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Soil Conductivity: An Important Factor for Detecting Landmine Threats and Terrain Rehabilitation

T. Hutsul[1*], M. Khobzei[2], Y. Popiuk[3], V. Tkach[2], O. Krulikovskyi[2] and A. Samila[2]

[1] *Department of Geomatics, Land and Agromanagement, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine*
[2] *Department of Radio Engineering and Information Security, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine*
[3] *Department of Physical Geography, Geomorphology and Paleogeography, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine*

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Abstract:

Post-war demining of territories is a global problem. Further research is required because none of the technical methods for mine detection are satisfactory in terms of basic parameters. The soil electric conductivity index may be taken into consideration as a completely touchy indicator of diverse residences of the soil without digging into the soil. Soil properties show high variability in space and time. Atypical heterogeneous objects of anthropogenic origin (by shape and material of manufacture) can be identified by maps of variations in the electromagnetic properties of the soil. Electromagnetic properties of the soil, mainly electric conductivity and magnetic susceptibility, have an effect on the operation of steel detectors, which can be historically most usually used for demining territories.

Keywords:

electromagnetism, electrical conductivity, GIS, soil, identification, mapping, modeling, resistivity, demining, object recognition

1 Introduction

Electric conductivity is the ability of a substance to conduct an electric current under the action of an electric field. According to electrical resistivity, which characterizes the ability of substances to create resistance during the passage of an electric current, all substances are classified as conductors (10^{-5} Ω·m), semiconductors (10^{-5} Ω·m to

* *Corresponding author: Department of Geomatics, Land and Agromanagement, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Kotsyubynsky 2, Ukraine. Phone: +380 66 544 14 33. E-mail: t.gutsul@chnu.edu.ua. ORCID 0000-0002-7192-3289.*

$10^5\ \Omega\cdot m$) and insulators ($10^5\ \Omega\cdot m$). Electric conductivity is influenced by the nature (structure) of the substance, its chemical and aggregate state, as well as the physical conditions of substances and the environment. The unit of measurement of electric conductivity in the International System of Units (SI) is Siemens per meter [S/m]. Decimal multiples and divisible units are formed using standard SI prefixes. Soil conductivity is expressed in millisiemens [mS/m] or decisiemens [dS/m].

Soil (from an engineering-geological point of view) is any upper layer of rocks, which is a material consisting of an accumulation of individual particles that are connected to each other by mechanical or other connected means. The book [1] defines soil as "an uncemented or weakly cemented accumulation of mineral particles that are formed as a result of the weathering of rocks, as well as the empty space between the particles filled with water and/or air".

Electrical conductivity of soil refers to the capacity of soil to transmit an electric current. This indicator of electrical conductivity is influenced by various factors, including soil moisture levels, the state of moisture, the concentration of salts present in the soil, as well as its temperature, density, and granulometric composition.

Conductivity and resistivity are physically opposite phenomena. If the soil has a high conductivity, it will have a low resistivity.

The accuracy of electrical conductivity measurements depends more on the measurement technique employed than on the inherent physical properties of the soil. It is essential to distinguish these measurements from other soil assessments that may utilize similar terminology, such as hydraulic conductivity, which refers to the soil's capacity to transmit water, or soil mechanical resistance, typically evaluated using a soil penetrometer. Additionally, confusion may arise from the distinction between soil conductivity values derived from laboratory analyses and those obtained through field measurements. Laboratory assessments of soil electrical conductivity are primarily conducted to classify salts for salinity evaluation, often utilizing a saturated paste extract or solution. These analyses are designed to maintain a consistent moisture level to mitigate any conductivity variations attributed to soil texture, thereby preventing any influence from clay-moisture interactions. In contrast, field conductivity, often referred to as bulk soil conductivity or apparent soil conductivity, is significantly influenced by variations in soil texture. When measuring on direct current, it is necessary to evaluate the effect of polarization. When measuring on alternating current, it is necessary to find out the influence of different frequencies of current oscillation on the measurement result.

The techniques for assessing electric resistance involve the introduction of an electric current into the soil via surface current electrodes called a Wenner grid (Fig. 1), while the potential difference of the currents is recorded using potential electrodes situated close to the area of current flow [2, 3].

The resistivity, r, measured using the Wenner grid is:

$$p = \frac{2\pi f\,\alpha\Delta V}{i} = 2\pi\alpha R \tag{1}$$

where V – the voltage, α – the interelectrode distance, i – the electric current, R – the resistance.

The fundamental apparatus required for assessing electric conductivity using the Wenner grid method consists of a power supply, a resistance meter, four metallic electrodes, connecting wires, a measuring tape, and a soil thermometer [4].

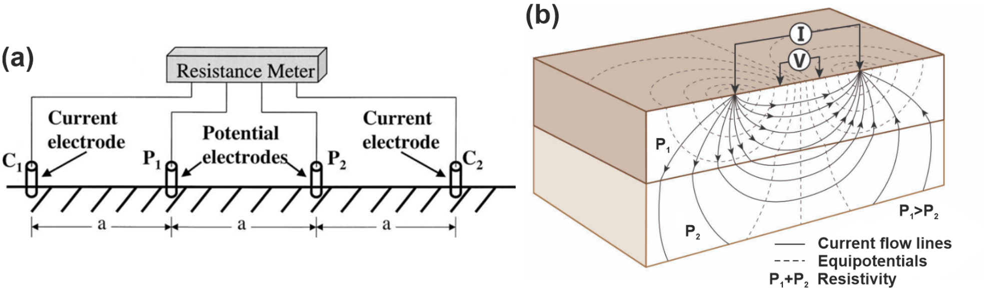

Fig. 1 Diagram of electrodes of Wenner grid (C_1 and C_2 – current electrodes, P_1 and P_2 – potential electrodes; a – interelectrode distance) – a; principle of measuring soil resistivity – b [3]

2 Evolution of Equipment for Measuring Soil Electric Conductivity

For the first time, such equipment was used by oil companies in geology to search for oil deposits and determining geological formations. In geodetic works, especially when searching for oil and minerals, electric methods have been increasingly used in recent years, the success of which depends on detailed knowledge of the electric conductivity of earth materials [5]. One of the first successful attempts to search for anomalies under the surface of the earth is the study by Bevan B. [6], which was based on the equipotential. The primary techniques for assessing soil conductivity include direct contact measurement and electromagnetic induction. The most common among existing direct contact methods for measuring soil resistance are Wenner (Fig. 2) and Schlumberger methods, which are also called four-contact methods.

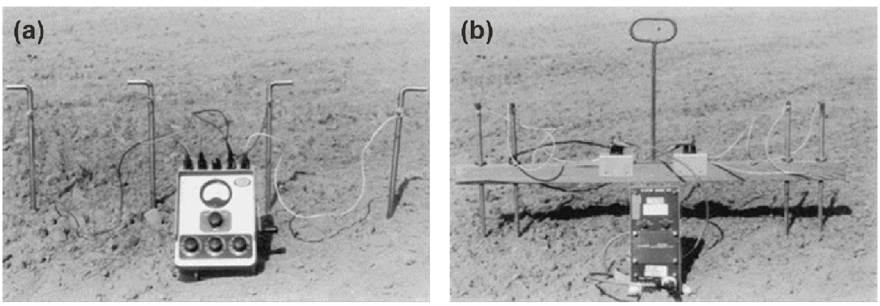

Fig. 2 Arbitrary installation of Wenner grid electrodes – a; the electrodes are installed in a position fixed by the grid – b [7]

In the 1980s, positioning was achieved using tape measures, wheels, or surveying equipment. As a result, the creation of maps of electric conductivity of soils was a painstaking and rather conditional process. The commercial availability of GNSS receivers with centimeter positioning accuracy has greatly revitalized and increased the accuracy of such studies.

Practice has shown that the measurement of the physical parameters of soil electric conductivity is more accurate when using conductometric meters, which have built-in electrodes designed for both measurement and supply of test voltage. Such meters are often made in the form of hand probes, for example, with an SMTE sensor, which simultaneously measures electric conductivity, volumetric moisture content and soil

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temperature with the ability to transfer data to a personal computer via the RS 232 port (Fig. 3a). Using the meter requires material costs and a lot of manual labor, which leads to a significant increase in the cost of a unit of information obtained. Most instruments for measuring electromagnetic compatibility require daily calibration, and some models may require more frequent calibration due to instrument drift [8]. Today, three main systems that allow soil scanning have become the most widely used: (Fig. 3b-d). The EM-38 works using the principle of electromagnetic induction.

Fig. 3 SMTE sensor of moisture content, temperature and soil electric conductivity – a; Geonics EM-38 for measuring soil electromagnetic conductivity – b; Veris sensor system for measuring acidity (pH), percentage of organic matter at the depth of growth (0-30 cm) *and in the root zone* (0-90 cm) *– c; Topsoil Mapper to determine structure, moisture availability, compaction and optimal loosening depth – d*

The development of devices for recording the conductive properties of the soil environment has the tendency of equipment miniaturization, interaction with navigation networks and IoT networks. One of these designs (Fig. 4), proposed in [9], measures 42 × 31 × 12 cm and weighs only 6.3 kg. The system is operated on a radio-controlled chassis made from a set of ready-made elements of an aluminum frame and chassis and an internal combustion engine with a volume of 3.45 cm^3.

In the study [10], a mine detector (Fig. 5) is presented, which works according to the principle of electric impedance topography – the construction of images of flat sections of electrically conductive bodies. The proven recognition depth is 14-21 cm.

The role of electric and magnetic properties of soils in the ability of mine detectors to detect mines, such as those used in humanitarian demining, has come to the fore as a major issue in the development of new optimal detectors. These efforts included measurements of electric and magnetic properties of soils in Cambodia and Croatia with Geonics EM38 and Bartington MS2 instruments [11]. The influence of soil proper-ties on demining dates is explained in [12]. The modern development of soil conductivity methods is also based on the processing of measurement results using intelligent modeling methods. In particular, in [13], the thickness of each layer is calculated and optimized using the experimental curve of the electric resistivity of the soil. The process of deriving soil electric conductivity from ground-based GPR data is thoroughly examined in the works of Lambot et al. [14] and Minet et al. [15]. This derivation is feasible only to a limited degree for multilayered media, contingent upon the specific model configuration and the operating frequencies employed.

There are ways to measure electric conductivity using Remote Sensing (RSD) data, based on changes in soil moisture using radar satellite images obtained from RADARSAT. Consistency of images of soil moisture for different dates may indicate good characteristics of moisture retention in the soil, which is characteristic of a significant amount of the clay fraction in its composition [16].

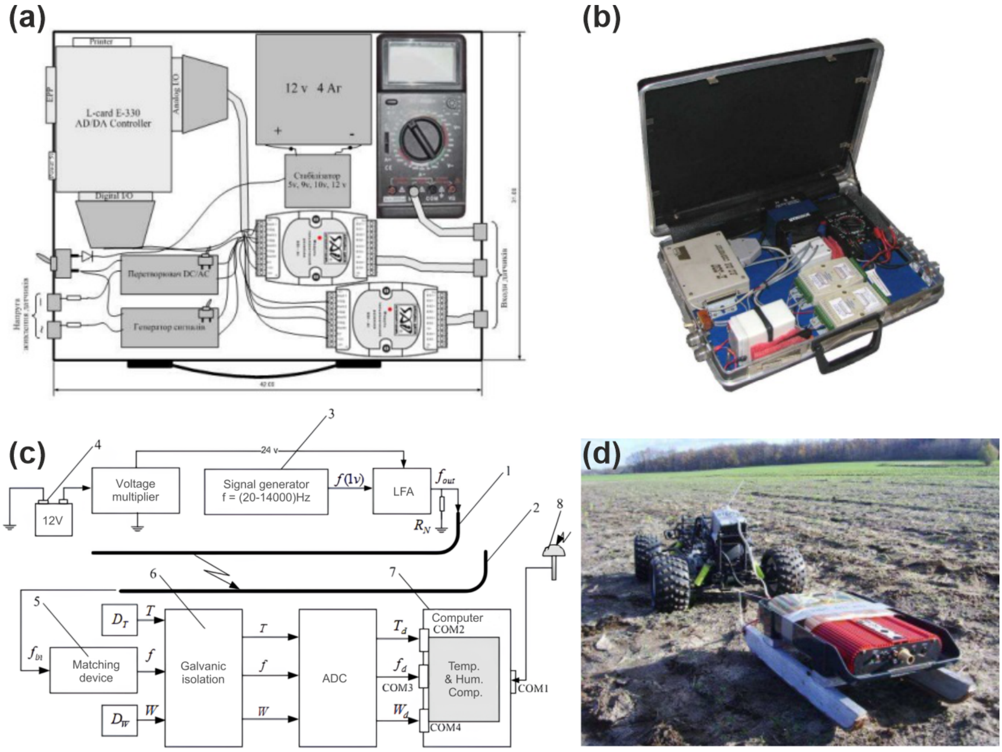

Fig. 4 Device for determining the conductive properties of the soil: the composite diagram of the measuring and recording device – a; general view of the measuring and recording device – b; scheme of equipment for measuring conductive properties of soils – c; laboratory-field installations in working condition – d.

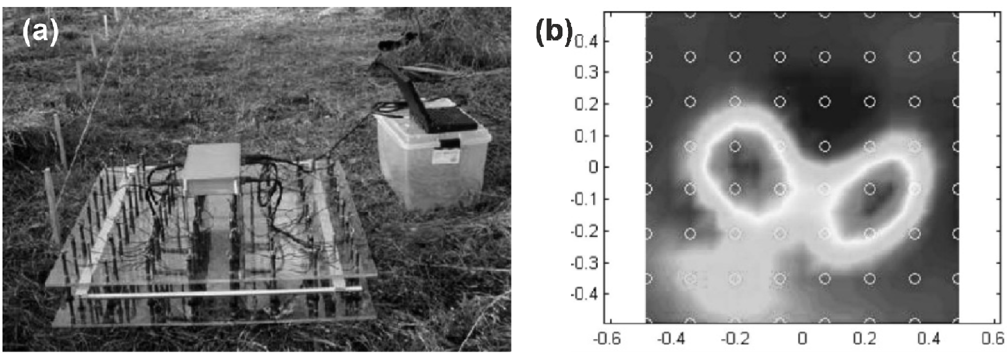

Fig. 5 Electric impedance tomography (EIT) in working position – a; contour map of EIT detector triggering on two mine-like targets buried in sandy soil to a depth of 14 cm *and located at a distance of* 7 cm *from each other – b.*

3 Features of the Electric Conductivity of the Measured Media

There are many methods (Fig. 6) for detecting explosives and landmines, differing in limited sensitivity and/or difficulty of operation due to terrain, climate, and soil cavities [17]. The variety of methods for detecting explosives and landmines and their effectiveness depends on structural features (metal, wood, plastic), differences in shape, size, purpose, type and amount of explosive substance. Any mine or explosive object, as a rule, is installed in different areas of space, which have their own surface features.

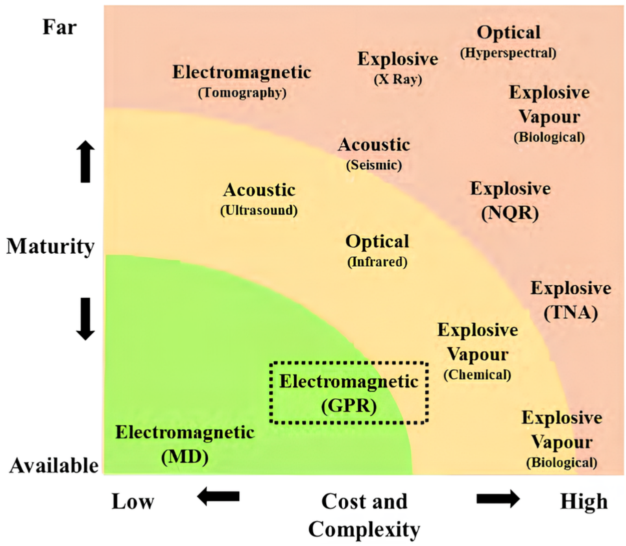

Fig. 6 Conclusions about the maturity of mine detection technologies [18]

The relevant properties of soils determine the development of various technologies for their detection, in particular those based on electric conductivity [19]. Therefore, we will consider separately the electric conductivity of mines and explosives and the electric conductivity of the environments in which they are likely to be installed.

3.1 Electric Conductivity of Surfaces

The conventional application of metal detectors for the detection of antipersonnel mines at depths reaching 30 cm encounters challenges posed by the magnetic susceptibility and electric conductivity of various soil types. Consequently, efforts to establish a comprehensive global database of soils, as outlined in Tab. 1, that pertains to the electromagnetic properties of soils are ongoing [20, 21]. The range of physical, chemical and electromagnetic properties of this near-surface layer of the earth potentially affects a wide range of technologies being developed around the world for the detection and disposal of landmines.

Soil can be considered as a three-phase medium consisting of soil matrix and pore space filled with air and water (Fig. 7).

Each soil component is described by electric and magnetic parameters. The electric conductivity of soil is not uniform; it fluctuates based on the arrangement and dimensions of the soil particles [23]. Godwin R. J. and Miller P. claim that soil conductivity is mainly influenced by moisture and texture [24]. Soils are modeled according to different mixing schemes depending on whether they have a high or low content of clay and soil solution [25].

Tab. 1 Electric conductivity characteristics of some basic soils and clays [21]

Material		Electric conductivity [S/m]
Soils	Clay (general term)	0.01-1
	Loam	0.025-0.25
	Topsoil	0.005-0.025
	Soil with a high content of clay fraction	0.0025-0.01
	Sandy soil	0.00025-0.0025
	Loose sands	0.00001-0.001
Clay	Kaolinite	0.0002-0.02
	Montmorillonite	0.067-0.25

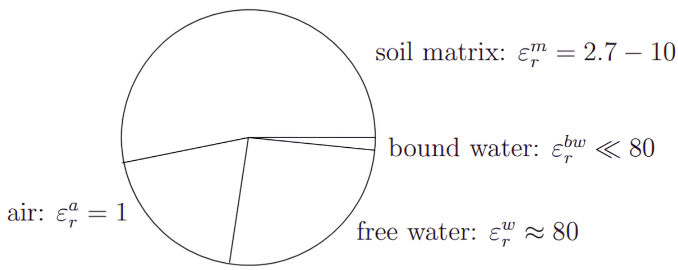

Fig. 7 Schematic representation of the soil as a 4-phase medium [22]

In the case of soil, these variations in electric conductivity are extremely large. The most common model corresponds to the soil represented by horizontal layers, where the same value of specific electric resistance is observed in all its points within each layer [26]. Data collected on apparent electric conductivity can be interpolated and stratified in the soil in a three-dimensional configuration (Fig. 8).

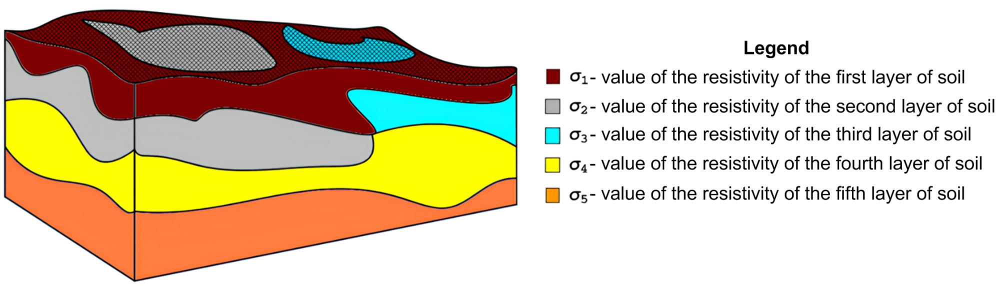

Fig. 8 Schematic representation of the soil as a 4-phase medium [22]

Determining the dominant characteristics of the soil in each area is necessary for the correct interpretation of electric conductivity maps [27, 28]. Soil properties always change depending on the location. These changes can be quantified using geostatistical analysis and length-variability correlation parameters.

Within the realm of soil mapping, the specific electric resistance exhibits a broad spectrum of values, ranging from 1 Ω·m to 10^5 Ω·m, as illustrated in Fig. 9. The specific resistivity measured by Giao et al. [26] across 25 clay samples sourced globally varied from 1 to 12 Ω m [29].

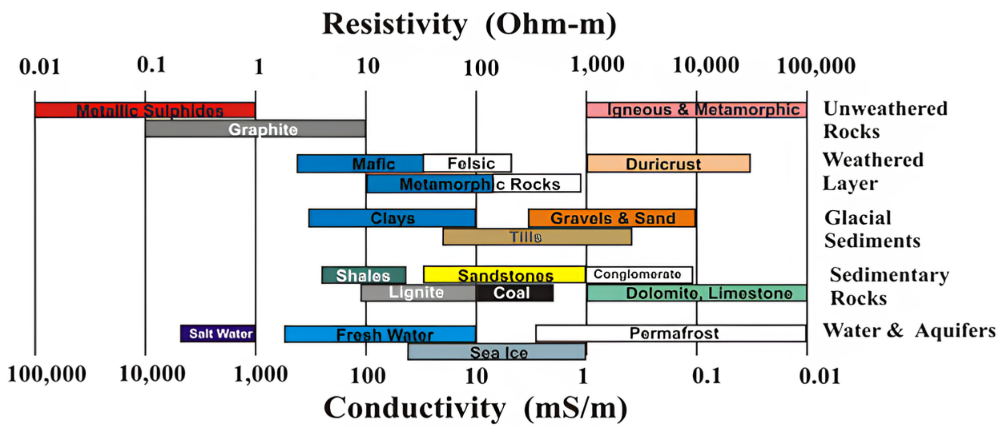

Fig. 9 Typical ranges of specific electric resistances of soil materials (as modified by Palacky, 1987) [30]

Attention was drawn to the necessity of using soil databases in humanitarian demining in [20]. The capabilities and further development of geographic information systems (GIS) make it easy to store and retrieve data on soils and their properties, as well as to create geospatial soil databases. Many national and international organizations and institutions have made soil databases available on the Internet [31].

These soil databases and many other national databases provide information on topsoil composition, such as texture, organic matter content, bulk density, and salinity. However, none of the soil databases will provide information about a specific site, since the number of selected representative profiles is only an infinitesimal fraction of the total soil volume. However, in many cases the database can provide a clear picture of the average soil conditions in the region and the associated soil variability [32].

The international organization IMSMA NG faced a lack of data during humanitarian demining in the Western Sahara. Borrowing the experience of Afghanistan, free data sources were identified and used for the spatial analysis of the territory of the Western Sahara, in particular the global land cover map GlobCover [33].

A review of the literature shows that local studies differ in duration, conditions, and methods of determining electric conductivity. In particular, in the territory of Western Polissia, within the limits of three test sites (Polozhevo village, Rymachi village, and Kolka town), the electric conductivity of reclaimed soils was determined in 2021-2022 on plots of various agricultural uses [34].

Electrophysical properties of soils are closely related to their agro-hydrological properties [35]. The correlation coefficient R between K of the device and Q of the soil reached 0.95 and was always above 0.75. (the coefficient K was determined based on data measured by the VPG-1 device (soil parameters meter) and the thermogravimetric method). Therefore, agro-hydrological properties of different types of soils are currently much better studied than their electric properties.

3.2 Electric Conductivity of Surfaces

Some explosive mine casings are still made of metal or wood, but most modern mines are made of plastic and are difficult to detect with standard metal-detecting equipment. Conveyor production of explosive objects and mines mainly takes place from expensive raw materials. For example, an artillery projectile contains steel, brass, and explosives (Tab. 2). Contemporary landmines are characterized by a minimal metal composition. In certain instances, the sole metallic component of a landmine is a diminutive pin. Homemade explosive devices are made from any available materials: pots and pans, garbage cans, mobile phone components, etc.

Tab. 2 Electric conductivity of some substances at 20 °C

Substance	[S/m]	Material	[S/m]
Copper	59 500 000	Cast steel	7 690 000
Aluminum	38 000 000	Lead	4 810 000
Magnesium	22 700 000	Nickel	11 500 000
Molybdenum	18 500 000	Pure iron	10 000 000
Tungsten	18 200 000		
Zinc	16 900 000	Plastic[1]	dielectric
Tin	8 330 000	Wood[2]	dielectric

[1] with the exception of conductive polymers; [2] provided there is no humidity.

The most common explosive for the main charge in landmines is TNT (2, 4, 6-trinitrotoluene), which is the most widely used military explosive. Explosives such as RDX (hexogen), PRTN (nitrogen), HMX (octogen) and other compounds are also used (Tab. 3) [36]. In general, explosives consist of carbon (C), hydrogen (H), nitrogen (N), and oxygen (O), as well as many other organic compounds [37].

Military explosives primarily consist of mixtures of TNT, hexane, and various organic compounds such as waxes, plasticizers, stabilizers, and oils. Notable examples of these mixtures include composition B, which combines RDX, TNT, and wax, and composition C-4, which is made up of RDX, polyisobutylene, di(2-ethylhexyl) sebacate, and fuel oil. Furthermore, mines may incorporate a booster charge to enhance the energy produced by the detonator, ensuring it reaches a level adequate to trigger the main charge [38, 39].

Since February 2022, Russian troops in Ukraine used [40, 41] at least 8 types of anti-personnel mines.

Tab. 3 Electric conductivity of some explosive substances [39]

Substance	Electric conductivity 10^{-7} [S/m]
TNT	0.93-1.21
RTV3110	1.14
Comp B-3	1.03
Tetryl	0.50

4 Technical Implementation of Soil Conductivity in Humanitarian Demining

The plan for the development and integration of autonomous systems until 2036 of the US Department of Defense predicts an increase in the number of all robotic means, and developers are tasked with giving these systems «supervised autonomy» (that is, with human control), and eventually full independence [42].

UAVs, GIS, remote sensing and artificial intelligence possess the potential to transform conventional methods of landmine detection and removal [43]. The United Nations Mine Action Service acknowledges UAV technologies as a significant asset for the humanitarian demining of affected areas [17].

An effective method for creating sets of spatial data with a very high resolution is the technology of photogrammetry from a UAV [44]. Using even a non-professional UAV, it is possible to achieve deviations of the coordinates of the control points at the level of the mean square errors of the plan and height position of the points: $m_x = 0.10$ m, $m_y = 0.12$ m, $m_h = 0.18$ m [45]. The obtained values meet the requirements of the instructions for drawing up topographic and cadastral plans on a scale of 1:2 000 [46]. This is also consistent with the accuracy claimed by DJI for the multi-rotor platform 4 RTK [47].

The ground apparatus must be placed on a remote-controlled platform that provides direct contact with the soil surface for electrodes to touch it. The use of ground demining systems causes significant risks associated with damage to special equipment and, most importantly, increases threats to the lives of personnel. Therefore, there is a condition regarding the maximum weight of the equipment, which is less than 8 kg, which will prevent the emergence of a useful force necessary for the activation of anti-personnel mines.

The gyroscope and accelerometer should facilitate the installation of electrodes perpendicular to the earth's surface. The platform should be equipped with a GNSS-positioning sensor focused on centimeter accuracy and the possibility of receiving differential RTK corrections (both for the movement of the ground vehicle and for increasing the accuracy of DEM generation from the UAV). Real-time data exchange is ensured by the use of IoT capabilities [48]. The mandatory inclusion of meteorological sensors enables real-time corrections to measurements based on weather conditions.

At each point, the following attributive data is transmitted – the exact coordinates of sampling (x,y); surface height (z_0); indicator of electric conductivity of the soil for depth layers ($z_{0\text{-}5}$; $z_{5\text{-}10}$; $z_{10\text{-}15}$; $z_{15\text{-}20}$; $z_{20\text{-}25}$; $z_{25\text{-}30}$; $z_{30\text{-}35}$; $z_{35\text{-}40}$; $z_{40\text{-}45}$; $z_{45\text{-}50}$; $z_{50\text{-}55}$; $z_{55\text{-}60}$; $z_{60\text{-}65}$; $z_{65\text{-}70}$; $z_{70\text{-}75}$; $z_{75\text{-}80}$; $z_{80\text{-}85}$; $z_{85\text{-}90}$; $z_{90\text{-}95}$; $z_{95\text{-}100}$) in centimeters; air temperature t_0, surface temperature t_1, air humidity φ_0, surface moisture φ_1.

Mapping of soil electric conductivity for precision agriculture is carried out on the basis of accurate positioning of at least 80 values per 1 acre of area [49]. Obviously, for humanitarian demining, the resolution of sampling per unit of likely affected area should consider the size and features of the location of the smallest explosive objects. Usually, the diameter of most antipersonnel mines does not exceed 10 cm [37]. Any data from additional measurements will only increase the accuracy of interpolation and modeling of soil heterogeneities, which will facilitate their identification.

Movement along a straight line with a certain multiplicity, for example 5 cm, allows to accumulate a sufficient amount of data to construct 2D longitudinal and transverse profiles. Measuring one more line of data creates a sufficient amount of data to obtain a 3D surface – a voxel. Multiple lines create enough data for spatial analysis.

GIS play an important role in spatial analysis. The growing ability to receive and process geographic data is directly reflected in its results.

In this case, the spatial analysis is based on the search for voids caused by dielectric non-conductivity within the profile (wood and plastic) and values of anomalous superconductivity (metal parts, fragments). The discreteness of the measurements makes it possible to detect the “useful void volume” or “superconductivity anomaly volume” [50].

5 Validation of Electric Conductivity Data with Magnetic Conductivity Data

The electric conductivity of soils, even for highly saline systems, is usually orders of magnitude lower than the typical conductivity of metallic compounds. Soils with significant magnetic susceptibility are more widespread in the world than saline soils [51]. Henry Elles was one of the first people to propose a connection between electricity and magnetism. Maxwell's equations mathematically describe the physics of electromagnetic waves and the corresponding properties of the environment. The basic equations quantify three physical properties of materials, namely electric conductivity (σ), dielectric permeability (ε) and magnetic permeability (μ), relating to the electromagnetic field [52].

Apparent electric conductivity of the soil can be measured remotely using electromagnetic sensing. Inductive electromagnetic devices can be used to determine the depth distribution of electric conductivity with sufficient accuracy, which allows specialists to recommend the device for field measurements of profiles [53].

Electromagnetic measurement methods offer great potential for non-invasive and non-contact acquisition of geological and hydrological soil properties of the upper six meters of the underground surface with an area resolution in the sub-meter range [54].

Each material has a unique set of electromagnetic properties [55] that mainly affect the way the material interacts with electromagnetic waves in a certain spectrum [53].

Plastics are made from organic (carbon-containing) chemicals that contain mainly carbon, nitrogen, oxygen and hydrogen. None of these elements are magnetic. Wood, like most other materials that we encounter around us, has very weak magnetic properties. Both plastic and wood are dielectric materials. Therefore, the detection of the practical absence of electromagnetic properties will additionally confirm the presence of these materials during non-contact research.

6 Additional Options for the Use of Data Collected During the Measurement of Electric Conductivity to Establish the Sequence of Humanitarian Demining of Territories

Since the ground passage of the remotely controlled platform is preceded by the creation of an orthophoto plan of the area based on the results of the UAV flight, actual spatial data is additionally obtained – large-scale cartographic works and topographic plans (1:500 – 1:10 000). Given the significant destruction and even the destruction of buildings and structures, as well as the change in terrain due to artillery shelling and aerial bombardment and significant forest fires, any previous pre-war cartographic information will not be relevant and it will be inconsistent with the real state of the area.

One of the stages of humanitarian demining includes mandatory marking and drawing up of special maps of the surveyed and cleared territory. This is necessary, including for modeling the mine-affected community's ability to adapt to landmine contamination and for creating risk maps that highlight high-danger areas requiring priority demining Digital modeling of the terrain and detailing of all elevations down to centimeter values can be directly refined through the GNSS receiver installed on the mobile ground platform and its coordinated operation with the RTK network. The DEM analysis makes it possible to obtain a number of morphometric indicators that allow one to assess the steepness and exposure of the slope, the directions of surface runoff, the dismemberment of the relief, the depth of erosional dismemberment, etc. These indicators make it possible to make a preliminary assessment of the suitability of the territory for residential and industrial construction of various objects [56].

When assessing the cost of the consequences of landmines for agricultural lands, it is worth remembering that the costs are measured from the point of view of the value of the cultivated agricultural products and the land plots themselves, taking into account cost uncertainty and benefit uncertainty. The owner of the land plot, by selecting a crop that is optimally suited to the specific conditions, can increase the benefits of demining [57].

The electric conductivity of soils allows to assess the quality of the soil and its spatial variability. This, together with the topography of the surface obtained with DEM, is quite sufficient for calculating the application of fertilizers with a variable rate. Thus, it allows to reduce the cost of cultivation of shallow or less productive soils, to stimulate deeper, highly productive soils and to increase yield levels. At the same time, electric conductivity maps for acidic soils with a high pH level allow choosing the optimal amount of lime application, returning them to active economic cultivation. Finally, conductivity maps can be overlaid on other field data to more efficiently search for additional solutions from multiple sources of information [58]. Detailed information on the state of the soil cover and the level of damage to the natural relief and landscape also allows to take these points into account when mapping damage from military operations.

7 Conclusions

Although there are many technologies for detecting mines and explosive objects, they are all subject to some type of physicochemical interference related to soil properties. Knowledge of the distribution of soil properties is necessary for choosing the most effective landmine detection technology and for further safe work on target minefields. For this purpose, methods of rapid mapping of soil properties using remote sensing technology are being developed, starting with soil conductivity mapping.

In recent decades, the equipment available for demining operations has improved. Modern detectors are good at rejecting interference from mineralized soil, although they still suffer from problems with metal debris and the most unfavorable soils. Ground-penetrating radar is becoming a key technological equipment for detecting mines and explosive objects. Two-module detectors go one step ahead and reduce the number of false alarms and are successfully used by NATO troops.

Soil conductivity research systems have disadvantages, in particular, the need for direct contact of sensors (electrodes) with the ground surface, but the advantage is the uniqueness of information collection and the variety of methods of its interpretation. This allows not only to detect with a high level of reliability a foreign object (not even only a metal one), its shape and size, the depth of its occurrence, as well as the degree of heterogeneity of the soil cover. All this comprehensively allows, in addition to humanitarian demining, to collect information to determine the sequence (priority) of reclamation of disturbed lands, their return to active economic development with the possibilities and achievements of precision agriculture. All this will broadly increase the level of income from cleared land and create the prerequisites for further faster recovery of the economy. Most mine detection technologies can identify objects but do not ensure proper classification by type or recognition of the target. In this regard, establishing electric conductivity indicators can help reduce the number of false responses in ambiguous cases.

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