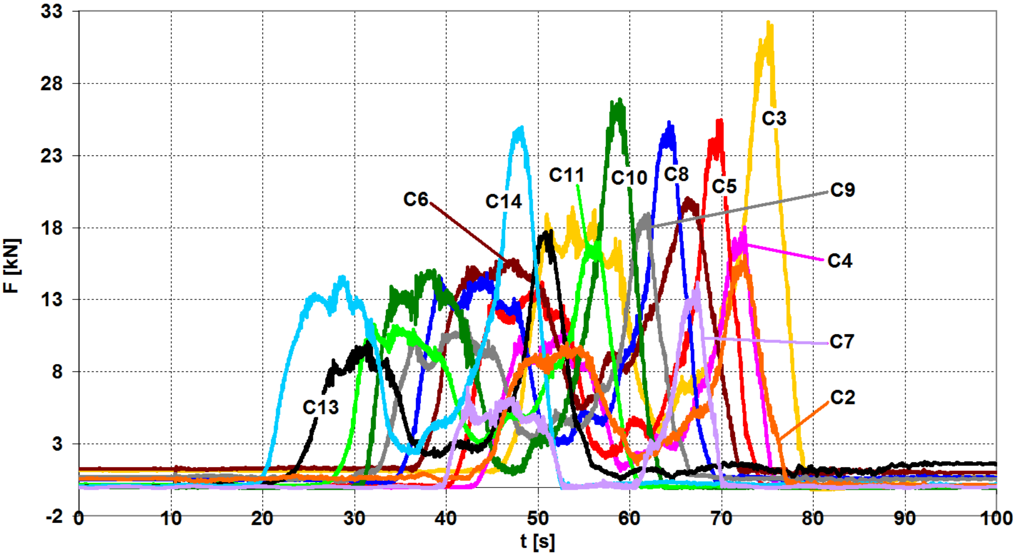


Fig. 10. Force waveforms registered in transducers monorail run at a speed of 1 m/s – Trial P01

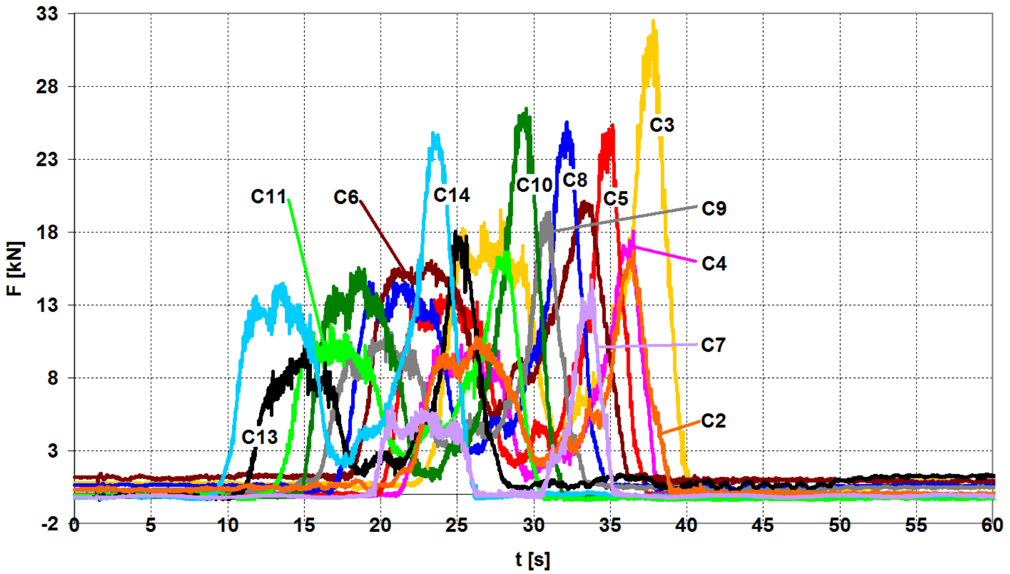


Fig. 11. Force waveforms registered in transducers during monorail run at a speed of 2m/s – Trial P09

Small amounts of forces in relation to the main slings were registered in the sling responsible for the stabilization of the transverse rail (sensors 12 and 15). Forces in these slings reached 10% of the major forces in single main slings during the established ride without any turns.

Forces and accelerations were also recorded during the braking tests of the transport unit. Fig. 12 shows the course of the accelerations and forces in slings registered during drive braking at a speed of 1.0 m/s. The recorded values of forces (slings 6, 10, 14) did not differ significantly from the forces generated when riding at a constant speed. A small, single-digit increase in the forces occurred at the time of braking. Also the acceleration values during braking action did not significantly change in relation to run at a constant speed. At the time of braking, the acceleration in the direction of movement of the monorail decreased by about 2.5 m/s^2. In other directions the values amounted to around 0, larger amplitudes were observed in the vertical direction.

Different waveforms were recorded in the same conditions in the case of emergency braking – Fig. 13. Emergency braking by braking trolleys, even at low speed (1.0 m/s), resulted in approximately a 20% increase in forces in the slings at the time of release of the brake (t = 40 s). This is clearly indicated in the course of forces in sling 14. Acceleration values increased to 30 m/s^2. The overload under such conditions was equal to 3g. Therefore, it should be concluded that increased speed of monorails may require means of protection for the staff in case of overload caused by the action of emergency braking.

The values of forces acting on the frame set, perpendicular to its plane, are extremely important from the perspective of maintaining support stability. In the simplest scenario – of travel through a horizontal working at stable speed – the loads are vertical, in the frame set planes, while their values result only from the mass of the monorail and the transported cargo as well as its distribution. Travel through an inclined working or changing the travel speed are more complex. These cases lead to the generation of a component of force normal to the frame set plane. To maintain support stability, this force must be transferred from the support to the rock mass. At the same time, it must be noted that the support frame set together with the stabilizing elements constitutes a spatial frame that is intended to transfer the loads acting in the frame set plane. The resistance of such a construction to other directions of load is low and related to the strength of the sprags and the rigidity of the sprag-section connection, which finds its reflection in the stability index w_{st} (Drzęźla et al., 2000). This is also confirmed by the results of bench tests (Rotkegel, 2001). A different support capacity for transferring horizontal loads is obtained depending on the utilised sprags. Stabilizing elements such as sprags or horseheads make it possible to transfer and distribute the horizontal loads to adjacent frame sets. As a result, the horizontal point load acting directly on the single frame set is transferred to the rock mass by a number of successive frame sets.

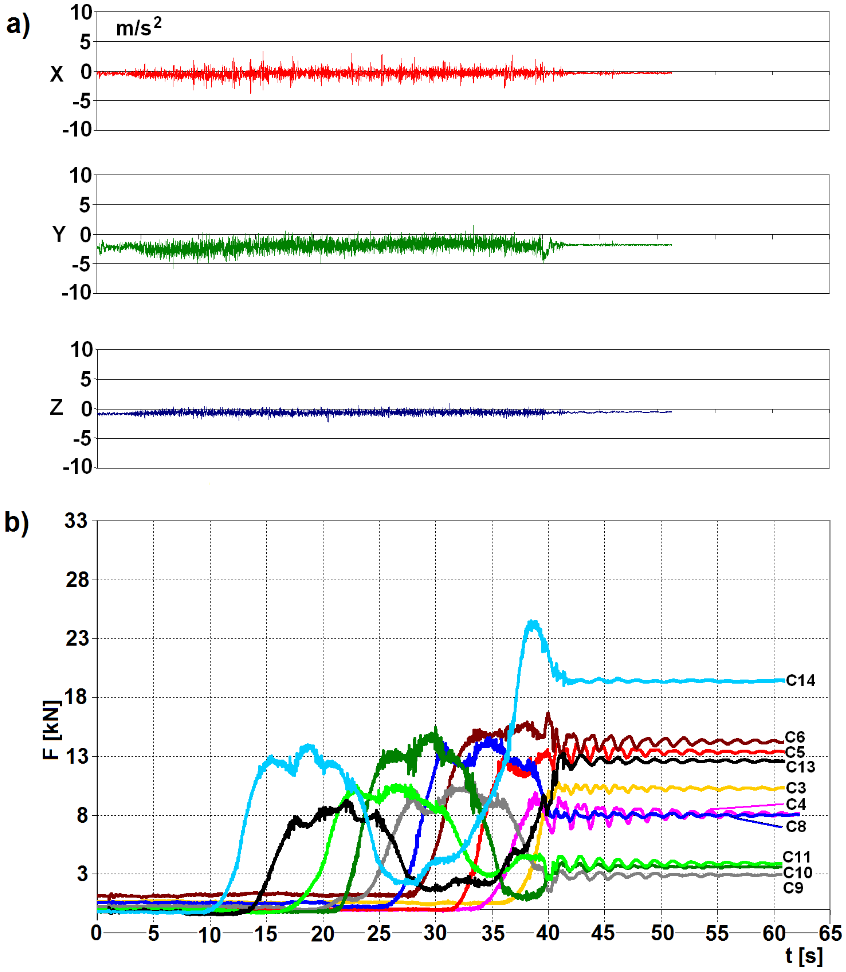


Fig. 12. Graph of accelerations and forces in selected transducers during braking action, ride speed – 1 m/s (a). Trial P14. Braking action initial stage t = 40 s (b)

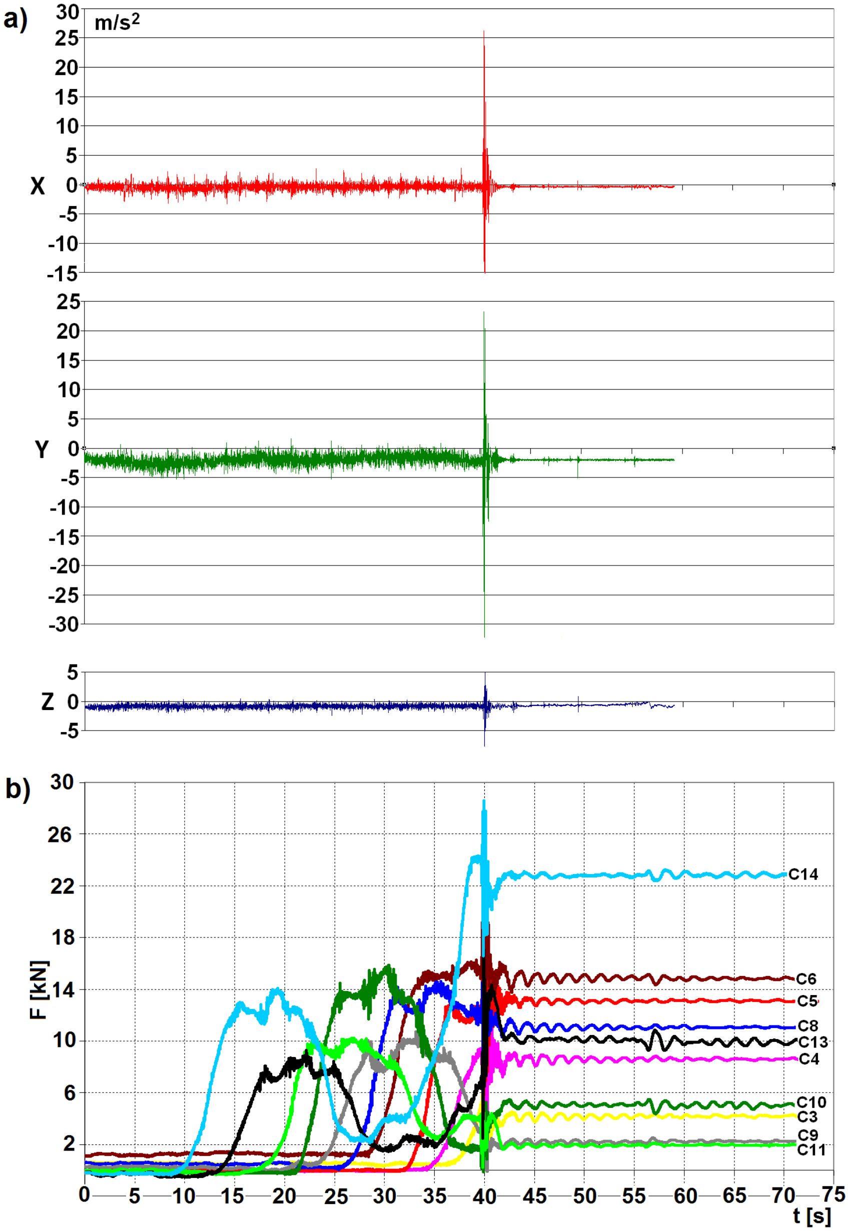


Fig. 13. Graph of accelerations and forces in selected sensors during emergency braking action, ride speed – 1 m/s (a). Trial P16: Braking action initial stage t = 40 s (b)

From the perspective of safety and maintaining support and working stability under the conditions of loads induced by suspended monorail transport, it is important for the horizontal forces generated during the process of suspended monorail transport to be lower than the strengths of the sprags and horseheads, and for them to be transferable to the surrounding rock mass by a number of adjacent frame sets. Underground tests of the forces necessary to destabilize single frame sets in a gallery working (Rotkegel et al., 2011) demonstrated a significant result scatter, which can be seen in Fig. 14. As can be observed in certain cases, even relatively low force acting on the frame set, perpendicular to its plane, can result in its significant displacement. Due to the above, it is very important to identify and subsequently limit the values of such forces exerted on the frame set during suspended monorail transport.

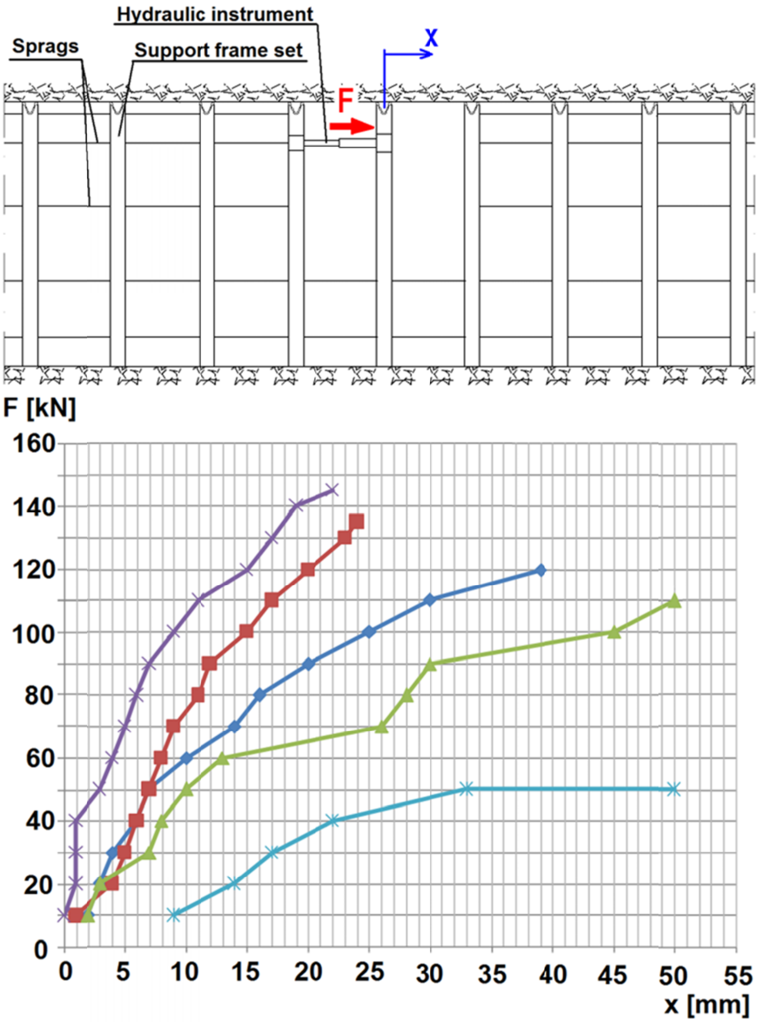


Fig. 14. Test method and registered cases of forces destabilizing the support (Rotkegel et al., 2011)

The values of forces registered during the previously described tests in sensors designated 2 and 7 (Fig. 3) are particularly significant in this situation, as can be seen in Fig. 15 and 16.

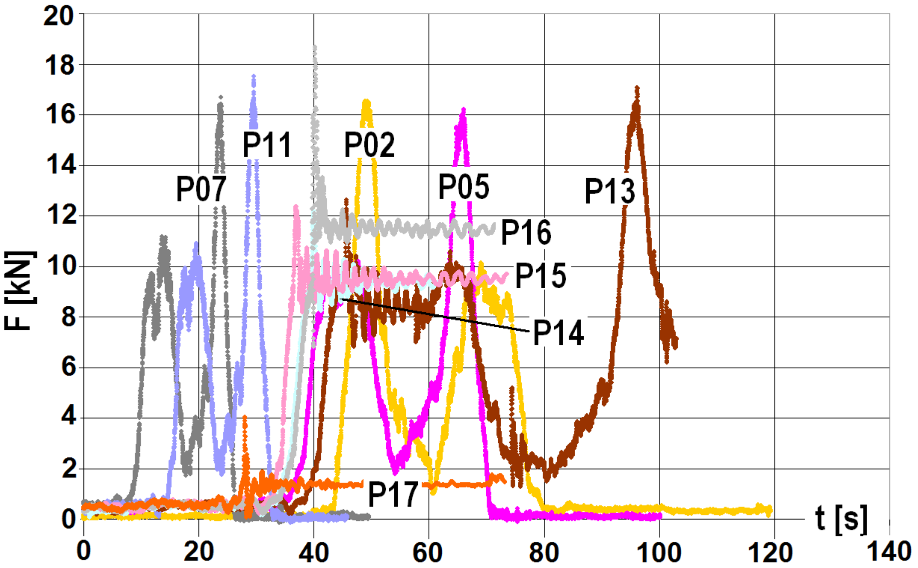


Fig. 15. Courses of forces registered in sensor C2 during selected tests

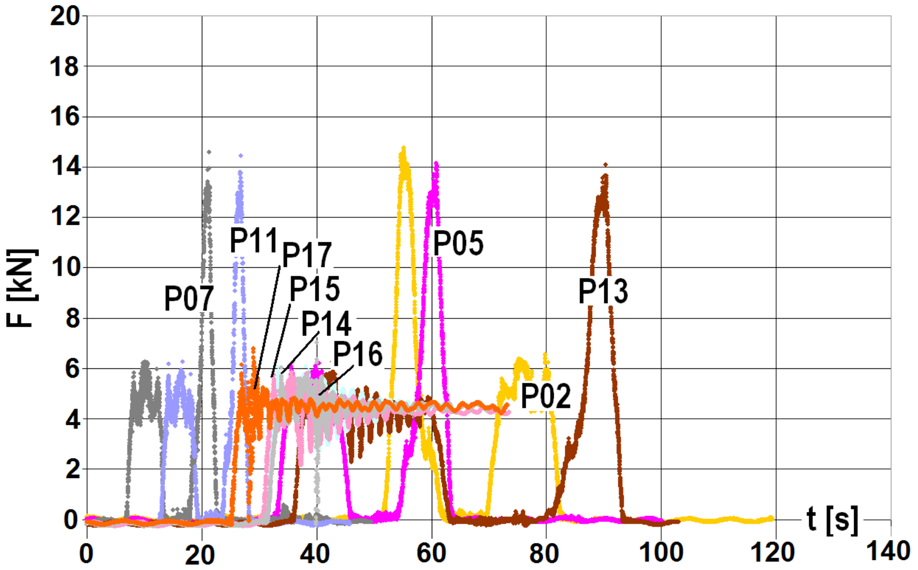


Fig. 16. Courses of forces registered in sensor C7 during selected tests

The above drawings refer to stabilizing slings, because they mainly transfer longitudinal force in an emergency braking situation. In this way, it possible to assess impact of the braking on the suspended track and further – yielding arch support. The names of individual measurement tests (P01-P17) are consistent with those given in the Table 2. As can be observed in the presented charts, the values of forces destabilizing the frame set are not particularly high – they amount to approximately 17 kN in sensor C2 and approximately 15 kN in sensor C7. However, it must be considered that relatively minor masses of transported cargo and speeds lower than 2 m/s were utilised during underground testing. Under actual conditions, greater masses of transported cargo should be expected. Therefore the values of the forces destabilizing the support, depicted in Fig. 15 and 16, will increase, which may be hazardous to the stability of the support and the working.

5. Conclusions

The conducted research allowed the values of selected parameters of the impact of the transport unit on the route, roof support, transported load and staff to be determined. Increased speed did not result in a significant rise in route and sling load. Changes were observed in the case of a braking action, and in the case of emergency braking action by braking trolleys the changes were substantial (even at low speed − 1.0 m/s). Emergency braking caused significant overload (about 3g), and an increase in the load in slings by about 20%. Therefore, it should be concluded that the increased maximum speed of the suspended monorail requires proper adaptation of the roof support by additional means of stabilization, and protection of the operator, transported people and load transported against overloads that may occur during emergency braking. It is possible to reduce overload by modifying the braking trolleys. The continuation of the presented works is currently carried out as part of the European project with the acronym INESI (INESI, 2017-2020).

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References

Budniok T., Zasadni W., Kania J., Mrowiec H., Rusinek J., Szymiczek K., Chluba G., 2014. *Możliwości zwiększenia prędkości transportu ludzi kolejkami podwieszonymi z napędem własnym*. Mechanizacja prac transportowych. Rybnik.

Budniok T., Zasadni W., Mrowiec H., Kania J., Rusinek J., Szymiczek K., 2014. *Analiza możliwości zwiększenia prędkości jazdy ludzi kolejkami podwieszonymi z napędem własnym.* XXII Międzynarodowa Konferencja Naukowo-Techniczna TEMAG, Ustroń, 22-24 October, Poland, 35-49.

Drzęźla B., Mendera Z., Burchan A., Głąb L., Schinohl J., 2000. *Obudowa górnicza. Zasady projektowania i doboru obudowy wyrobisk korytarzowych w zakładach górniczych wydobywających węgiel kamienny. Wydanie II – poprawione*. Politechnika Śląska, Instytut Eksploatacji Złóż, Gliwice, Poland.

INESI European Project, 2017-2020. *Increase Efficiency and Safety Improvement in Underground Mining Transportation Routes.* RFCS, Contract No. 754169.

Rotkegel M., 2001. *Podstawy teoretyczno-badawcze projektowania konstrukcji stalowych obudów odrzwiowych o zwiększonej stateczności*. Prace Naukowe GIG, No 846, Katowice, Poland.

Rotkegel M. et al., 2011. *Wykonanie oceny stateczności stalowej obudowy łukowej w wyrobisku korytarzowym w KWK „ZIEMOWIT" wraz z projektem stabilizacji odrzwi obudowy*. Research work No. 581 452251-151, GIG, Katowice, (unpublished).

Rotkegel M., Szot Ł., Pytlik A., 2016. *Badania wpływu prędkości kolejek podwieszonych na siły w wybranych elementach trasy*. Przegląd Górniczy **11**, 30-37.

Tokarczyk J., 2015. *Wirtualne prototypowanie systemów podwieszonego transportu kopalnianego z napędem własnym*. Research work, KOMAG, Gliwice, (unpublished).

Tokarczyk J., 2017. *Methodology for identifying the selected mechanical hazards in auxiliary transport of underground mines*. Monograph vol. 52, Institute of Mining Technology KOMAG.

Tokarczyk J., Kania J., 2016. *Systems and tracks of self-powered suspended monorails for transportation of people in horizontal workings and workings with inclination up to 45°*. Mining Informatics, Automation and Electrical Engineering **3**, 31-39.

Tokarczyk J., Michalak D., Rozmus M., Szewerda K., Żyrek L., Železnik G., 2020. *Ergonomics assessment criteria as a way to improve the quality and safety of people's transport in underground coal mines*. Rebelo F., Soares M. (eds) Advances in Ergonomics in Design. AHFE 2019. Advances in Intelligent Systems and Computing **955**. Springer, Cham.