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Simulations of the ground pressure exerted by demining rollers with rigid wheels

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ABSTRACT

The effectiveness of conventional demining rollers, especially in real working conditions constitute an open scientific problem. The paper provides a description of developed simulation model (simplified assumptions, it's kinematic structure, interaction between separate bodies and dynamic) of tracked vehicle equipped with a single demining section of roller systems with rigid wheels. This model was used for simulation assessment of possibility of mine pressure fuse activation during route clearance operations with different speeds and on different terrain profile and roughness.

Keywords: anti-tank landmine, pressure fuse, demining roller, route clearance, multi-body simulations.

INTRODUCTION

Landmines used by military units are weapons whose task is to delay, channel or break up an enemy advance [1–3]. They are still a commonly used means of warfare, which was particularly highlighted by the course of the Russian-Ukrainian conflict [4, 5]. They are an effective and essential element of anti-tank defense [6, 7]. Moreover, a survey of contemporary asymmetric armed conflicts indicates that the threat is not only from conventional mines, but also from improvised explosive devices – IEDs [8, 9].

Anti-tank mines (or IEDs) typically use pressure-acting fuses [10, 11]. The explosion is usually initiated by the application of a specified minimum force to the fuse pressure plate, induced by the vehicle's running gear. Depending on the design of the mine, the activation force of anti-tank mines is in the range of approximately 1200–3000 N [12, 13]. A special type of mines are those with pneumatic fuses that have a shock-resistant mechanism [14, 15]. Activation of such a mine requires applying an appropriate pressure force for a certain minimum time to cause air to flow between the internal chambers of the fuse, which causes its detonation.

Ensuring the mobility of own troops requires the removal or neutralization of mine obstacles placed by the enemy. The most frequently used method is the use of demining rollers, which allow for the highest demining speed and do not destroy the ground on which they perform their task, compared to other methods using mine ploughs and mine flails [16, 17]. The principle of operation of demining roller is similar to the operation of the caterpillar of a tank or armored personnel carrier, or to the operation of a vehicle's wheel. After hitting a mine or IED, the wheel exerts pressure, activating the fuse and detonating the explosive. These devices are both suitable for making passages in minefields but also enabling route clearance operations. One of the factors for assessing and comparing a demining rollers is the effectiveness of its use. Effectiveness is mainly due to the demining speed (when the required pressure force is achieved) but may also be related to the mine explosion resistance and the mobility and maneuverability of the minesweeper-vehicle assembly.

This study is focused on demining rollers with a conventional structure, i.e. with rigid, non-deformable wheels (discs). The main advantage of this solution is mechanical durability to multiple mine explosions under the disc section. These devices are installed mainly as additional equipment of the breaching vehicle (most common - fast tracked vehicle). Ground pressure values results from the weight of the wheel and there is no additional pressing element. Demining rollers have been the subject of numerous field experiments. The Study of SDDT (Survivable Demining Tractor and Tools) segmented roller [18] showed that due to limitations, in order to increase demining effectiveness, it is beneficial to use demining rollers in combination with other mine neutralization methods. The authors focused on examining the influence of the number of passes on the level of neutralization of surrogate anti-tank mines in a specific area. Nevertheless, the analysis did not include the study of the pressure exerted by the minesweeper's disc on the ground. Another experiment [19] involved examining the effect of increasing velocity on the performance of the mine roller system. For this purpose, an isolated rigid wheel representing a single demining disc, was tested on a special testing track. It was identified that above a certain velocity, low amplitude vertical vibration of rigid wheels begin, which ultimately reduces the demining effectiveness. The experiment also points out that in terms of roller dimensions, narrow rollers appeared to produce higher pressures, but have also been observed to bounce more. Nevertheless, the experiment was performed only on a flat terrain and did not include the influence of the kinematic connection of the demining section with the vehicle. Another performance testing was carried out by the designer and manufacturer of mechanical demining machines [20]. Novel anti-personnel mine roller tests revealed that increasing the velocity may negatively affect the effectiveness of demining. However, this study concerned anti-personnel mines, whose structure, dimensions and method of laying them in the ground are different than in the case of anti-tank mines. In another experiment [21] a smooth steel roller, representing mechanical demining device was tested in an indoor soil bin. Subsoil forces were measured at variable roller travel speed. The study indicated that slower operating speed could create higher subsoil forces for the same vertical load.

The interaction of a vehicle-mounted mechanical minesweeper with an anti-tank mine or the ground is the subject of numerous scientific studies. Nanivskyi and Yemelianov [22] proposed a modified design of the roller working body in the form of a U-shaped rocker with two working disks. Analysis of analytical dependences showed that the magnitude of the unevenness' may affect the disc pressure force. The same modernized design of roller was tested in [23] but in terms of the explosion shock wave impact. By numerical simulation, it was estimated that proposed model of roller with discs of smaller diameter and smaller thickness, smaller angles between the legs of the U-shapes rocker arm, are more viable. The same modified design of roller was also examined in [24]. The analysis showed that the use of the proposed working body in the demining device in the form of a U-shaped rocker with discs at the end allows to reduce the total weight of the device and improve maneuverability, while maintaining the same demining efficiency. Raymond and Jayakumar [25] modeled tracked vehicle – soil interactions using multi body simulations. The aim of the research was to compare the mobility of two notional path clearing implements pushed by a tracked vehicle. The study indicated that the flail system experienced lower peak loads at the interface brackets and lower peak accelerations at the vehicle's center of gravity than the roller system. Renwick [26] used the finite element analysis (FEA) to investigate the effectiveness of rollers with rigid wheels in relation to pneumatic tires. After performing a computer simulation using a simplified model, the analysis showed that the use of pneumatic tire for road proofing has limitations, namely it is difficult to induce high stresses in the road. Moreover, the use of a rigid wheel is less able to adapt lateral contours and results increased rolling resistance.

Analyzes and studies in the field of mechanical demining devices revealed many investigations related to testing the resistance of the vehicle-mounted minesweeper to a mine explosion. The papers [27–29] describe the method of shaping the structure demining roller section using computer aided engineering (CAE) software. Then, under field conditions, the manufactured segment of the mine roller was subjected to experimental analysis of the impact of the explosive charge. This study confirmed the previously performed calculations, consistent with the imposed boundary conditions. The results confirm the validity of computer simulations when testing mechanical demining devices in order to reduce time and costs.

Baranowski and Małachowski [30] showed that it is possible to dissipate the explosion energy of an explosive material by using and appropriately shaping a non-pneumatic tire. Trajkovski et al. [31] demonstrated the possibility of increasing the explosion resistance of a vehicle by using a V-hull floor insert.

The authors of the analyzes and studies cited in this paper focused mainly on phenomena related to the mobility and maneuverability of the minesweeper-vehicle assembly and on research on the resistance of the structure of the minesweeper itself to multiple mine explosions under the demining discs. Nevertheless, there is a lack of research results on the influence of the dynamics of minesweeper operation on demining effectiveness. Several papers have indicated the effect of increasing velocity on the performance of the mine roller system, but the experiments were mainly conducted on flat terrain using special test tracks. This paper fills the gaps in the current literature and covers a novelty scientific area related to investigating the influence of terrain unevenness (with incidentіal, periodic and random terrain profile) and demining speed on mine clearance capabilities, while taking into account the interactions resulting from kinematic connection with the vehicle. The article attempts to quantitatively analyze the effects of simultaneous variability of these factors in real operating conditions. Therefore, the aim of this paper is to investigate the possibility of mine pressure fuse activation during route clearance operations with different speeds and on different terrain profile and roughness using demining rollers with rigid wheels.

MATERIALS AND METHODS

Simulation assessment of possibility of mine pressure fuse activation during route clearance operations was studied via simulation. In the commonly used solutions, single demining sections are kinematically connected to the prime vehicle. In the real working conditions, due to vibration and pitching of the vehicle's hull, mutual interaction between the demining section and mine-clearing vehicle may affect the forces exerted under the rollers. Therefore, an advanced model of a vehicle equipped with a single demining section of roller systems with rigid wheels was used. The model (Figure 1) was developed in Adams/View, commonly used software based on the multibody method [32, 33]. The following simplifying assumptions were used when developing the model:

- simulation model considered a system composed of two subsystems: mine-clearing vehicle and demining device;
- a vehicle model is a numerical representation of the chassis of a fast tracked vehicle;
- the elements constituting the sprung mass of the vehicle were reduced to a hull of mass m_H, characterized by mass moments of inertia I_{xH}, I_{yH}, I_{zH};
- the running gear was modeled using 12 wheels (6 per side) connected to the hull using suspension elements (Figure 2);
- each of the road wheels are connected to the rocker arms using ideal (without friction) rotational kinematic pairs (J);
- the rocker arms are connected to the hull by ideal rotational kinematic pairs (J);
- the action of the suspension torsion bars was modeled using torsional stiffness in rotational

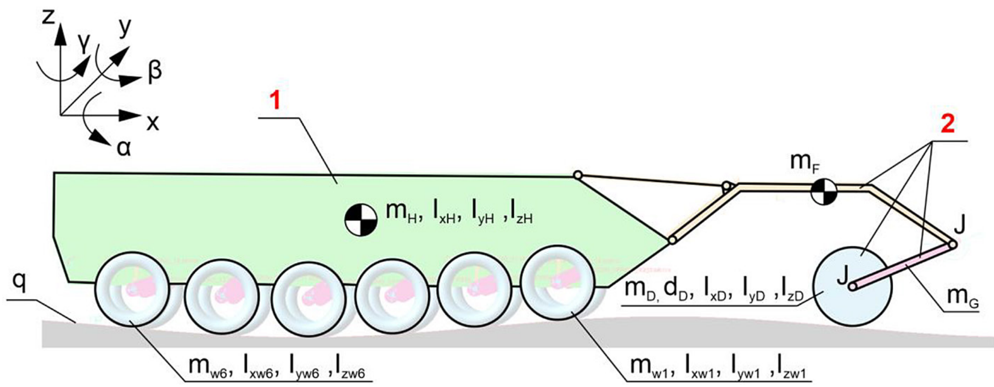

Figure 1. Structure and main parameters of a model of a fast tracked vehicle with a single demining section developed in the MSC Adams software: 1 – mine-clearing vehicle; 2 – demining device; *m* – mass of hull, road wheel, section frame, guiding element, demining disc; *I* – mass moment of inertia of hull, road wheel, demining disc, d_D – demining disc diameter, *J* – rotational kinematic pair; *q* – road kinematic excitation

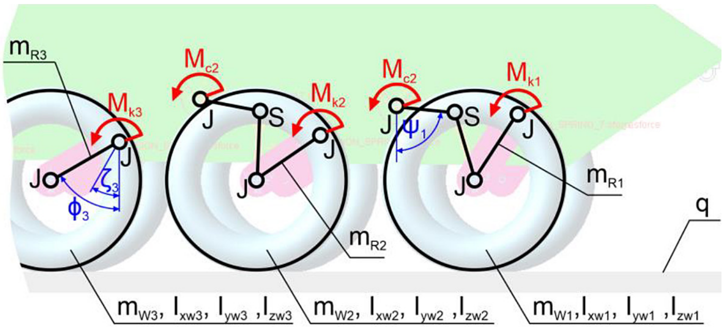

Figure 2. Diagram of the fast tracked vehicle model suspension: m – mass of road wheel, rocker arm; I – mass moment of inertia of road wheel, M_k – torque occurring in the constraint placed in torsion bar position; M_c – torque occurring in the constraint placed in rotary damper position, ψ – shock absorber arm position angle; ϕ – rocker position angle; ϕ – rocker mounting angle; J – rotational kinematic pair; S – spherical kinematic pair; q – road kinematic excitation

joint of rocker arm; torque M_{ki} occurring in the i-th constraint placed in torsion bar position, was determined according to the equation

$$M_{ki} = k_i \cdot (\phi_i - \zeta_i) \quad (1)$$

where: k_i is the torsional stiffness coefficient, ϕ_i is the rocker position angle, ζ_i is the rocker mounting angle;

- in the 1st, 2nd and 6th road wheel, the action of rotary damper was modeled using torsional damping in the rotational axis of the hydraulic shock absorber; the shock absorber arm is connected to the suspension rocker arm by rocker-shock absorber link; these bodies are connected by an ideal spherical kinematic pair (S) in order to reduce redundant constraints; torque M_c occurring in the j-th constraint placed in rotary dampers' position, was determined according to the equation

$$M_{cj} = -c_j \cdot \dot{\psi}_J \quad (2)$$

where: c_j is the torsional damping coefficient and $\dot{\psi}_J$ is the time derivative of the shock absorber arm position angle ψ;

- the fast tracked vehicle simulation model has 30 DoF (degrees of freedom);
- interaction between road wheels and ground was modeled using contact model with Adams default parameters [34];
- the mass of the track was reduced to the mass of the vehicle hull (this methodology is known, among others, from [35], where it was shown that such a simplifying assumption does not affect the results of the vehicle response to kinematic excitation when conducting computer simulations of the dynamics of suspensions of fast tracked vehicles using the multi-body method);
- ground profile constitutes the kinematic excitation q;
- demining device is attached in front of the mine-clearing vehicle (fast tracked vehicle);
- the model of demining device consists of a demining wheel (disc), a guiding element and a section frame;
- the demining wheel was modeled as a rigid, non-deformable disc;
- disc guiding element was modeled as single rigid link, connected on one side by revolute joint to the section frame, and on other by a revolute joint to the disc;
- the demining device is connected to the vehicle model via interface brackets between the section frame and the vehicle hull, defined as kinematic constraints that take away six degrees of freedom (three translational and three rotational).

The values of main parameters of the simulation model of a fast tracked vehicle with a single demining section are presented in Table 1.

The parameters of the developed simulation model of a fast tracked vehicle were determined on the basis of experimental research available in the literature [36, 37]. On their basis, a validation process was also carried out. The experimental tests involved driving the vehicle at a set speed through an obstacle with specified geometry (Fig. 3a). During the test, the displacement, velocity and acceleration of markers placed on the vehicle's hull were recorded. The experiment conditions were repeated in the simulation, using an obstacle with the same dimensions and the same speed as in experimental studies (Fig. 3b).

The curves obtained in simulation studies were compared with experimental curves [37]. The validation results are presented in Figure 4.

Table 1. Values of main parameters of the model of a fast tracked vehicle with a single demining section

Type	Parameter value
Demining disc mass	m_D = 500 kg
Demining disc mass moment of inertia	I_{xD} = 2,16 · 10^7 kg·mm^2 I_{yD} = 4 · 10^7 kg·mm^2 I_{zD} = 2,16 · 10^7 kg·mm^2
Demining disc diameter	d_D = 800 mm
Vehicle hull mass	m_H = 40 000 kg
Vehicle hull mass moment of inertia	I_{xH} = 6,6 · 10^{10} kg·mm^2 I_{yH} = 1,5 · 10^{11} kg·mm^2 I_{zH} = 2,07 · 10^{11} kg·mm^2
Demining device frame body mass	m_F = 500 kg
Demining disc guiding element body mass	m_G = 20 kg
Road wheel mass	m_{W1} = m_{W2} = … = m_{W6} = 190 kg
Road wheel mass moment of inertia	I_{xw1} = I_{xw2} = … = I_{xw6} = 9,21 · 10^6 kg·mm^2 I_{yw1} = I_{yw2} = … = I_{yw6} = 1,79 · 10^7 kg·mm^2 I_{zw1} = I_{zw2} = … = I_{zw6} = 9,21 · 10^6 kg·mm^2
Road wheel diameter	d_{W1} = d_{W2} = … = d_{W6} = 750 mm
Rocker arm body mass	m_{R1} = m_{R2} = … = m_{R6} = 60 kg
Rocker arm length (between revolute constraint position points)	l_{R1} = l_{R2} = … = l_{R6} = 250 mm
Rotational stiffness of the torsion bar	k_1 = k_2 = … = k_6 = 17 · 10^6 N·mm/rad
Equivalent damping coefficient of the rotational damper	c_1 = c_2 = c_6 = 2,662 · 10^6 N·mm·s/rad

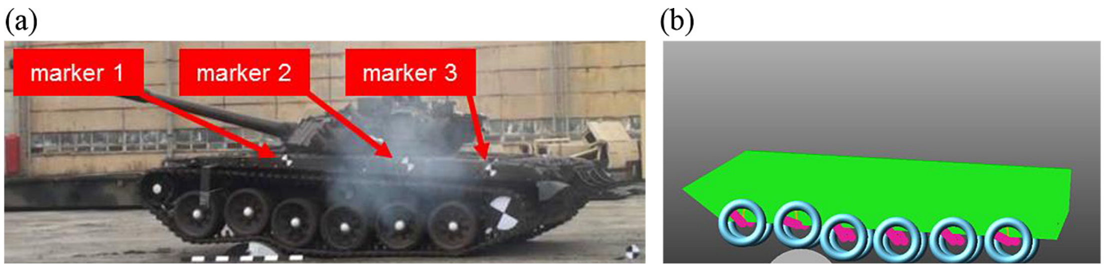

Figure 3. Validation method of the developed simulation model of a fast tracked vehicle: (a) method of conducting the experiment [37]; (b) simulation of driving through an obstacle with the same dimensions

The presented simulation results show high consistency in terms of both acceleration oscillation signal value and time period, compared to the experiment. The following indicators were used to assess the reliability of the model results with the experiment:

- mean relative error $\bar{\delta}_r$ = 9%;
- mean absolute error $\bar{\delta}_a$ = 0.2 m/s^2;
- Pearson correlation coefficient ρ = 0.73.

The obtained results show that the developed model of the fast tracked vehicle is reliable and can be used for simulation tests of the effectiveness of the use of demining rollers. The interaction between the demining disc and the ground was modeled using a contact constraint of the IMPACT type, in which contact parameters are defined. This methodology is known from the scientific studies [38, 39], where researchers modeled the interaction of rigid wheels with the ground in a multi-body environment. The IMPACT contact is described [40] as

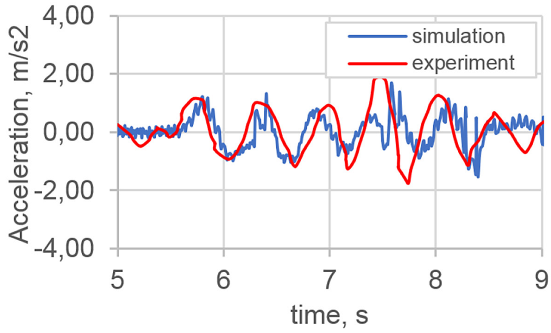

Figure 4. Results of validation of the simulation model of a fast tracked vehicle (acceleration in the vertical direction of marker 1, v = 4 km/h)

$$\text{IMPACT}\ (x, \dot{x}, x_1, k, e, c_{max}, d) \quad (3)$$

where: x – distance variable describing the instantaneous distance between the model's bodies, $\dot{x}$ - time derivative of x to IMPACT, x_1 – positive real variable that specifies the free length of x (the minimum value of the distance between the bodies at which the normal contact force is not yet calculated, k – stiffness of the boundary surface interaction, e – exponent determining the shape of the force deformation characteristic, c_{max} – maximum value of damping coefficient, d – boundary penetration at which full damping c_{max} is applied.

The arguments x, ẋ, and x_1 are computed numerically for each integration step. The remaining ones are determined at the stage of numerical contact definition. Table 2 lists the values of main parameters used to describe the IMPACT disc-ground contact model. The normal contact force F is expressed using the following formula [34]:

$$F = \begin{cases} 0 \text{ if } x > x_1 \\ k(x_1 - x)^e - c_{max}\dot{x} \cdot \text{STEP}(x, x_1 - d, 1, x_1, 0) \text{ if } x \leq x_1 \end{cases} \quad (4)$$

Frictional forces between demining disc and ground at contact location are modeled based on the Coulomb friction principle using a relatively simple velocity-based friction model. The coefficient of friction μ is determined by function based on specified parameters. These parameters include the static friction coefficient μ_s, the dynamic friction coefficient μ_d, stiction transition velocity v_s, and the friction transition velocity v_d. The function follows cubic step functions from respectively $-\mu_d$ to $-\mu_s$, $-\mu_s$ to $+\mu_s$ and $+\mu_s$ to $+\mu_d$. Value of the coefficient of friction μ is expressed by following equation

$$\mu(v) = \begin{cases} -\text{sign}(v) \cdot \mu_d \text{ for } |v| > v_d \\ -\text{step}(|v|, v_s, \mu_s, v_d, \mu_d)\text{sign}(v) \text{ for } v_s < |v| < v_d \\ \text{step}(v, -v_s, \mu_s, v_s, -\mu_s) \text{ for } -v_s < v < v_s \end{cases} \quad (5)$$

Table 2. Values of main parameters of the demining disc-ground IMPACT contact model

Type	Parameter value
Contact stiffness	k = 800 N/mm
Contact damping	c_{max} = 40 N·s/mm
Contact force exponent e	e = 1.1
Contact penetration depth	d = 0.1 mm
Static friction coefficient	μ_s = 0.8
Dynamic friction coefficient	μ_d = 0.5
Stiction transition velocity	v_s = 100 mm/s
Friction transition velocity	v_d = 1000 mm/s

Validation of interaction between demining disc and ground was carried out on the basis of experimental research available in the literature [19]. The experimental test involved recording the normal force exerted by the disc while moving on plain surface (Figure 5a) and recording the distance "x" that disc jumped when passing over a single bump, with specified dimension (Figure 5b). The experimental conditions were recreated in a simulation, in two variants with a roller weighing 253 kg (as in [19]), and a roller weighing 500 kg (as in the developed model of a fast tracked vehicle with a single demining section). By selecting the IMPACT contact parameters (the final values are listed in Table 2) and using the eccentric position of the center of mass of disc, the experimental and simulation results were consistent, which is confirmed by the data presented in Figure 6 and Table 3. For the same simulation parameters, the 253 kg and 500 kg roller model generates similar results and is consistent with the experimental data from the reference object in the literature. It follows that the simulation model correctly and equivalently describes the wheel-ground interaction.

A simulation study of the demining roller section was carried out for five types of terrain profiles:

- incidental – a bump-type convex irregularity (Figure 7a) with a length of 70 cm and a height of 7 cm, representing a special case of a ground profile with a mine laid in the center of irregularity;
- incidental – a pothole-type concave irregularity (Figure 7b) with a length of 80 cm and a depth of 7 cm, representing a special case of a ground profile with a mine laid in the center of irregularity;
- periodic – a sinusoidal profile (Figure 7c) with an amplitude of 10 cm and wavelength of 4 m, representing the profile of a dirt road after multiple passes with wheeled and tracked vehicles [41, 42];
- periodic – a sinusoidal profile (Figure 7d) with an amplitude of 10 cm and wavelength of 7 m, representing the profile of a dirt road after multiple passes with wheeled and tracked vehicles [43, 44];
- random – implementation of a single random profile (Figure 7e), determined based on the ISO 8608 standard, generated using Adams/Tire software [45, 46].

During simulations, the mentioned irregularities constituted the kinematic excitation q during

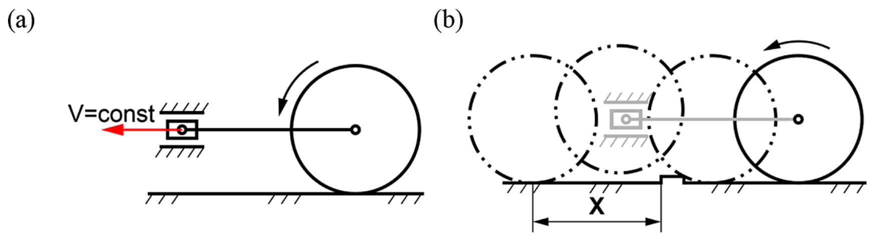

Figure 5. Method of conducting of experimental study of demining disc: (a) moving on plain surface; (b) passing over a single bump

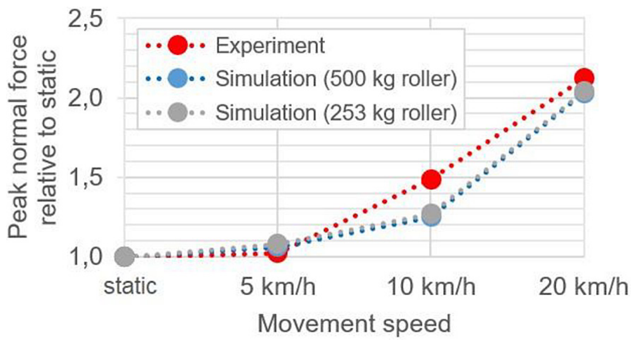

Figure 6. The ratio of the peak normal force of demining disc to the static value on flat surface

Table 3. Results of validation of the simulation model of interaction between demining disc and ground

Speed	Distance that disc jumped "x"		
	Experiment [19]	Simulation (500 kg roller)	Simulation (253 kg roller)
10 km/h	~ 0 m	0.059 m	0.067 m
20 km/h	1.2 m	1.163 m	1.147 m

the movement of the mine-clearing vehicle with attached demining section along the test track at a set speed. The study included conducting tests with four driving speeds: 4, 8, 12 and 16 km/h.

RESULTS AND DISCUSSION

To evaluate the effectiveness of the demining rollers with rigid wheels, i.e. the possibility of mine pressure fuse activation during route clearance operations with different speeds and on different terrain profile and roughness, the indicator of the minimum obtained pressure force of the demining disc while passing over an obstacle or test track was used. In certain anti-tank mines with a pneumatic fuse, in addition to the pressure force, the time of action of this force on the fuse is also essential. Therefore, in the simulation of incidental unevenness (bump and pothole) passing, the value of the impulse exerted over a distance of 15 cm relative to the center of the bump was also analyzed. Figure 8 shows the method of determining the distance at which the force impulse was determined. In this study, the impulse was defined as the product of the contact force and the time of this force (the impulse represents the area under the curve on the force plots, during the time of the disc's impact on the mine fuse), according to the following equation

$$J_F = \int_{t_1}^{t_2} F(t)dt \tag{6}$$

As a result of the simulation tests, the curves of normal forces exerted by the roller as a function of displacement relative to the center of the unevenness (for bump and pothole tracks) or relative to the start of the test track (for sinusoidal and random tracks) were obtained (Figures 9, 11, 13, 15, 18).

In the case of negotiating a single bump-type convex unevenness, the recorded values show that when the demining disc drives over the obstacle, the normal force increases first, and then decreases in the area of the center of the unevenness (Figure 9). As the speed increased, a decrease in the normal force in the area of the center of the

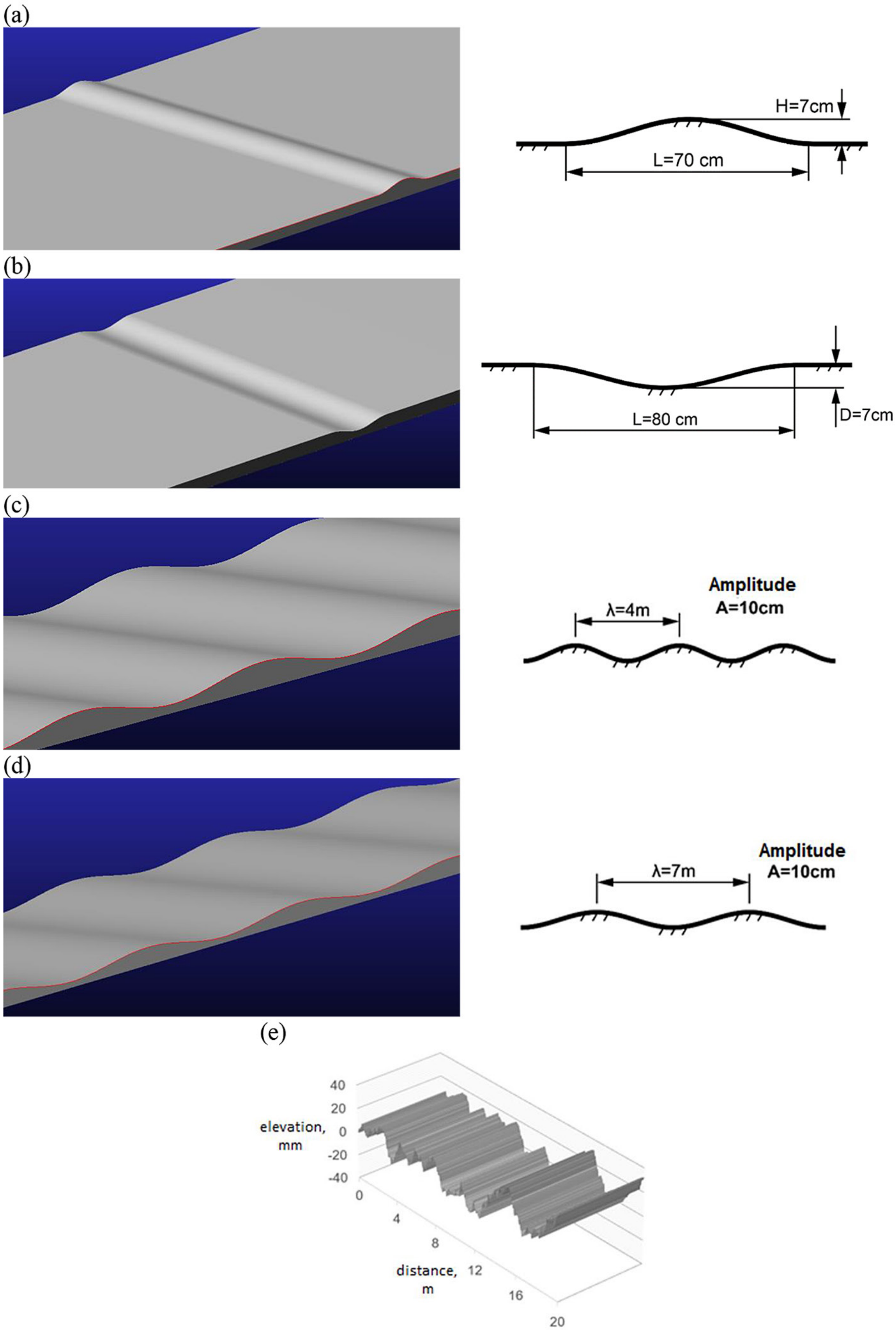

Figure 7. Shape and dimensions of selected test tracks for testing the effectiveness of demining roller

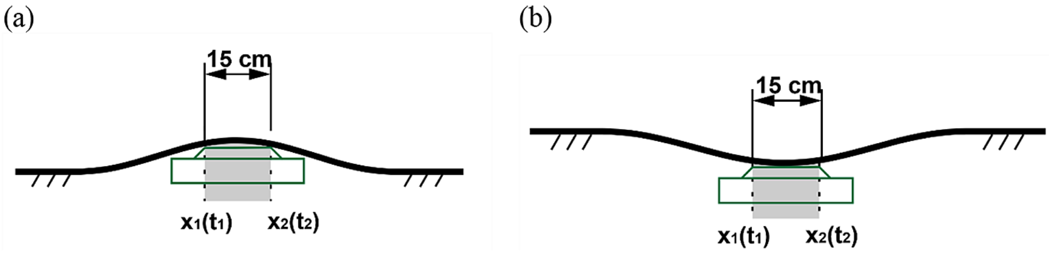

Figure 8. Method of determining the distance to determine the value of impulse exerted by the roller: (a) on a bump-type unevenness; (b) on a pothole-type unevenness

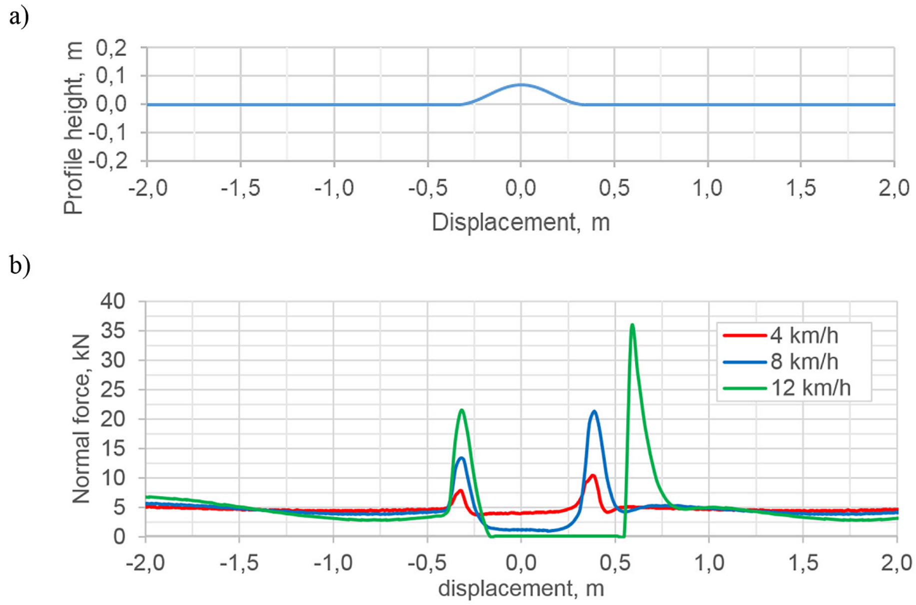

Figure 9. Values of normal forces exerted by the roller in relation to the distance to the center of bump-type unevenness: (a) terrain profile; (b) force variation graphs

unevenness was observed, caused by the inertia of the demining disc. At 12 km/h, there was a tendency for the roller to bounce in the air, therefore the test was abandoned for a speed of 16 km/h.

Figure 10 shows a graphical comparison of the changes in the assessment indicator values depending on the speed of passing over a single bump-type convex unevenness. The results of the tests show that at 8 km/h the normal force F is lower than mine activation force (at a distance of 34 cm, determined from Figure 9). At a speed of 12 km/h the normal force decreases to zero at the distance of 71 cm. It was found that two-fold increase in driving speed from 4 to 8 km/h leads to decrease of the impulse almost ten-fold. At 12 km/h, due to the tendency for the roller to bounce into the air, impulse is zero.

During the simulation of passing over a pothole-type unevenness, when the obstacle is driven over, the normal force exerted by the roller decreases, then increases in the area of the center of the unevenness and decreases again when driving off the obstacle (Figure 11). As the speed increased, this phenomenon intensified due to the inertia of the demining disc. At 12 km/h, the demining disc was already observed to bounce in the air, therefore, similarly to the case of the bump-type obstacle, the test was abandoned for a speed of 16 km/h.

The results of simulation of passing over a single pothole-type concave unevenness (Figure 12) show that at 8 km/h the normal force F is lower than mine activation force (at distance of 17 cm). At a speed of 12 km/h the normal force decreases

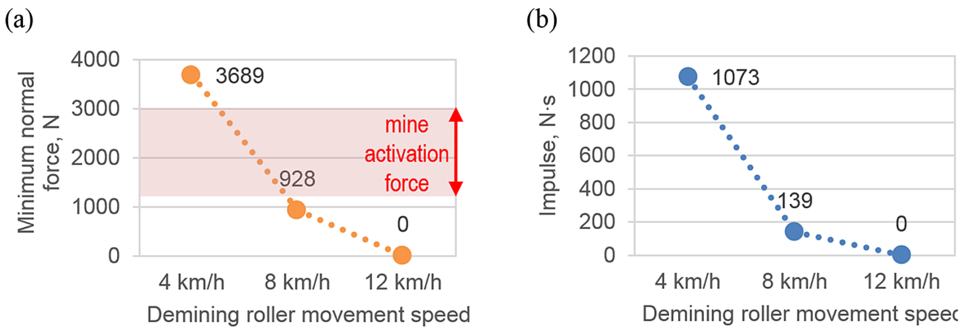

Figure 10. Changes in the values of indicators for assessing the effectiveness of the demining section while passing bump-type unevenness: (a) the influence of speed on the value of the demining roller normal pressure force; (b) the influence of speed on the value of the impulse

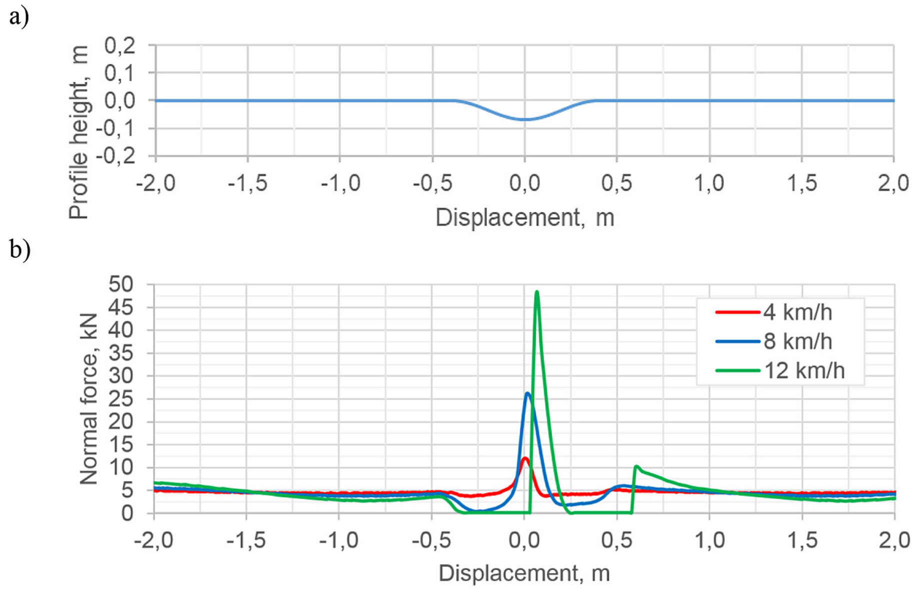

Figure 11. Values of normal forces exerted by the roller in relation to the distance to the center of pothole-type unevenness: (a) terrain profile; (b) force variation graphs

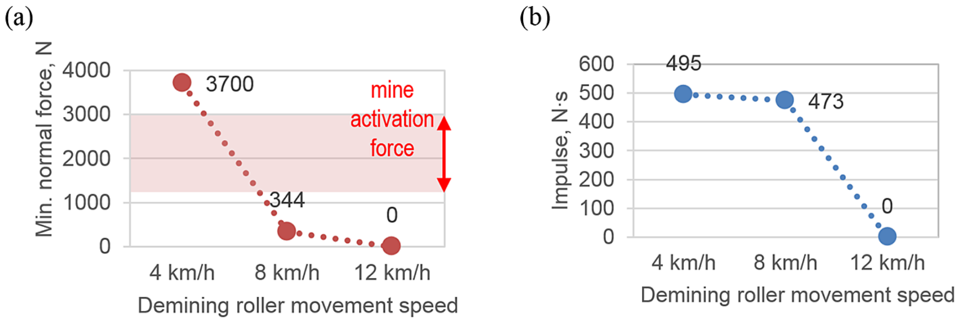

Figure 12. Changes in the values of indicators for assessing the effectiveness of the demining section during passing pothole-type unevenness: (a) the influence of speed on the value of the demining roller normal pressure force; (b) the influence of speed on the value of the impulse

to zero twice, at a distance of 33 and 36 cm. The conducted test shows that increase in driving speed from 4 to 8 km/h does not significantly affect the impulse value. At 12 km/h, due to tendency for the roller to bounce twice, impulse is zero.

The recorded values during the simulation of the vehicle's passage with the demining section through a sinusoidal ground profile (with an amplitude of 10 cm and a wavelength of 4 m) show that with the distance traveled, the normal force alternately increases and decreases, relative to the value in static conditions (Figure 13). An increase in the travel speed causes the phenomenon to intensify. At a speed of 16 km/h, the demining disc was repeatedly observed to bounce in the air due to its inertia.

The simulation test of passage through a sinusoidal ground profile (with an amplitude of 10 cm and a wavelength of 4 m) shows that at 4 and 8 km/h, the minimum required force to initiate the explosion of an anti-tank mine is achieved (Figure 14). When driving at a speed of 12 km/h the normal force at certain points drops below the fuse activation value. During the simulation of driving at a speed of 16 km/h, due to regular tendency for the roller to bounce into the air (during the simulation, a distance of 95 cm, 117 cm and 107 cm was recorded) the minimum normal force is zero.

In the case of passing through a sinusoidal ground profile (with an amplitude of 10 cm and a wavelength of 7 m), the recorded values show that, similarly to the previous case, the normal force exerted by the roller increases and decreases with the distance traveled (Figure 15). At a speed of 16 km/h, the demining disc bounce in the air multiple

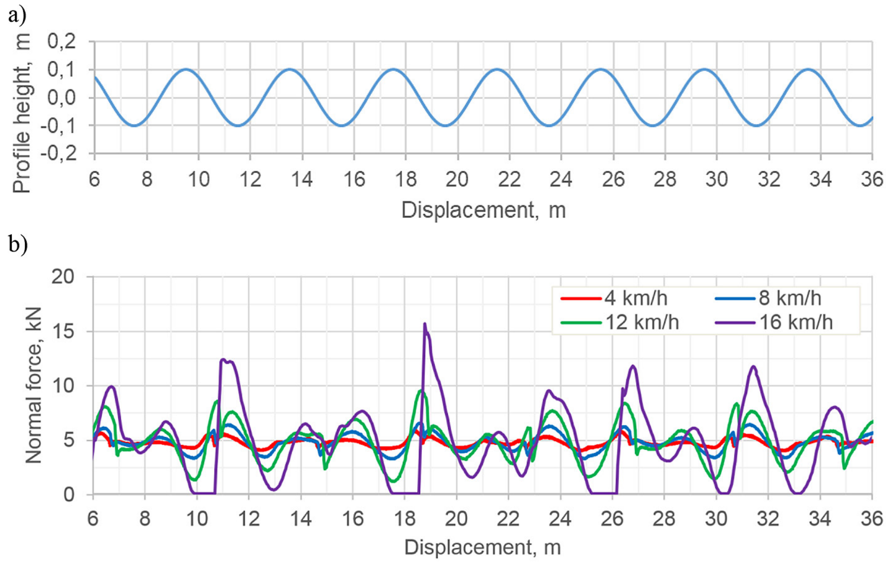

Figure 13. Values of normal forces exerted by the roller in relation to the distance to the start of the sinusoidal test track (wavelength 4 m): (a) terrain profile; (b) force variation graphs

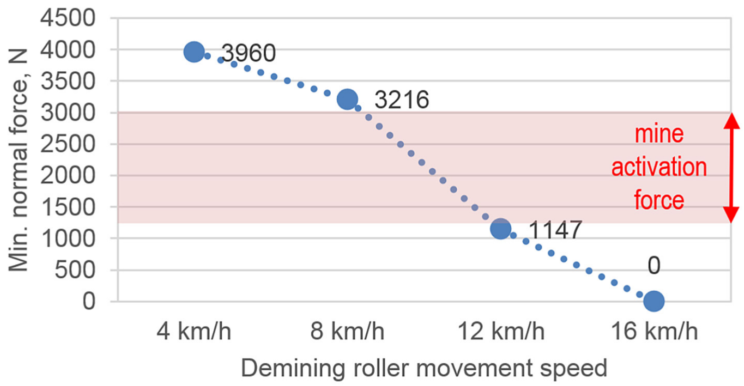

Figure 14. The influence of speed on the value of the demining roller normal pressure force during passing over a sinusoidal ground profile (with an amplitude of 10 cm and a wavelength of 4 m)

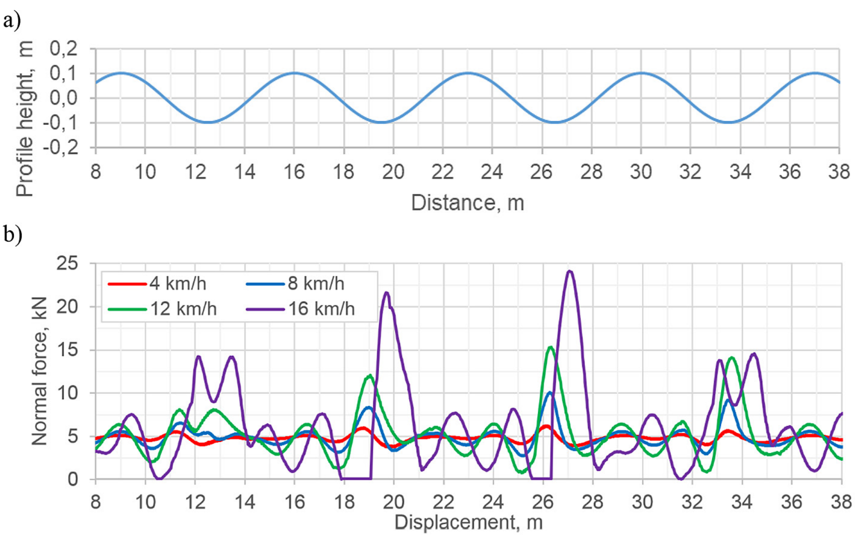

Figure 15. Values of normal forces exerted by the roller in relation to the distance to the start of the sinusoidal test track (wavelength 7 m): (a) terrain profile; (b) force variation graphs

times. Analysis of the simulation result showed that the phenomenon of the roller bouncing results mainly from the resulting “hull pitching” of the fast tracked vehicle hull and a simultaneous momentary increase in the inclination of the element towing the disk section (Figure 16). Hull pitching is the response of the dynamic system (vehicle body with suspension elements) to kinematic excitation such as ground unevenness. The results of simulation of passing over a sinusoidal ground profile (with an amplitude of 10 cm and a wavelength of 7 m) show that at 4 km/h the minimum mine activation force is achieved (Figure 17). The study shows that at 8 km/h, the normal force is lower than the activation force of selected mines. However, at 12 km/h the normal force is lower than the activation force of any mines. It was found, that at 16 km/h, due to vehicle hull pitching and the increase of demining section inclination, minimum normal force is zero (during the simulation, a distance of 113 and 78 cm was recorded).

During the simulation of passage through a random road profile, normal force of the demining roller irregularly oscillates around the static value along with the distance traveled (Figure 18). At a speed of 16 km/h, the demining disc is repeatedly bounced in the air due to its inertia.

The analysis of the results of the simulation of passing over random profile test track (in accordance with the ISO 8608 standard for category H) shows that at 4 km/h the minimum mine activation force is achieved (Figure 19). At 8 km/h normal force decreases below the value of the activation force of any mines. At 12 km/h the normal force at certain points decreases to zero. The study shows, that at 16 km/h, due to inertia of the disc and its tendency to bounce, it was recorded that normal force is zero over a distance of 26, 73 and 51 cm.

The simulation tests carried out showed that the speed of movement significantly limits the operational properties of the demining rollers with a conventional structure with rigid wheels, without

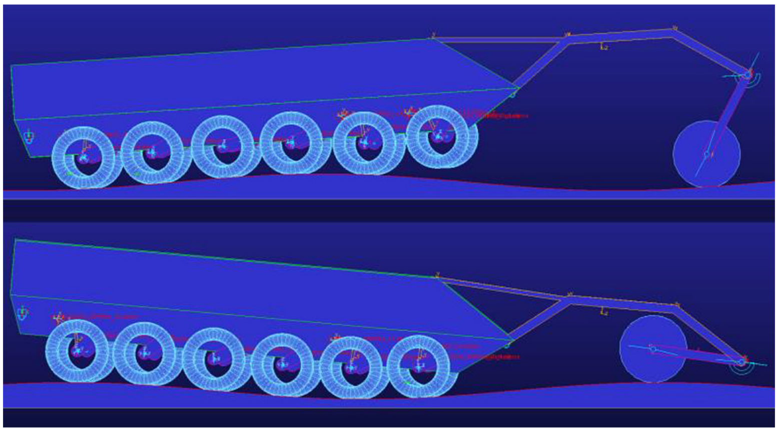

Figure 16. Simulation sample – fast tracked vehicle hull pitching affecting the decrease in the normal force exerted by roller when passing through a sinusoidal profile (wavelength 7 m)

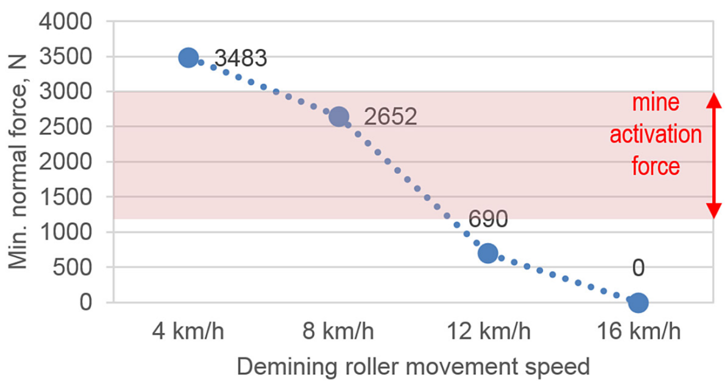

Figure 17. The influence of speed on the value of the demining roller normal pressure force during passing over a sinusoidal ground profile (with an amplitude of 10 cm and a wavelength of 7 m)

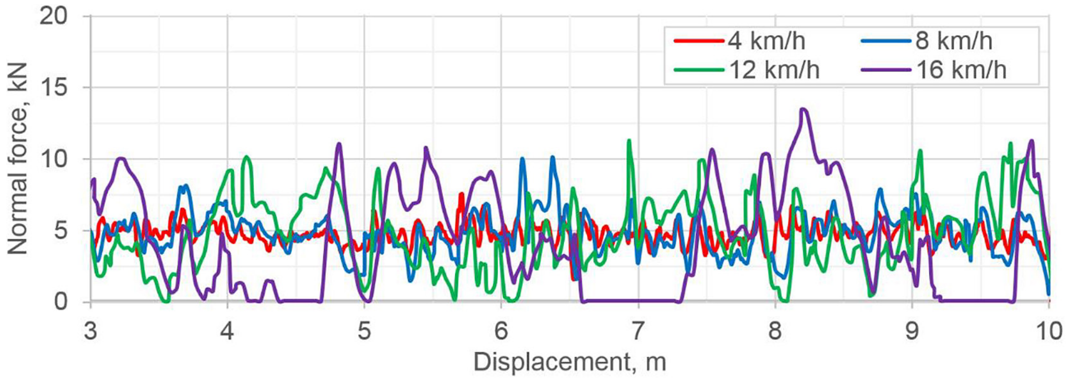

Figure 18. Values of normal forces exerted by the roller in relation to the distance to the start of random profile test track

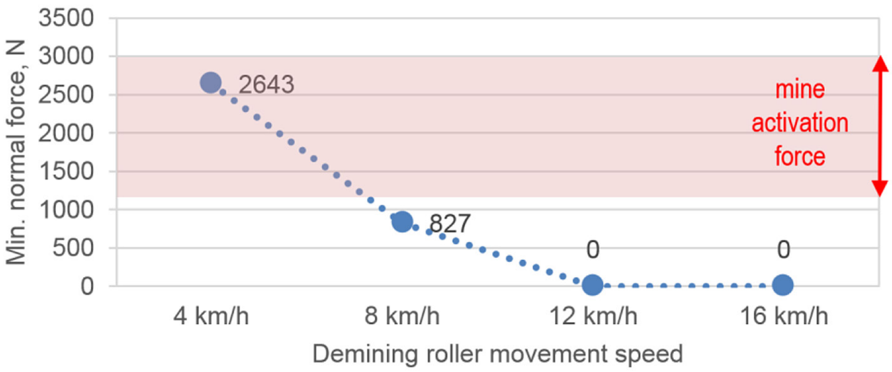

Figure 19. The influence of speed on the value of the demining roller normal pressure force during passing over random profile test track

an additional ground pressure system. In each of the analyzed cases, up to a speed of 4 km/h, the normal pressure forces assume the minimum values required to activate the anti-tank mine fuse. At 8 km/h, there is contact between disc and ground, but the normal forces decrease below the required value, which may result in not cleaning all types of mines or in the complete lack of demining effectiveness. At a speed of 8 km/h, the phenomenon of an intense reduction of the exerted impulse (disproportionate to the increased speed) was identified. At a speed of 12 km/h and higher, the phenomenon of wheels bouncing was identified, which results in a complete lack of demining effectiveness (at such a moment, both the normal pressure force and the impulse value become zero).

The conducted research revealed limitations in the use of conventional demining rollers with rigid wheels, without an additional system of pressing elements. Despite their main advantage related to resistance to multiple anti-tank mine explosions, the proven maximum speed limit may constitute a significant limitation in the area of use in military operations. A lower movement speed increases the time required to conduct route clearance operation and may potentially expose the crew or equipment to enemy fire. On the other hand, the use of demining rollers at higher speeds may result in the mine not detonating, i.e. not fulfilling the main purpose for which it was intended.

CONCLUSIONS

The aim of the study was to assess the possibility of mine pressure fuse activation during route clearance operations with different speeds and on different terrain profile and roughness. For this purpose, tests were conducted using multibody simulations using an advanced model consisting of a fast tracked vehicle with an attached demining section with rigid wheels. The normal pressure force of the demining disc and the impulse while passing through a determined ground profile at a determined driving speed were tested. The identified limitation of use of the examined minesweepers can be reduced by using demining rollers which construction includes a system of pressing components, e.g. in the form of a suspension with linear or non-linear elastic or elastic damping elements. Elastic suspension can potentially prevent the demining wheels from detaching from the ground on uneven terrain. In such solution, the pressure on the ground is caused by a kinematic system that uses the mass of the demining device or vehicle.

The results of this research indicates the need to conduct further studies on demining roller, especially those with elastic or hydrostatic pressure system and deformable wheels, and in particular the influence of the characteristics of the pressure system on the ability to obtain constant and uniform downward force.

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