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Applications in Engineer and Artillery Support: Mathematical Modeling of Symphatetic Detonation

Michal ŠVEHLÍK[1], Martin SEDLÁČEK[2]*, Kamila HASILOVÁ[3], Jan DRÁBEK[1] and Vlastimil ŠLOUF[1]

[1]Department of Fire Support, Faculty of Military Leadership, University of Defence, Kounicova 65, 66210, Brno, Czech Republic
[2]Department of Engineer Support, Faculty of Military Leadership, University of Defence, Kounicova 65, 66210, Brno, Czech Republic
[3]Department of Quantitative Methods, Faculty of Military Leadership, University of Defence, Kounicova 65, 66210, Brno, Czech Republic

*Correspondence: *martin.sedlacek@unob.cz*

Abstract

The work deals with the symphatetic detonation from active to passive charge, which is an area in both engineer and artillery support. The aim of the work is to mathematically model the effect of the active charge on the passive charge due to the variable mass of the active charge and the distance from the active to the passive charge. This modelling is then applicable in all engineer support tasks where explosives are involved. The contribution of the work lies in suggestions for the reduction of firing mechanism and also in suggestions for the establishment of passage lines in obstacles. The calculations become the basis for determining proposals for establishing passage lines in minefields by artillery.

KEY WORDS: *fire support, engineer support, explosive charge, regression model, mobility, counter-mobility.*

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1. Introduction

Symphatetic detonation is one way to initiate the explosion of a passive charge. This means that in the context of this activity there will always be two charges - active and passive. The purpose of an active charge detonation is to transfer sufficient initiating pressure to the explosive in the passive charge. This design can be used in military work as well as in the civilian sphere [1]. As a rule, this is done depending on the sensitivity of the detonator which is embedded in the passive charge [2]. The detonator contains a sufficient quantity of the primary explosive which is capable of transferring the explosion to the secondary explosive of the detonator and thus serving as the initation for the entire charge. Primary explosives are generally very sensitive to external stimulus. This can be caused by either an external mechanical stimulus (impact, shock, friction) or by the delivery of energy (heat, spark) [3].

The aim of this work is to calculate and extend the data for symphatetic detonation. Currently, these data are limited to only a few values [4]. As the war in Ukraine shows further possibilities of using munitions (mobility and counter-mobility tasks) it is appropriate to consider data with active charge weights approaching artillery, engineer (e.g. engineer mines) and aerial munitions (from 5 kg).

Artillery, rocket or e.g. aerial ammunition is one of the options for active charges. Passive charges may be those explosives which contain a detonator. These are engineer munitions (e.g. mines, charges). Symphatetic detonation without a detonator in a passive charge is also possible, but the distance between these charges is significantly reduced. However, this correlation is not the aim of the paper.

2. Methodology

Authors used the basic scientific methods for processing and analysing the available sources of information and drawing conclusion. The values are examined using a linear regression model, which provides a basic estimate of the

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dynamics of detonation transport. The estimation of the true model is determined using bootstrap sampling from a uniform distribution.

The values examined are based on a literature search where the authors focused on mathematical modelling of detonation transfer and its application to the creation of passages in minefields by artillery fire and engineer work. The fundamental source is the regulation *Žen-2-6 Demolition works* [4], which defines the currently set procedures and safety standards for engineer work with explosives. Key literature sources are the professional books *Mathematical Modeling and Simulation. Introduction for Scientists and Engineers* [5], which focus on the theoretical aspects of mathematical modeling and statistical methods in engineering. Based on this information, the authors developed appropriate mathematical models for detonation transfer. Scientific publications *Creating of Minefield Breaches with Artillery* [6], Multiple round simultaneous impact fires and possibilities of its application in Czech Army [7], *Selection of Mobility Support Engineering Devices of NATO Armies Usable in the Czech Armed Forces Combat Operations* [8], *The Evaluation of the Possibilities of New Organizational Structures of Engineer Troops in the Field of Engineer Mobility Support* [9] and *Influence of Quality of Remote Sensing Data on Vegetation Passability by Terrain Vehicles* [10] provide an overview of innovative technologies and new methods leading to increased efficiency of engineer work, including the creation of passages in minefields using land artillery forces. In the development of the models, the authors make use of the data from article *Modelling fragmentation of a 155 mm artillery shell IED in a buried mine blast event* [11], where a numerical model of artillery munition fragmentation is described.

3. Combat Support

Combat support units make conditions for combat forces in selected tactical activities and thus form temporary task groups whose structure corresponds to the task to be performed. In the conditions of the Czech Armed Forces (CAF) it is usually in the strength of a battalion or brigade task group. They support mobility, counter-mobility or survivability. This enables faster, safer and more complex task execution by individual soldiers or units of the combat forces. Combat support units are limited in the activities they perform by their organic equipment and are thus augmented, supplemented, or supported by combat support force assets. Depending on the nature of the support, they are responsible for determining the mission and prioritizing the tasks to be performed. Combat support units retain responsibility for selecting the mode and execution of support in accordance with established priorities.

The symphatetic detonation can be used by units of combat forces in certain circumstances (e.g. demolition of objects of a smaller nature, especially in built-up areas, demolition of enemy equipment, during mobility measures – passage in an obstacle, etc.). This activity, as well as the method of rapid demolition, is particularly useful in those places and tasks where the units are limited by time, the amount of ammunition and the establishment of more demanding firing mechanism.

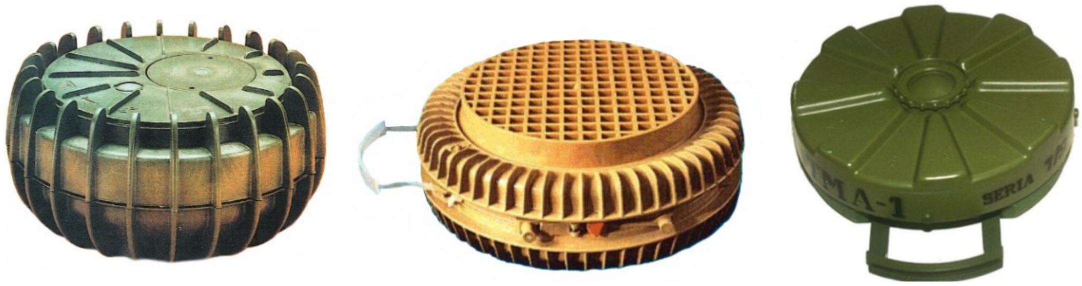
3.1 Engineer Support

One of the specialized tasks of engineer units is to support other units by performing demolition operations to achieve the intended effect of combat or support of the firing system. Demolition work can be divided according to the complexity of the work. There is simple demolition work, which is mastered by members of the combat forces, and more complex demolition work, which is only within the expertise of engineer units. However, symphatetic detonation is a method of initiation and can be applied in any range of demolition work.

In military engineering, the symphatetic detonation can be used, provided that the distance is shorter and auxiliary firing mechanism is lacking. On the other hand, this activity requires a greater number of detonators, as each must be in a single charge. Detonators contain a primary explosive that is sensitive to the transfer of energy and pressure from the active to the passive charge. Examples of the use of symphatetic detonation include the demolition of timber piles, structural elements of bridges and buildings, disposal of ammunition, etc.

In the context of the troop workload, engineer support may not be sufficient, and therefore it is advisable to look for other means of support [9]. One such capability is the ability to establish passages in explosive obstacles. By this is meant minefields, booby traps, or improvised explosive devices. A passage in minefields can be established manually, mechanically, or by remote means. Each of the options involves the use of explosives, and this is done through, for example, rocket-propelled deminers, explosive deminers, or towed charges [8]. The war in Ukraine shows that minefields are usually of non-standardized size and type, they also contain booby traps, and therefore establishing a passage, let alone conducting a full area mine clearance, is very problematic. There are not enough demining assets in this war, especially for first-line combat, and Ukraine is and will be supplied by NATO states with artillery ammunition. These are munitions of different calibre, with different fuzes and different predeterminations. The fact remains that the establishment of a passage in obstacles can also be implemented by artillery fire, where can be used of symphatetic detonation. The engineer units can then be used for other tasks and, above all, human resources are not exposed to such danger from enemy fire.

Engineer mines retain some similar characteristics, namely the body and the explosive charge, while the fuze may be of a different nature. The body of the mine is made of various types of plastic, metal or wood. Mines produced today are usually with a plastic body (see Figure 1). Manufacturers produce mines with different thicknesses and may also support the structure with struts or ribbing. This will then vary the mine's resistance to overpressure at the pressure wave front. The explosive charge contains explosives which are themselves resistant to mechanical and energy stimulus compared to primary explosives. Thus, a mine can go into detonation in two ways (in addition to the conventional detonator method): 1) by applying initiating pressure to the primary explosive of detonator or 2) by applying sufficient initiating pressure directly to the explosive charge of the mine itself. In both cases, however, it is necessary that the initiating pressure of the active charge deforms the mine body and also makes symphatetic detonation either to the detonator or directly to the explosive charge of the mine itself.



(a) Andrushy Landmine (b) MATS-2 Landmine (c) TMA-1 Landmine

Fig. 1. Selected anti-vehicle mines with plastic body

3.2 Fire Support

A possible way of creating passages in minefields is to use artillery fire. It is in this context that the problem of transfer of detonation from active to passive charges can be applied in the field of artillery fire support. The transfer of detonation is one of the important factors enabling the evaluation of effectiveness and determination of artillery ammunition consumption for this method of overcoming explosive roadblocks.

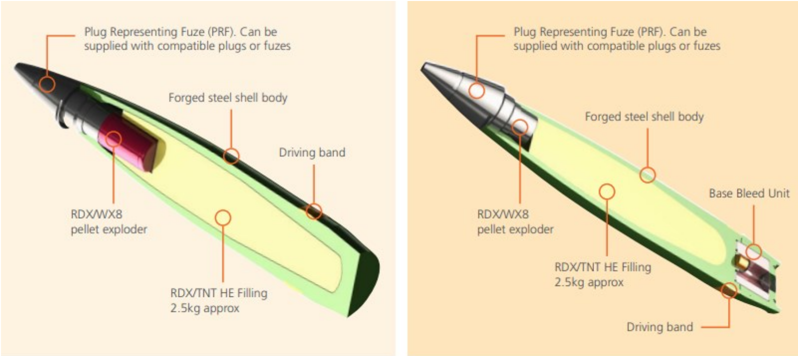
Artillery units in Ukraine have a wide range of ammunition available, both in standard NATO calibers (155 mm, 81 mm, etc.) and in calibers of Eastern provenance (152 mm, 122 mm, 120 mm, etc.). Artillery ammunition can be fitted with different types of fuses. The types of fuzes are impact, delayed, non-contact and smart fuzes The function of the fuzes can have a high impact on the detonation transfer capability. The choice of the type of projectile fuze will depend on the design of the mines used, the size and density of the minefield, and the distance over which the artillery units will conduct fire. Impact or delayed fuzes will be used to destroy roadblocks with buried and more resistant mines. Non-contact fuses may be used to destroy minefields where mines are spread out on the surface and are easily damaged. Smart fuses will be used for small minefields and in situations where artillery units will be destroying minefields at long range. As the firing distance increases, accuracy decreases and smart fuzes will guide the missile to the exact desired location.

Another option to achieve the desired effectiveness in destroying minefields is to conduct the firing mission using Missile Ready Single Impact (MRSI). MRSI is a method of firing in which the weapon fires multiple rounds at different barrel diameters and powder charge sizes within a short time interval and then all the rounds fired in this manner strike the target at the same moment. Artillery units are time-constrained in conducting firing missions in a single firing position because of potential enemy counterbattery activity. The use of MRSI can reduce this risk by reducing the time required to fire the required number of all rounds or, conversely, can increase the number of rounds that can be fired in a specified time interval. [7]

The accuracy of fires also has a direct influence on the effectiveness of creating passages in minefields. At the moment when the artillery units of the Czech army do not have automated artillery, it is necessary to conduct survey of firing positions and subsequent preparation of firing positions [12]. Precision in the preparation of firing positions for artillery and their available quantity contributes in the process of correction calculation for firing with manual methods to remain competitive even among autonomous weapon systems [13]. Last but not least, meteorological data from meteorological units must be included in the calculations. The ability to obtain or produce a meteorological report allows elements to be prepared for firing with such accuracy that effective fire can be conducted without adjusting [14]. In the case where artillery units can fire without adjust fires, the enemy's ability to return fire is limited. In the case of a firing mission with rocket artillery, the enemy air defence response to this fire is reduced and the impact on the target will achieve a higher percentage of success [15].

The design of the standard fragmentation ammunition (Figure 2), which is the basic ammunition of artillery of all armies of the world, shows the large volume of the bursting charge enclosed in the projectile body. The bursting charge can have different compositions, e.g. TNT, TNT in combination with RDX, and act as an active charge when detonated. When the missile is initiated, the detonation will be transferred to the mines in the vicinity of the explosion, thereby achieving their destruction.

In the case of artillery fires on explosive obstacles, it is necessary to assess, in addition to the shrapnel effect, the effect of the symphatetic detonation, which may result in a chain reaction and a subsequent series of detonations [11].



(a) L31 HE (b) XL32E1

Fig. 2. The cross-section of a BAE Systems 105 mm Artillery Shell [16]

4. Symphatetic Detonation

Limitation of the data used in this work is due to the fact that they were created with the assumption of using moulded TNT. For this issue the following principles apply:

- Direct distances between charges without obstruction;
- The detonators are oriented so that their open ends face the active charges;
- The detonator serves as a fuze and is not included in the total weight;
- Symphatetic detonation is valid for land use.

Currently, the limiting values for the distances between active and passive charges are set to lengths between 0.5 m and 2.5 m [4]. The research question for mathematical modelling becomes – how do the variables (charge mass vs. distance between charges) differ for values up to 0.5 m and above 2.5 m? There are cases where symphatetic detonation is not desirable (e.g. own minefields). The opposite is true for situations where the nature of the task requires it (e.g. the demolition of timber piles or enemy minefields [10]).

For any munition, it is necessary to convert its explosive composition to the equivalent of moulded TNT (coefficient 1). This is achieved by using the ballistic and sealing coefficients in addition to the explosive efficiency coefficient. This coefficient is particularly necessary to take into account for artillery munitions whose total mass is primarily composed of a metal body.

In the case of artillery ammunition, sypmhatetic detonation may also occur by the detonator being affected by the mechanical stimulus of the shrapnel from the active charge. It is not the purpose of this work to determine the extent, size and spread of shrapnel from the detonation of artillery munitions.

5. Mathematical Modeling of Symphatetic Detonation

The examined data were obtained from a military document dealing with demolition works [1] and their limitation lies in their small quantity and short range. The aim is to construct a model describing the data and to extrapolate the values beyond the given range. Statistical modeling is used to describe the relationship between the weight of the explosive charge and the distance between the active and passive explosive charges.

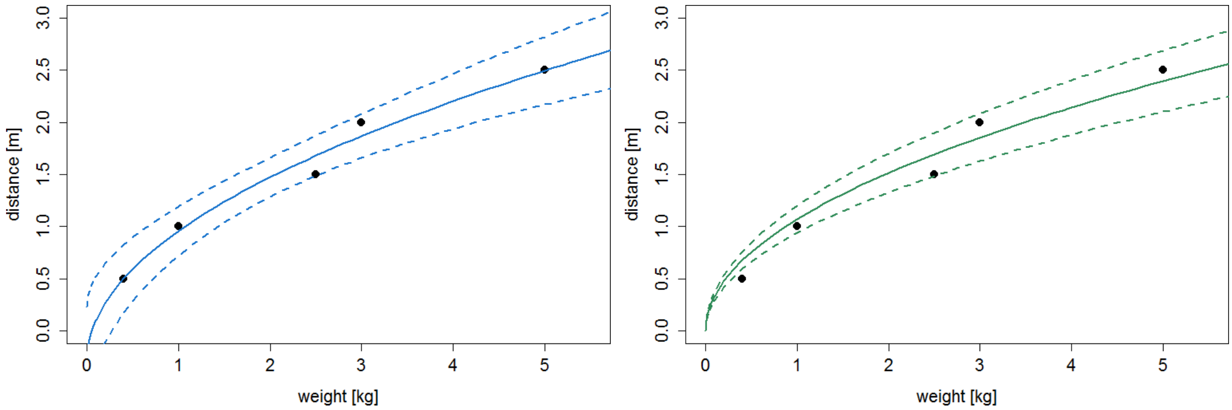
A linear regression model [5] is proposed based on the typical blast characteristics. The distance increases with the increasing weight of the explosive charge, however, characteristics of the environment have to be taken into account, e.g. the decrease of the pressure wave with the increasing distance. Therefore, we applied a linear regression model using a square root function to capture the behavior of the explosive charge: $distance = a + b \cdot (weight)^{1/2}$, where a, b are parameters of the regression function. The regression model based on the measured data is summarized in Table 1.

Table 1.

Linear regression model in its two possible forms

Model	Equation	Model significance	Residual std. error	Coef. of determination
full	$distance = -0.285 + 1.243 \cdot (weight)^{1/2}$	$p = 0.001$	$s = 0.134$	$R^2 = 0.972$
submodel	$distance = 1.071 \cdot (weight)^{1/2}$	$p < 0.001$	$s = 0.163$	$R^2 = 0.990$

In evaluating the square root model, it was found out that the intercept is not statistically significant and a simpler model (i.e., a model without the intercept) could be applied. The summary of the submodel is also included in Table 1 and both models are presented in Fig. 3.



(a) full model (b) submodel without the intercept

Fig. 3. Linear regression models – full model using the square root function (left panel) and its submodel dropping the intercept (right panel), both accompanied by a 95% confidence band (dashed lines).

We can see that both models provide a very satisfactory fit to the data, as shown by the residual standard errors, which are small, and the coefficient of determination, which is close to one. However, for the prediction outside the range of the given data, the two models differ, see Fig. 4, where both models are superimposed. Therefore, to evaluate how the weight of the explosive charge influences the distance for values up to 0.5 m, and especially for the values above 2.5 m, the expert advice or field measurement has to be used.

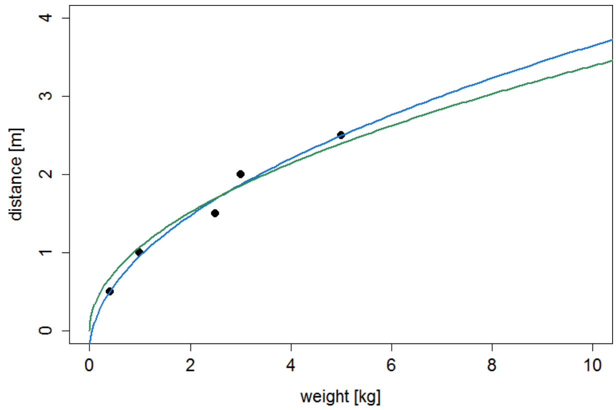


Fig. 4. Extrapolation of the linear regression models – full model (blue line) and its submodel (green line).

6. Discussion

The range, size, and direction of spread of munition fragments (e.g., artillery, rocket, or aerial) mechanically affect passive charges. This means that, although the pressure induced by the explosion of an active charge may not cause symphatetic detonation in a passive charge, it can happen due to the effect of shrapnel [17]. These have a much larger radius of action than the radius of detonation of the explosive. Thus, initiation may occur when a shrapnel hits the pusher disc of an engineer mine. Therefore, the mathematical modelling in this work becomes the basis for further calculations that will also take into account the effects of shrapnel.

As a first step, it is necessary to verify the mathematical model proposed in Chapter 5. This will be done in the following period on the blasting pit. It becomes the basis for determining the design of procedures and methodologies for establishing passages in minefields by artillery. In particular, they will be used to evaluate theoretical ammunition consumption and to determine the duration of artillery support [].

Furthermore, the dimensions of the detonator body have an influence on the initiation by symphatetic detonation. "Ž" detonators used in the CAF are characterised by their narrow width. In addition, the primary explosive of the detonator is protected by an aluminium cover and the detonator itself is usually held in the detonation receptacle by a detonating screw in the charge. All this reduces the net diameter of the hole to the primary explosive to 2 mm. For symphatetic detonation, on the other hand, it is preferable for the detonator to be closer to the outer edge of the charge, provided that both the primary and secondary explosives are always embedded in the body of the charge, i.e. the detonator is shorter and larger in diameter. This becomes a prerequisite for further investigation and verification of this hypothesis.

7. Conclusions

The results of this modeling study show that the linear regression model with the square root function describes the data quite well and the bootstrap resampling with the uniformly distributed errors characterizes the unknown rounding errors. The resulting lower confidence curve can then be taken as the optimal combination of distance and the weight of the explosive charge. This modeling is then applicable to all tasks of engineer support where explosives are involved. Examples include the disposal of unexploded ordnance, setting up or removing obstacles, and more.

The contribution of the work lies in the proposals for the reduction of detonation nets (counter-mobility) and in the determination of the distance of detonation during the explosion of artillery munitions in the case of establishing passages in engineering obstacles using artillery fire (mobility). Damage of wires is a common failure of a fuze (whether by detonating cord or by electrical fuze). Other benefits include the possibility of applying this predictive model to other types of explosives, thus creating a comprehensive data set for use in military engineering. Currently, there are no explosives that retain the sensitivity of a primary explosive while being as safe as explosives (e.g., trinitrotoluene) against impact, friction, and thermal effects.

Symphatetic detonation is based on the energy transfer and pressure of the explosion. The presence of shrapnel or other fragments is not taken into account. These can, of course, also initiate the detonator in a passive charge. The probability of shrapnel spread location and detonation of the passive charge by shrapnel can then be evaluated statistically. The explosion of active charges also affects the distance of shrapnel spread location with respect to their weight. Thus, artillery fragmentation munitions or hand grenades can become active charges to symphatetic detonation under certain circumstances.

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References

1. **Elshenawy T., Zaky M. G., Elbeih A.** Experimental and numerical studies of fragmentation shells filled with advanced HMX-plastic explosive compared to various explosive charges. Brazilian Journal of Chemical Engineering, 2023, 40 (2), p. 481–492. Springer Science and Business Media LLC. DOI 10.1007/s43153-022-00267-x
2. **Jafari, M., Keshavarz, M. H., Zamani, A., Zakinejad, S., Alekaram, I.** A Novel Method for Assessment of the Velocity of Detonation for Primary Explosives. Propellants, Explosives, Pyrotechnics, 2018, 43 (4), p. 342–347. Wiley. DOI 10.1002/prep.201700276.
3. **Pan, P.-Y., Wang, K.-X., Yi, Z.-X., Zhang, L., Zhu, S.-G.** Recent Advances in Primary Explosives. Hanneng Cailiao/Chinese Journal of Energetic Materials, 2021, 29 (6), p. 557 – 566. DOI 10.11943/CJEM2020264.
4. **Žen-2-6. Demolition works** (in Czech: Trhací práce). Ministry of Defence, Prague, 2024.
5. **Velten K.** Mathematical Modeling and Simulation. Introduction for Scientists and Engineers. Wiley, 2009.
6. **Švehlík M., Šustr M., Potužák L., Varecha J., Drábek J.** Creating of Minefield Breaches with Artillery. In: Proceedings of the 20th International Conference on Informatics in Control, Automation and Robotics – Volume 1: ICINCO, SciTePress, 2023. p. 266–272. DOI 10.5220/0012208500003543.
7. **Šustr M., Potužák L., Blaha M., Ivan J.** Multiple round simultaneous impact fires and possibilities of its application in Czech Army. Vojenské Rozhledy – Czech Military Review. 2020, 29 (4), p. 84–93. ISSN 1210-3292
8. **Cibulová K., Rolenec O., Garba V.** A Selection of Mobility Support Engineering Devices of NATO Armies Usable in the Czech Armed Forces Combat Operations. In: Proceedings of International Conference of Military Technologies Brno 2019. Brno: University of Defence, 2019. Article number 8870016. ISBN 978-1-7281-4593-8.
9. **Rolenec O., Cibulová K., Rolenec O., Zelený J.** The Evaluation of the Possibilities of New Organizational Structures of Engineer Troops in the Field of Engineer Mobility Support. In: Kolar P. 2021. 2021 8th International Conference on Military Technologies. ICMT 2021 – Proceedings. Brno: Institute of Electrical and Electronics Engineers, 2021. ISBN 978-1-6654-3724-0. DOI 10.1109/ICMT52455.2021.9502760.
10. **Rada J., Rybanský M., Dohnal F.** Influence of Quality of Remote Sensing Data on Vegetation Passability by Terrain Vehicles. ISPRS International Journal of Goe-Information, 2020, 9(11), 684. ISSN 2220-9964. DOI 10.3390/ijgi9110684
11. **Rasico J. G., Newman C. A., Jensen M. R.** Modelling fragmentation of a 155 mm artillery shell IED in a buried mine blast event. Vol. 4 [online]. Inderscience Publishers, 2018. DOI 10.1504/ijvp.2018.095752.
12. **Ivan J., Šustr M., Pekař O., Potužák L.** Prospects for the Use of Unmanned Ground Vehicles in Artillery Survey. International Conference on Informatics in Control, Automation and Robotics, 2022. DOI 10.5220/0011300100003271.
13. **Šustr M., Ivan J., Blaha M. Potužák L.** A Manual Method of Artillery Fires Correction Calculation. Military Operations Research, 2022. 27(3), p. 77–94. DOI 10.5711/1082598327377.
14. **Ivan J., Šustr M., Sládek D., Varecha J., Gregor J.,** Emergency Meteorological Data Preparation for Artillery Operations. In: Giuseppina Gini, Henk Nijmeijer, Dimitar Filev. Proceedings of the 20th International Conference on Informatics in Control, Automation and Robotics. Roma, Italy: ScitePress, 2023, Volume 1, p. 250-257. DOI 10.5220/0012205500003543.

15. **Hujer V., Šlouf V. Farlík J.** Utility as a Key Criterion of a Decision-Making on Structure of the Ground Based Air Defence. 2022. DOI: 10.1007/978-3-030-98260-7_15.
16. **BAE Systems.** 105mm Artillery Ammunition Brochure [online]. 2023 [cit. 2024-03-23].
17. **Palasiewicz T., Rolenec O., Kroupa L., Manas P., Coufal D.** Blast-Induced Deformations of the Building Entrance Part Caused by Improvised Shaped Charges. In: Modelling and Simulation for Autonomous Systems. MESAS 2022. Lecture Notes in Computer Science. Cham: Springer, 2023, p. 109–130. ISBN 978-3-031-31268-7. DOI 10.1007/978-3-031-31268-7_7