Sensors

Study of acoustic response of an object buried in sand with different water contents

L.V. Borkovska[1], V.P. Kyslyi[1], V.O. Morozhenko[1], Yu.G. Serozhkin[1], E.O. Soloviev[1], V.M. Nastych[2]

[1]V. Lashkaryov Institute of Semiconductor Physics NAS of Ukraine, 41 Nauky Avenue, Kyiv, Ukraine
[2]State Enterprise for Special Instrument-Building "ARSENAL", 8 Princes of Ostrozki Street, Kyiv, Ukraine
Corresponding author e-mail: l_borkovska@ukr.net

Abstract. The work is aimed at solving the problem of humanitarian demining by creating a laser-acoustic complex using a laser Doppler vibrometer for detecting landmines buried in the ground. The parameters of the acoustic response of a plastic mine simulant buried in sand at different depths were investigated. Dry sand and sand with various moisture degrees (5, 10 and 15%) were used in the studies. Soil vibrations were excited by acoustic white noise. It was found that the vibration spectra of the object buried in soil exhibit several resonances, the amplitude and frequency of which depend on burial depth and soil humidity. Specifically, immersion of the object in the sand resulted in a decrease in the vibrational amplitude and a shift of the resonance frequency. The latter demonstrated non-monotonic dependence on the burial depth. It was established that the nature of the acoustic vibration spectra of the soil surface allows for an unambiguous conclusion about the presence or absence of an object in the soil. The research results make it possible to increase the accuracy of object detection and identification.

Keywords: humanitarian demining, buried landmine detection, laser Doppler vibrometer.

https://doi.org/10.15407/spqeo28.03.367
PACS 42.79.Jq, 42.79.Qx, 43.60.+d, 81.70.Cv

Manuscript received 18.05.25; revised version received 15.07.27; accepted for publication 03.09.25; published online 24.09.25.

1. Introduction

The problem of detecting buried objects is extremely relevant in many areas of human activity, such as construction, environmental monitoring, and archaeological and geological research [1]. This issue is particularly significant in the field of humanitarian demining. Detection of buried explosive objects, especially mines and unexploded ordnance, poses a critically important global challenge, as millions of mines are buried worldwide, creating significant humanitarian and economic burdens. With the onset of the russia's military aggression against Ukraine, the issue of humanitarian demining has also become relevant for our country. According to the official data [2], more than 30% of the country's territory is potentially mined, making Ukraine one of the most heavily mined countries in the world. Many explosive devices have an indefinite service life and can cause death and injury, as well as economic disruption, for decades after the war ends. This creates serious risks to human life, limits access to agricultural land, and hinders recovery of affected regions.

Currently, the most common means of mine detection are electromagnetic metal detectors [3]. Their operating principle involves interaction of an electromagnetic field with a hidden object and the surrounding environment. Despite the numerous types and models of such devices, they share a common drawback: they are ineffective at detecting plastic mines with low metal content [4]. Increasing the sensitivity of the metal detectors makes them overly sensitive to metal fragments, which are often found in mine-contaminated areas, leading to high false alarm rates. Moreover, manual use of electromagnetic mine detectors poses an increased danger to the operator (deminer), who is in close proximity to the explosive object [4]. The dangers and inefficiencies associated with direct human interaction with minefields stimulate the development and implementation of remote, contactless technologies capable of rapidly detecting both metal and non-metal explosive objects. Transition to automated or semi-automated demining processes significantly enhances operator safety and potentially speeds up clearing the area.

At present, there are several methods for mine detection that are free from the aforementioned drawbacks, namely, biological, neutron, optical, thermal imaging, *etc*. [4, 5]. The effectiveness of each method depends on various factors such as soil type, environment, mine type, and weather conditions. Some methods can be used for all types of explosives, while others can only be applied for trinitrotoluene as a filler [5]. In this context, laser-acoustic method using a laser Doppler vibrometer (LDV) is a promising non-contact, safe, and reliable method, capable of detecting various types of buried objects, including plastic mines, with high detection probability and low false alarm rate. This method involves exciting acoustic vibrations in the soil and subsequently measuring the frequency and amplitude of the displacement of the vibrating surface by analyzing the frequency shift (Doppler effect) of the reflected laser beam. When the soil is acoustically excited, the mine vibration produces an anomalous spectrum of surface vibrations directly above it, ensuring reliable detection.

Numerous laboratory and field investigations of acoustic response of real antipersonnel land mines revealed well-defined resonances in the frequency range of 40 to 1000 Hz, which were ascribed to mine's structural resonances [5–16]. The strongest resonances were observed for the mines with relatively compliant upper casing [14–16]. It has been demonstrated that vibrational characteristics of a "soil+burried mine" system (the frequency and amplitude of vibrational resonances) depend not only on the parameters of the hidden mine but also on the burial depth as well as on the physical and deformation characteristics of the soil itself. In particular, soil moisture was found to be an important factor that may affect resonance frequency especially at larger depths [15].

This research focuses on examining the seismic response parameters of a plastic mine simulant buried in sand depending on depth and water content in the sand, to enhance the accuracy of mine detection and identification. This work continues our activity aimed at creating a laser-acoustic complex based on LDV [17]. The complex is intended to investigate the vibrations of soil and buried objects under various conditions As shown in our previous studies as well as the studies of other authors cited above, non-destructive nature, the possibility of remote sensing, and high reliability of detecting various types of buried objects, including plastic mines, confirm that the complex can be useful for use in humanitarian demining.

2. Methodology and experimental setup

The laser-acoustic method of mine detection is based on the phenomenon of acoustic-seismic coupling. When an airborne sound wave reaches a soil surface, part of its energy is converted into seismic waves that propagate through the soil. Buried mines begin to vibrate under the influence of these seismic waves. Essentially, a mine may be considered as a mechanical oscillator with its own resonance frequencies, which are determined by its physical properties (size, shape, material, *etc*.) and the characteristics of the surrounding soil. These resonance frequencies can serve as a unique signature indicating the presence of a mine.

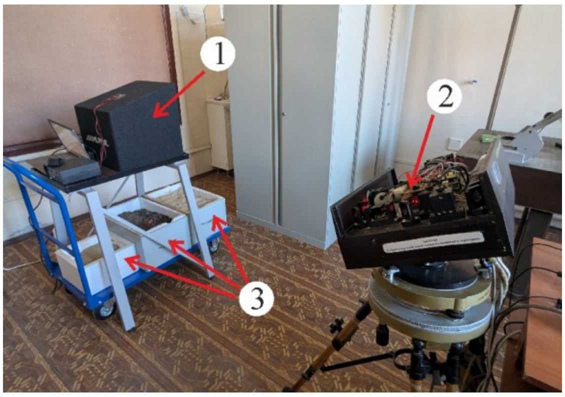


Fig. 1. Photo of the installation for laser-acoustic study of seismic response of objects buried in soil: *1* – loudspeaker, *2* – laser Doppler vibrometer, *3* – containers with soils of different types.

A laser beam from the LDV is directed at the surface under investigation. Movement of the surface causes a change in the frequency of the reflected light, which is then compared with the frequency of the reference beam. As a result of heterodyne detection of these two waves, a frequency difference, which is directly proportional to the velocity of the vibrating surface, is extracted. The output phase-modulated signal is demodulated to obtain information about the vibration frequency and amplitude. The fundamentals of laser Doppler vibrometry are described in detail in [18].

The vibrational spectra of the soil surface as well as of the objects buried in the soil were studied using the developed laser-acoustic complex. Fig. 1 shows a photo of the installation for laser-acoustic study. The laser-acoustic complex is composed of a loudspeaker (*1*), a single-beam homemade LDV (*2*) and containers with soil of different types (*3*).

LDV was mounted on a tripod, allowing for adjustment of the laser beam direction both horizontally and vertically and ensuring that the beam was directed into the soil at the epicenter of the buried object. The LDV had the following parameters: the wavelength of the laser radiation was 0.63 μm (corresponds to the frequency of 473.6122 THz), the power of the probing radiation was 1 mW, and the noise level in the 10 kHz band at a frequency of 1 kHz was ≤ 1 nm. The design of the used LDV is described in detail in [17, 19].

The containers with soil of different types (see Fig. 1) were placed on a cart, enabling quick changes between them. Dry sand and sand with humidity of 5, 10 and 15% were used. The moisture content in the sand was calculated as the ratio of the mass of water to the mass of solid particles, expressed as a percentage. Vibrations in the soil were excited using acoustic white noise in the frequency range of 50 to 1000 Hz delivered through

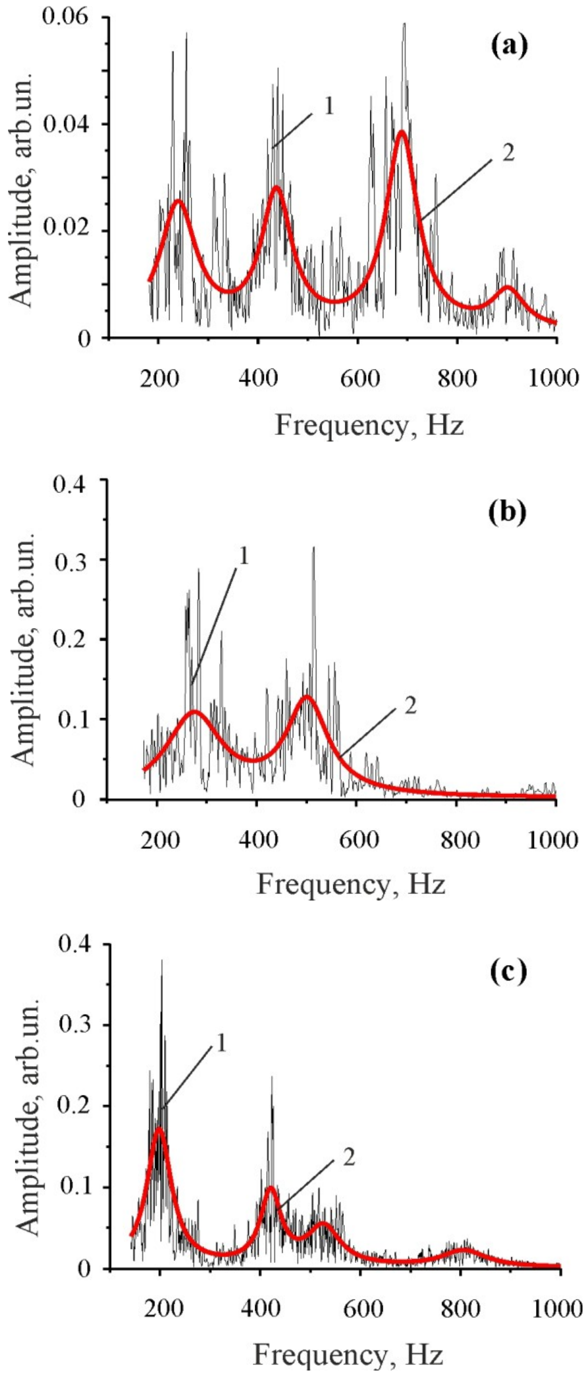


Fig. 2. Surface vibration spectra: a – dry sand, b – sand with 5% humidity, c – sand with 10% humidity. *1* – experimental spectra, *2* – averaging of experimental data using Lorentzian distribution.

the loudspeaker. The sound pressure level on the surface ranged from 80 to 110 dB in different measurements.

A plastic mine simulant (MS) was chosen as the object buried in the soil. It consisted of a round hollow container with a diameter of 92 mm and a thickness of 33 mm. The object under study was buried 0 to 60 mm in the soil ensuring that the soil surface was parallel to the wider side of the object.

3. Experimental results and discussion

To identify a buried object, it is important to know the vibration spectra of the soil without hidden objects. Acoustic waves are generated and propagate in the soil due to the interaction between the solid particles, water, and air in the pores [20]. Therefore, their acoustic characteristics depend on the physical and mechanical properties of the soil, such as density, porosity, and moisture content, as well as on the structure and interactions between the particles.

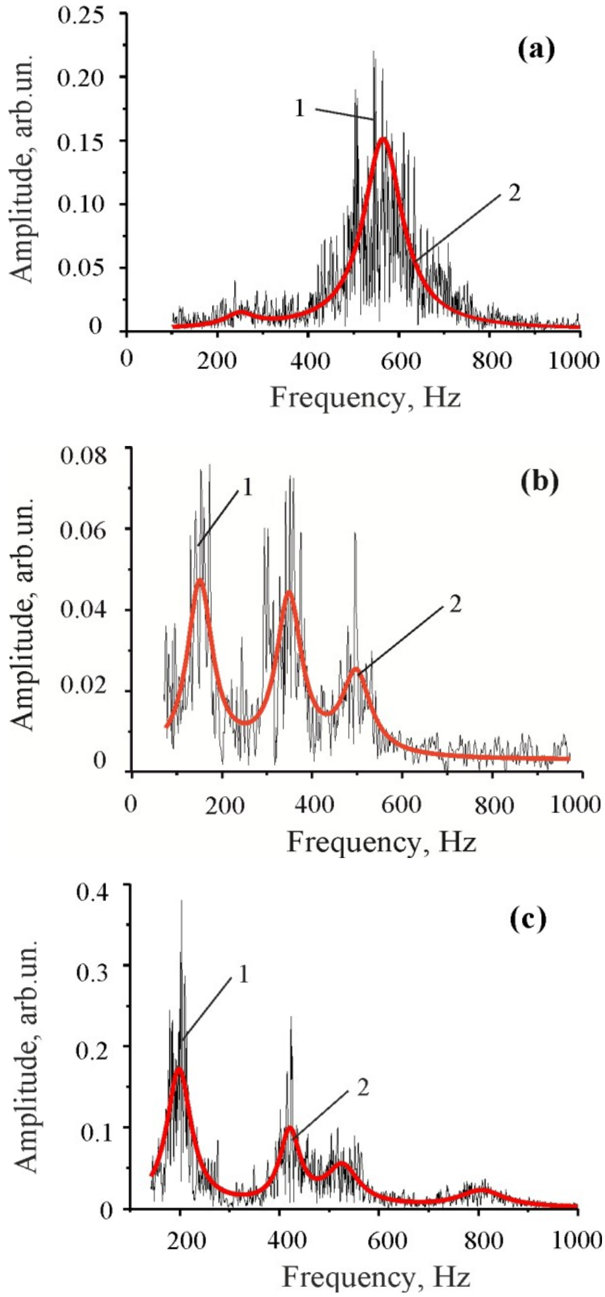


Fig. 3. Vibration spectra of an unburied plastic mine simulant (a) and a surface of the sand with the humidity of 15% above the mine simulant buried at the depth of 15 mm (b) and 50 mm (c). *1* – experimental spectra, *2* – averaging of experimental data using Lorentzian distribution.

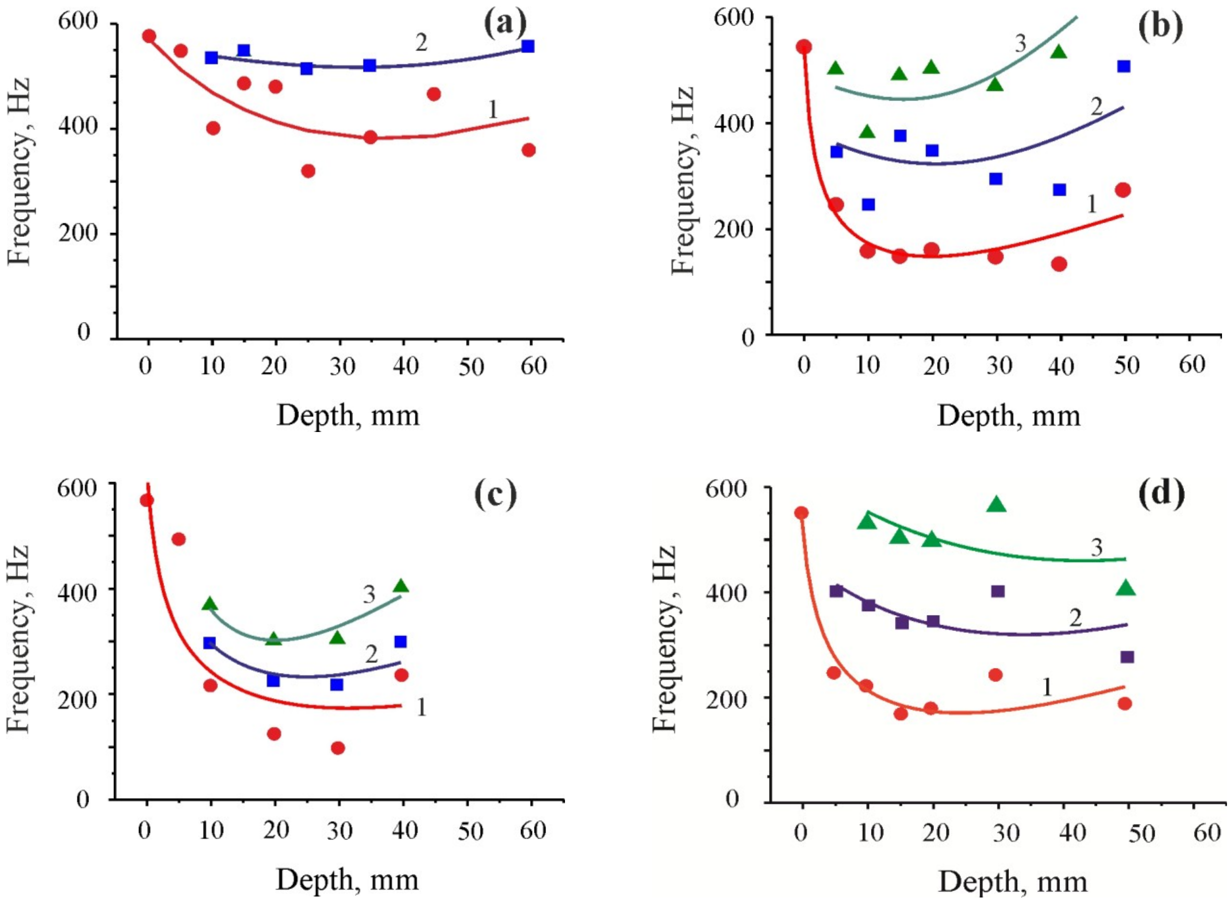


Fig. 4. Resonance frequency of a mine simulant *versus* burial depth: a – dry sand, b – sand with 5% humidity, c – sand with 10% humidity, d – sand with 15% humidity. *1* – first mode, *2* – second mode, *3* – third mode. Dots – experimental results, lines – non-linear curve fit.

Fig. 2 shows the vibration spectra of the surface of sand with different humidity degrees, measured without a hidden object. The spectra are characterized by a high noise level. Therefore, to separate and analyze the vibration resonances, a data averaging approach was applied using Lorentzian amplitude distribution (shown in Figs 2 and 3 by curves 2). As can be seen from Fig. 2, the vibrational spectra are different. Dry sand exhibits three intense peaks at the resonance frequencies of 239, 437, and 689 Hz, in addition to the weak line at a frequency of 902 Hz. Wetting the sand leads to filling of pores between solid particles with water and introducing adhesion forces absent in dry sand. The liquid forms "liquid bridges" between neighboring grains due to surface tension and capillary effects [21]. This radically changes the mechanical properties of the medium, resulting in modifications of the spectrum of surface vibrations. The sand with the humidity of 5% exhibits two intense resonances at the frequencies of 274 and 501 Hz. When the sand is moistened to 10%, its vibration spectrum contains one intense line at 198 Hz, two medium-intensity lines at 421 and 526 Hz, and a weak line at 807 Hz.

In geological systems, resonance effects are explained by heterogeneity of soil layers, such as when a layer consisting of sediments and characterized by low seismic wave velocities is situated above a layer of rocks having higher seismic wave velocities [22]. However, this mechanism cannot fully explain the features of the surface vibrations recorded in our experiments. The presence and characteristics of the detected resonances in the soil surface vibrations may be attributed to structured surface or near-surface bulk systems, such as micro-columnar [23] or layered [24] resonator formations. Moreover, vibrations of soil particles at the resonance frequencies [25] may also contribute to the overall acoustic response of the soil surface to external excitation.

Fig. 3 shows the vibration spectra of the surface of the MS (Fig. 3a) and the surface of the wet sand with a humidity of 15% and the MS buried at the depths of 15 mm (Fig. 3b) and 50 mm (Fig. 3c). The depth is measured from the MS upper surface to the sand surface.

As can be seen from Fig. 3, in the studied frequency range, the vibration spectrum of the MS free surface shows only one pronounced resonance at 540 Hz. The object buried in the sand demonstrates several resonances that depend on the interaction between the soil and the object as well as their properties. For the depth of 15 mm, three distinct resonance vibration modes at 156, 359, and 512 Hz are observed as a result of the interaction between the MS and the adjacent sand vibrations. The modes are shifted to lower frequencies relative to the ones for the non-buried MS. As the depth increases to 50 mm, the vibration spectrum shows one intense resonance at 144 Hz and three low-intensity modes at 290, 410, and 532 Hz. The decrease in the amplitude of vibrations with increasing the depth is explained by both the damping effect of the soil layer and the resistance it creates against vibrations of the MS upper surface, the increasing soil shear stiffness, and the absorption and scattering of acoustic waves by soil inhomogeneities [14].

Fig. 4 shows the dependences of the resonance frequencies of the MS on the depth of immersion in dry sand and the sand with different degrees of humidity. The dots represent the experimental results, and the lines indicate the results of a non-linear curve fit. As can be seen from this figure, the dependences are non-monotonic in nature. With increasing the depth, there is a shift of the resonance frequency toward lower values followed by its increase. Moreover, this behavior is characteristic not only of the first resonance but also of higher-frequency modes.

In [14], a simplified model of a soil-mine interaction was proposed. In this model, the soil-mine system was considered as a system of discrete elements with equivalent physical parameters and characteristics. The non-monotonic dependence of resonance frequency *versus* burial depth was explained by several competing physical mechanisms. When an object is initially immersed in a soil, it effectively increases the oscillating mass of the system. In a simple mass-spring system, increasing the mass leads to a decrease in the resonance frequency. As the object is immersed deeper, the weight of the overlying sand increases the confining pressure on the object and the surrounding environment, thereby increasing the stiffness and shear modulus of the system. This leads to an increase in the resonance frequency.

The experimental results presented in Fig. 4 also show that humidity significantly effects the dependence of the resonance frequency on the burial depth. For dry sand, this dependence is relatively weak and smooth. However, for wet sand with the humidity of 5%, there is a sharp decrease in the frequency, followed by its smooth increase as the thickness of the sand above the MS increases. This sharp change in the dependence on the humidity can be explained by the fact that addition of water leads to stiffening of the sand due to its compaction and a significant change in its elastic characteristics. As the obtained results indicate, even relatively small water content creates a noticeable compaction effect. Further increase in humidity results in only slight changes in the soil parameters, leading to minor changes in the dependence of the resonance frequency on the burial depth.

It should be noted that the obtained dependences qualitatively correspond to the theoretical and experimental results of other authors [12, 14]. Moreover, this applies not only to the first resonance but also to the higher-frequency modes.

4. Conclusions

This work addresses the problem of humanitarian demining by creating a complex based on a laser Doppler vibrometer. To ensure reliable detection and identification of buried objects, spectral parameters of acoustic vibrations of the surface of sand with and without buried plastic objects were investigated. Attention was paid to the amplitude and frequency of vibrational resonances as functions of the object burial depth and moisture of the soil.

It has been found that objects buried in the soil exhibit complex structural vibrations that depend on the interaction between the soil and the object, as well as their physical and deformation characteristics. The spectral distribution of the soil surface vibrations is defined by the physical and elastic properties of both the particles and the medium between them.

It is established that the shape of the spectra of acoustic vibrations of the soil surface allows us to draw unambiguous conclusions about the presence or absence of an object in the soil. The results of this research enhance the accuracy of detection and identification of buried plastic mines. Furthermore, it has been demonstrated that the laser Doppler vibrometer developed at the V. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine can be successfully used in humanitarian demining for detecting non-metallic explosive devices. However, it is evident that design modifications to the LDV are needed to improve the signal-to-noise ratio.

Acknowledgement

This work was supported by the National Research Foundation of Ukraine under the project # 2023.04/0088.

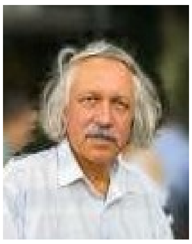
References

1. Alshamy H., Sadahb J.W., Saeed T.R. Different techniques in detection of buried objects using ground-penetrating radar. *Al-Qadisiyah J. Eng. Sci.* 2022. **14**, No 2. P. 223–231. https://doi.org/10.30772/qjes.v14i4.892.
2. Government portal. https://www.kmu.gov.ua/news/denys-shmyhal-rozminuvannia-ukrainy-tse-hlobalnyi-proekt-ta-investytsiia-u-bezpeku-ievropy.
3. Barbashyn V.V., Nazarov O.O., Ryutin V.V., Tolkunov I.O. *Fundamentals of Pyrotechnic Works Organization*. Textbook. Ed. V.P. Sadkovy. Kharkiv, VRVD UZZU, 2010.
4. Bello R. Literature review on landmines and detection methods. *Front. Sci.* 2013. **3**, No 1. P. 27–42. https://doi.org/10.5923/j.fs.20130301.05.
5. Kasban H., Zahran O., Elaraby S.M. *et al*. A comparative study of landmine detection. *Sens. Imaging*. 2010. **11**, No 3. P. 89–112. https://doi.org/10.1007/s11220-010-0054-x.
6. Pan Y., Luo Q., Fan Y. *et al*. Detection of vibration signal by plane scanning utilizing wavefront sensors. *Photonics*. 2025. **12**, No 4. P. 377. https://doi.org/10.3390/photonics12040377.

7. Yuan K., Zhu Z., Chen W., Zhu W. Development and validation of a new type of displacement-based miniature laser vibrometers. *Sensors.* 2024. **24**, No 16. P. 5230. https://doi.org/10.3390/s24165230.
8. Aranchuk V., Aranchuk I., Carpenter B., Hickey C. Laser multibeam differential interferometric sensor for acoustic detection of buried objects. *Opt. Eng.* 2023. **62**, No 2. P. 024103. https://doi.org/10.1117/1.OE.62.2.024103.
9. Libbe B., Perea J. Doppler-vibrometer landmine-detection system operated from a moving vehicle. *SPIE Proc. Detection and Sensing of Mines, Explosive Objects, and Obscured Targets* XXIV. 2019. **11012**. P. 110120W(1–8). https://doi.org/10.1117/12.2519299.
10. Rajesh K.R., Murali R., Mohanachandran R. Realization of ultrasonic doppler vibrometer array for landmine detection. *Proc. IEEE Int. Ultrasonics Symposium.* Dresden, Germany, 07-10 October 2012. P. 1030–1027. https://doi.org/10.1109/ULTSYM.2012.0257.
11. Sabatier J.M. Advances in Acoustic Landmine Detection. In: Battlefield Acoustic Sensing for ISR Applications. *Meeting Proc. RTO-MP-SET-107*. 2006. P. 5(1–10). Neuilly-sur-Seine, France, RTO.
12. Alberts W.C.K., Sabatier J.M., Waxler R. Resonance in land mine burial simulation experiments. *J. Acoust. Soc. Am*. 2006. **120**, No 4. P. 1881–1886. https://doi.org/10.1121/1.2338294.
13. Wang C., Zhou Y.-Q., Shen G.-W. *et al*. Numerical analysis of the resonance mechanism of the lumped parameter system model for acoustic mine detection. *Chin. Phys. B*. 2013. **22**. P. 124601. https://doi.org/10.1088/1674-1056/22/12/124601.
14. Zagrai A., Donskoy D., Ekimov A. Structural vibrations of buried land mines. *J. Acoust. Soc. Am.* 2005. **118**, No 6. P. 3619–3628. https://doi.org/10.1121/1.2108754.
15. Sabatier J.M., Burgett R.D., Aranchuk V. High-frequency A/S coupling for AP buried-landmine detection using laser Doppler vibrometers. *Proc. SPIE*. 2004. **5415**. https://doi.org/10.1117/12.540511.
16. Xiang N., Sabatier J.M. An experimental study on antipersonnel landmine detection using acoustic-to-seismic coupling. *J. Acoust. Soc. Am.* 2003. **113**, No 3. P. 1333–1341. https://doi.org/10.1121/1.1543554.
17. Borkovska L.V., Kyslyi V.P., Morozhenko V.O. *et al*. Detection of buried mines and other explosive devices using a single-beam laser Doppler vibrometer. *SPQEO*. 2024. **27**. P. 472–477. https://doi.org/10.15407/spqeo27.04.472.
18. *Laser Doppler Vibrometry: A Multimedia Guide to its Features and Usage*. P. Tomasini, P. Castellini (Eds.) Springer, 2020.
19. Serozhkin Yu., Kollyukh O., Venger E. Detection of dust grains vibrations with a laser heterodyne receiver of scattered light. *J. Quant. Spectrosc. Radiat. Transfer*. 2008. **109**, No 8. P. 1517–1526. https://doi.org/10.1016/j.jqsrt.2008.01.008.
20. Lo W.-C., Yeh C.-L., Tsai C.-T. Effect of soil texture on the propagation and attenuation of acoustic waves at unsaturated conditions. *J. Hydrol*. 2007. **338**. P. 273–284. https://doi.org/10.1016/j.jhydrol.2007.02.034.
21. Mitarai N., Nori F. Wet granular materials. *Adv. Phys*. 2006. **55**, No 1–2. P. P. 1–45. https://doi.org/10.1080/00018730600626065.
22. Nakamura Y. A method for dynamic characteristics estimation of surface using microtremor on the ground surface. *Q. Rep. RTRI*. 1989. **30**, No 1. P. 25–33.
23. Lee T., Kwon H.-S., Li X., Yu Z. Surface acoustic wave direction sensing enabled by resonant mode interference in a single micropillar resonator. *Phys. Rev. B*. 2025. **111**, No 17. P. 174101(1–8). https://doi.org/10.1103/PhysRevB.111.174101.
24. Stoneley R. Rayleigh waves in a medium with two surface layers (Second Paper). *MN Geophys. Suppl*. 1955. **7**, No 2. P. 71–75. https://doi.org/10.1111/j.1365-246X.1955.tb00381.x.
25. Sholtz P., Bretz M., Nori F. Sound-producing sand avalanches. *Contemp. Phys.* 1997. **38**, No 5. P. 329–342. https://doi.org/10.1080/001075197182306.

Authors and CV

Lyudmyla Volodymyrivna Borkovska, Doctor of Sciences in Physics and Mathematics, Head of the Department of Sensor Systems, V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. Author of more than 90 scientific publications, 2 patents, and co-author of 6 collective monographs. The area of her scientific interests includes optical sensors, solid-state luminescent materials, light-emitting devices and structures, and modification of physical properties of solids by interacting with laser radiation.
https://orcid.org/0000-0002-7832-3796



Volodymyr Pavlovych Kyslyi, PhD in Physical and Mathematical Sciences, Senior Researcher at the Department of Sensor Systems, V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. He is the author of more than 20 scientific publications and 5 patents. The area of his scientific interests includes properties of semiconductors, infrared spectroscopy, and ecology systems.
E-mail: kyslyj@ukr.net,
https://orcid.org/0000-0002-8987-1499

Vasyl Oleksandrovych Morozhenko, PhD in Physical and Mathematical Sciences, Senior Researcher at the Department of Sensor Systems, V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. Author of more than 50 publications and 14 patents. The area of his scientific interests includes optical properties of semiconductors, photonics and magnetophotonics, infrared spectroscopy, and heterodyne spectroscopy.
E-mail: morozh@meta.ua,
https://orcid.org/ 0000-0001-7834-2260

Evgen Oleksandrovych Soloviev, PhD in Technical Sciences, Senior Researcher at the Department of Sensor Systems, V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. Author of more than 20 publications. The area of his scientific interests includes production technology of ultra-high-precision semiconductor temperature and magnetic field microsensors and multifunctional sensors, as well as mathematical and software support of operation of such sensors.
E-mail: gibber@ukr.net

Yuriy Georgiyovych Serozhkin, Researcher at the Department of Sensor Systems, V. Lashkaryov Institute of Semiconductor Physics, NASU. Author of more than 6 publications and 1 patent. The area of his scientific interests includes photoacoustic heterodyne spectroscopy and design of optical devices for a wide range of applications. https://orcid.org/0000-0003-0522-0195, e-mail: yuseroz@gmail.com

Viktor Mykolayovych Nastych, Deputy Head of the Department of Laser Gerometry at the State Enterprise for Special Instrument-Building “ARSENAL”. The area of his scientific-and-engineering interests includes development of optical laser devices for a wide range of applications.
E-mail: vnast@ukr.net

Authors’ contributions

Borkovska L.V.: supervision, project administration, resources, data curation, writing – review & editing.
Kyslyi V.P.: investigation, resources, formal analysis, visualization, writing – review & editing.
Morozhenko V.O.: investigation, calculations, writing – original draft, visualization, writing – review & editing.
Soloviev E.O.: resources.
Serozkin Yu.G.: conceptualization, problem formulation, methodology, resources, investigation, validation, data curation, formal analysis, visualization, writing – review & editing.
Nastych V.M.: resources, writing – review & editing.
All the authors have discussed the results.

Дослідження акустичного відгуку об’єкта, закопаного в пісок з різним вмістом води

Л.В. Борковська, В.П. Кислий, В.О. Мороженко, Ю.Г. Серьожкін, Є.О. Соловйов, В.М. Настич

Анотація. Робота спрямована на вирішення проблеми гуманітарного розмінування шляхом створення лазерно-акустичного комплексу з використанням лазерного допплерівського віброметра для виявлення закладених у землю мін. Досліджено параметри акустичного відгуку пластикового імітатора міни, заглибленого в пісок на різній глибині. У дослідженнях використовували сухий пісок і пісок різного ступеня вологості (5, 10 і 15%). Коливання ґрунту збуджувалися білим акустичним шумом. Установлено, що спектри коливань заглибленого в ґрунт об’єкта мають кілька резонансів, а їх амплітуда і частота залежать від глибини заглиблення та вологості ґрунту. Зокрема, заглиблення об’єкта у пісок приводило до зменшення амплітуди коливань і зсуву резонансної частоти. Остання продемонструвала немонотонну залежність від глибини заглиблення. Установлено, що характер спектрів акустичних коливань поверхні ґрунту дозволяє зробити однозначний висновок про наявність чи відсутність об’єкта в ґрунті. Результати досліджень дають змогу підвищити точність виявлення та ідентифікації заглиблених об’єктів.

Ключові слова: гуманітарне розмінування, виявлення закопаних мін, лазерний допплерівський віброметр.