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DETERMINATION OF GEOMETRIC CHARACTERISTICS OF EXPLOSIVE ERUPTIONS ON AGRICULTURAL LANDS USING REMOTE METHODS

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Abstract. The armed aggression of the Russian Federation against Ukraine led to significant damage to the fertile soil layer in the temporarily occupied territories. Damage assessment for agricultural lands damaged by ravines requires determination of their geometric characteristics. There are two groups of methods for finding the area and volume of pits. The first group is contact geodetic research, which allows you to accurately determine the parameters of craters, but it is impossible to apply them due to the significant risks of shelling the territory and a large number of damaged areas. Other methods are related to the determination of geometric characteristics based on the data of remote sensing of the Earth (RS). They make it possible to quickly identify the location of explosive holes, but in wartime they are not fully available. Therefore, the complex use of remote sensing data and contact research will allow to quickly and safely determine the location and geometric characteristics of explosive craters.

The purpose of the study is to develop a methodology for determining the geometric characteristics of explosive craters due to the complex use of contact and remote geodetic data in the conditions of military operations. The main tasks of the research: analysis of existing methods for determining the geometric characteristics of explosive craters; determination of the relationship between the force of the explosion and the geometric characteristics of the eruption; development of a methodology for determining damage to the fertile layer of agricultural lands from military operations using Geoinformation systems (GIS) or technologies; practical implementation of the developed methodology on the example of a test plot of agricultural land.

The developed technique consists in the use of geoinformation technologies and remote sensing (RS) of the Earth data to determine the location and area of explosive craters. Based on the existing statistical relationships between the trinitrotoluene (TNT) equivalent of the explosion and the geometric characteristics, new functions of the relationship between the radius of the rupture and the volume, depth, and TNT equivalent of the explosion were obtained.

Cartographic models of the distribution of craters by volume, the density of explosive craters and their distribution by radius were built in the ArcGIS geoinformation software.

The constructed geomodels made it possible to evaluate the level of damage to agricultural soils and to identify the most explosive areas. Based on the obtained data, it was established that there is no correlation between the density of the holes and their radius in the presence of holes larger than 25 m.

Assessment of damage to agricultural land as a result of military operations in Ukraine requires the use of images from UAVs and satellites with ultra-high spatial resolution. In the future, it is necessary to check the adequacy of the developed methodology by field geodetic methods.

Key words: explosive eruptions, soil damage, GIS technologies, space imagery, RS, ArcGIS.

Relevance

The armed aggression of the Russian Federation against Ukraine leads to catastrophic consequences. One of the most urgent problems is the damage to the fertile layer and the littering of agricultural lands with explosive objects due to the conduct of hostilities.

According to [1], as of the beginning of June 2022, about 125,000 km^2 of territory is temporarily occupied, which is 20% of the total area of Ukraine. Further agricultural activity in these territories is quite dangerous and, in some places, impossible due to the mechanical violation of the integrity of the fertile soil layer. The intended use of these lands is possible only after reclamation works. Carrying out restoration work requires the calculation of losses caused by military operations and the determination of the geometric characteristics of explosive eruptions. According to the resolution of the Cabinet of Ministers of Ukraine (CMU) [2], the calculation of the damage caused to the land and soil as a result of armed aggression requires the determination of the area of the pits and the volume of the displaced soil.

The location and geometric characteristics of explosive craters can be determined by existing field geodetic methods, but their use is complicated due to the significant risks of shelling the territory and the large number of damaged areas. Remote geodetic methods allow to quickly detect the location of explosive craters, but have lower accuracy compared to contact methods, and, unfortunately, some data cannot be obtained during the wartime. Therefore, the complex use of remote sensing data and contact research will allow to quickly and safely determine the location and geometric characteristics of explosive craters.

Analysis of recent research and publications

The problem of determining the geometrical characteristics of the eruptions and their relationship with the TNT equivalent of the explosion was addressed by many researchers, among them V. Adushkina, V. Khristoforova, I. Sochet Radun, Jeremić, Zoran Bajić, etc.

O. Butenko, N. Kussul, Falah Fakhri, Ioannis Gkanatsios and others worked with the issue of remote studies of the above-mentioned tasks. Their work is related to the methods of identifying man-made objects in space images.

The purpose of the study

The purpose of the study is to develop a methodology for determining the geometric characteristics of explosive craters due to the complex use of contact and remote geodetic data in the conditions of military operations.

To solve the set goal, the following tasks were completed: analysis of existing methods for determining the geometric characteristics of explosive pits; determination of the relationship between the power of the explosion and the geometric characteristics of the eruption; development of methods for determining damage to the fertile layer of agricultural lands due to military operations using GIS technologies; practical implementation of the developed methodology on the example of a test plot of agricultural land.

Research materials and methods

The evaluation of mechanical damage to the soil of agricultural lands from shell explosions is based on the determination of geometric characteristics such as radius (R), depth (h), area (S) and volume of the crater (V) with the mandatory determination of their geodetic coordinates. To calculate the area and volume of the crater, it is necessary to determine the geometric figure that most accurately describes it. Thus, explosive eruptions according to [3, c. 71] are described by three geometric forms: a truncated cone, a cone of rotation, and a paraboloid of rotation. The surface area of the hole is calculated as the area of a circle - $S=\pi R^2$, and the volume according to the formulas [3, pp.71-72]:

– a truncated cone, $$V = \frac{\pi}{3} \cdot h(R^2 + R \cdot r + r^2); \quad (1)$$

– a cone of rotation $$V = \frac{\pi}{3} \cdot R^2 \cdot h; \quad (2)$$

– a paraboloid of rotation $$V = \pi \int_0^h R^2 \cdot dH, \quad (3)$$

where r – is a radius of the smaller base of the truncated cone (the radius of the bottom of the hole);

It should be noted that when the projectile falls at a small angle, the hole has an approximate shape of an elliptical cone. The area of the base of this figure is $S=\pi R_1 \cdot R_2$, where R_1 i R_2 – the smallest and largest radius of the ellipse. Volume:

$$V = \frac{1}{3} \cdot \pi R_1 \cdot R_2.$$

There are many geodetic methods for determining the above parameters, which can be combined into two groups: contact and remote.

Three methods can be distinguished among contact studies: field, statistical and combined.

The field method consists of determining the coordinates and geometric characteristics directly on the site. The most optimal geodetic survey for determining the coordinates of potholes on the terrain is a ground-space survey using GNSS receivers, and a laser rangefinder can be used to determine the depth and diameter of potholes. This method is the most accurate, but requires significant material, time costs and is dangerous due to the contamination of the territory with explosive objects.

The statistical method is based on the correlation between the type of projectiles (amount of explosive substance) and the geometric characteristics of the explosions. The use of this method makes it possible to theoretically calculate the probable geometric characteristics of the eruption. In the publication [4, pp. 71-74] shows the results of dependence (4-6) between the TNT equivalent of the explosion (q) and the geometric characteristics of the craters, which are shown in Fig. 1. The disadvantage of this method is the complexity of the calculation for different areas of the terrain due to the different geological structure of the territory and the need to know the location of craters and the type of projectiles (amount of explosive).

- crater volume V, m^3: $V = 26{,}72q^{0{,}999}$; (4)
- crater radius R, m: $R = 3{,}36q^{0{,}366}$; (5)
- crater depth H, m: $H = 1{,}78q^{0{,}316}$. (6)

The combined method consists in the complex application of the field and statistical method. Using GNSS receivers, the location of each crater is determined, and one of its geometric characteristics (diameter or height) is measured. Measurements of geometric characteristics are carried out within the test areas in order to find correlation relationships. The volume is calculated using statistical methods. This method is more effective than the above, but is impossible during military operations and before the territory will be demined.

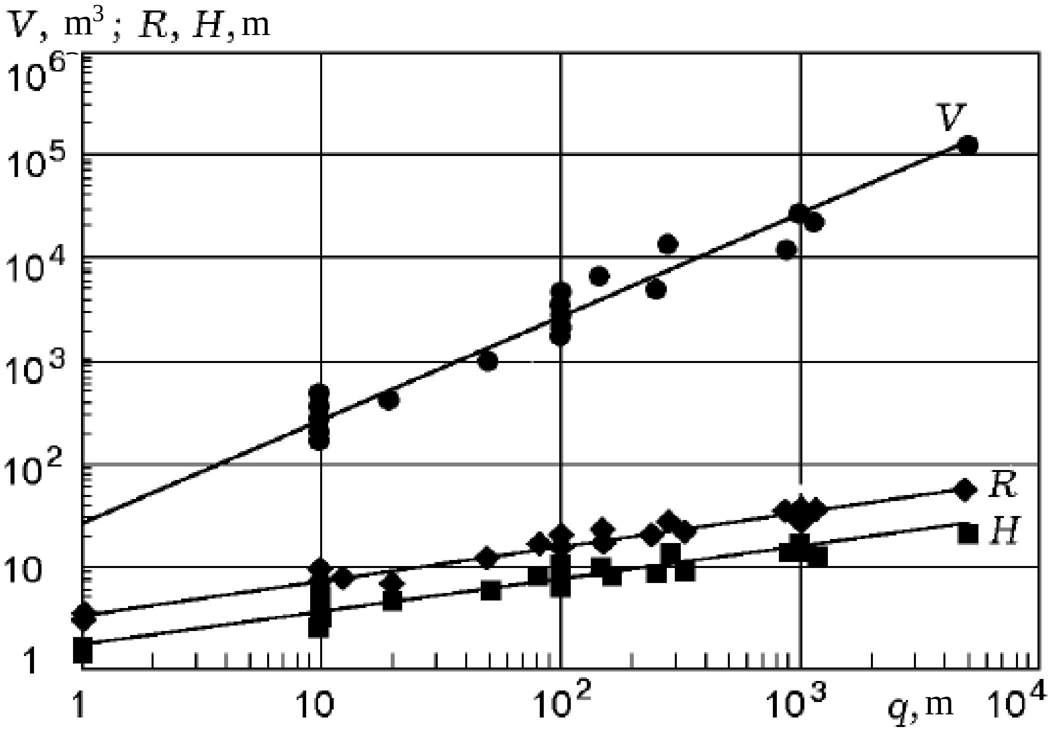


Fig. 1. The graph of the dependence between the volume (V), radius (R), depth (H) of crater and the TNT equivalent (q) of ground explosions (According to V.V. Adushkin [4])

Remote geodetic methods [5, pp. 106-110] make it possible to determine the coordinates and geometric characteristics of rifts based on images that can be obtained from satellites, airplanes, UAVs, etc. These methods are safer and more efficient and require less time and material costs. In wartime, remote sensing of the Earth data can only be obtained from satellites. Obtaining orthophoto plans from a UAV requires marking the terrain, which is dangerous due to the conduct of hostilities and the presence of unexploded shells. The use of aircraft for aerial photography during hostilities is not possible.

Satellite data with ultra-high spatial resolution is classified and will be available only after the end of wartime. Data with a spatial resolution of 10-15 m from the Sentinel and Landsat satellites, which are freely available, do not make it possible to determine the geometric characteristics of the explosion craters.

Therefore, in the near future, it is possible to determine the parameters of eruptions only with the help of space images. An archival space image with a test plot of agricultural land with ultra-high spatial resolution in the zone of environmental protection was used as a validation of the methodology (Fig. 2).

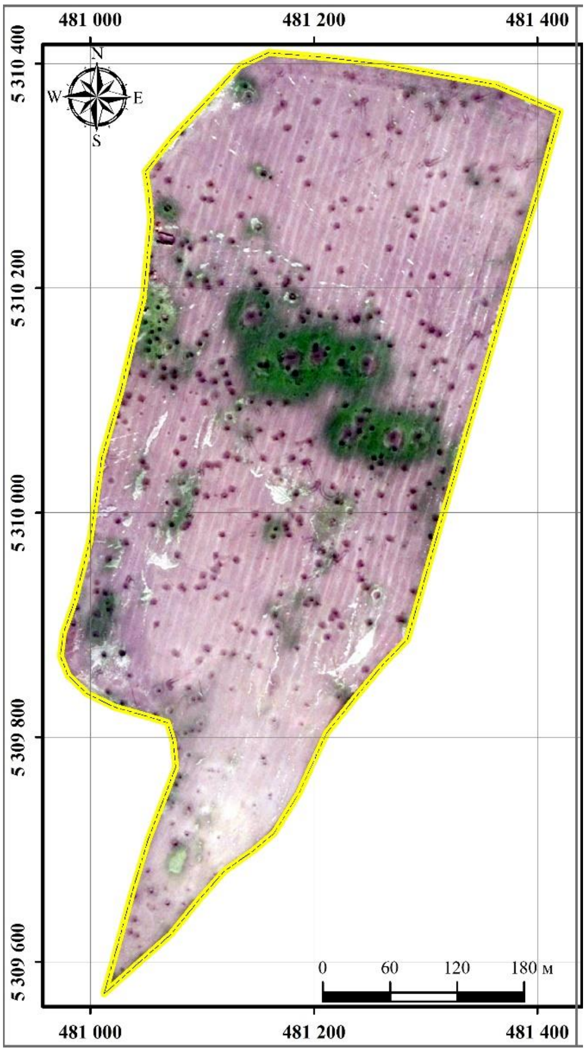


Fig. 2. Test plot of agricultural land, which is damaged by explosive holes

It is most effective to use GIS technologies for data processing and construction of geomodels [**Ошибка! Источник ссылки не найден.**, pp. 11-14]. ArcGIS (ArcMap 10.8) geoinformation software was used in the study.

The use of GIS technologies to determine the geometric characteristics of craters based on space imagery consists in the sequential execution of the following actions.

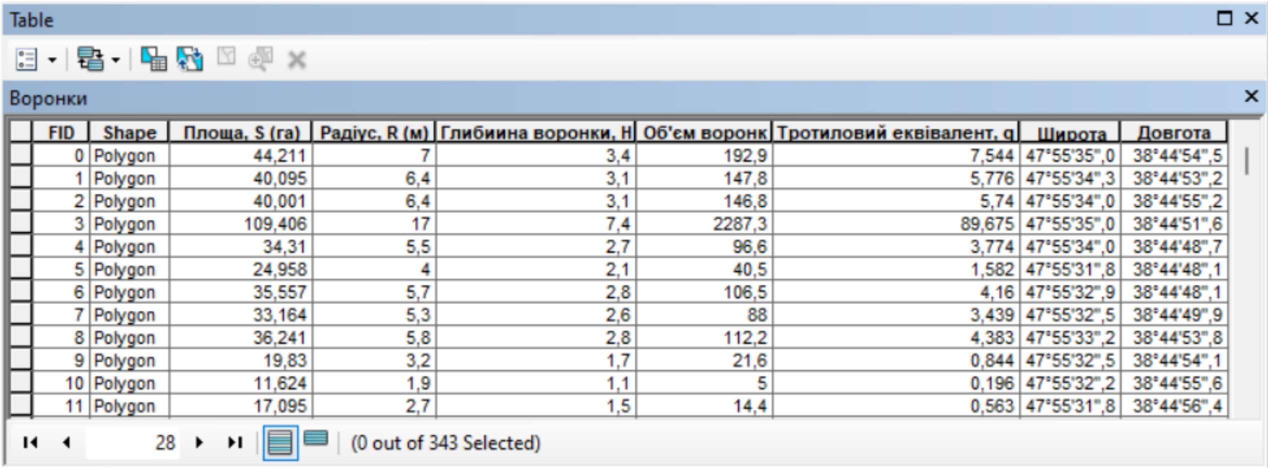
First, a project is created in ArcMap and a coordinate system is selected. Space images are attached. If there is no file with the geodetic coordinates of the corner of the picture, the raster is bound using the "Spatial binding" tool. A minimum of 3 reference points for an affine transformation (first-order polynomial) are required for accurate binding [7]. Next, the necessary vector shape layers (*.shp) are created in ArcCatalog with an indication of the object type and spatial reference. In the key layer, the vectorization of craters is carried out according to decryption features. The work describes the method of deciphering craters formed as a result of explosions of military shells [8, pp. 131-132]. An attribute table with the columns "Area", "Radius", "Depth of the crater", "Volume of the crater", "Toltile equivalent", "Latitude", "Longitude" is created to calculate the geometric characteristics of the craters. Built-in ArcGIS tools allow you to automatically determine the area of craters using the Calculate Geometry and Area functions. The calculation of the geometric characteristics of the craters was carried out using the "Field Calculator" tool. According to statistical dependences (4-6), the authors obtained new functions of the relationship between the radius of craters and their volume, depth, and TNT equivalent (7-9), which were used to determine the geometric characteristics of explosive craters. The radius is calculated by the formula: $R = \sqrt{S/\pi}$.

$$V = 0{,}977R^{2{,}729}, \tag{7}$$

$$H = 0{,}625R^{0{,}863}. \tag{8}$$

$$q = \left(\frac{R}{3{,}36}\right)^{2{,}732}. \tag{9}$$

The view of the attribute table for the test area is shown in Fig. 3.



Table

Воронки

FID	Shape	Площа, S (га)	Радіус, R (м)	Глибиина воронки, Н	Об'єм воронк	Тротиловий еквівалент, q	Широта	Довгота
0	Polygon	44,211	7	3,4	192,9	7,544	47°55'35",0	38°44'54",5
1	Polygon	40,095	6,4	3,1	147,8	5,776	47°55'34",3	38°44'53",2
2	Polygon	40,001	6,4	3,1	146,8	5,74	47°55'34",0	38°44'55",2
3	Polygon	109,406	17	7,4	2287,3	89,675	47°55'35",0	38°44'51",6
4	Polygon	34,31	5,5	2,7	96,6	3,774	47°55'34",0	38°44'48",7
5	Polygon	24,958	4	2,1	40,5	1,582	47°55'31",8	38°44'48",1
6	Polygon	35,557	5,7	2,8	106,5	4,16	47°55'32",9	38°44'48",1
7	Polygon	33,164	5,3	2,6	88	3,439	47°55'32",5	38°44'49",9
8	Polygon	36,241	5,8	2,8	112,2	4,383	47°55'33",2	38°44'53",8
9	Polygon	19,83	3,2	1,7	21,6	0,844	47°55'32",5	38°44'54",1
10	Polygon	11,624	1,9	1,1	5	0,196	47°55'32",2	38°44'55",6
11	Polygon	17,095	2,7	1,5	14,4	0,563	47°55'31",8	38°44'56",4

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(0 out of 343 Selected)

Fig. 3. Attributive table of geometric characteristics of explosive eruptions vectorized according to a space image

At the next stage, cartographic models of the distribution of craters by volume, density of explosive craters and their distribution by radius were built. The above geomodels were created using the Kriging interpolation tool [9].

Research results

As a result of deciphering the space image, 343 eruptions were identified in the test area. The minimum set size (radius) of the crater is 0.4 m, the maximum is 48.5 m, the average radius is 5.4 m, the mode is 4.8 m, and the median is 4.1 m. The frequency distribution of craters by size is shown on Fig. 4.

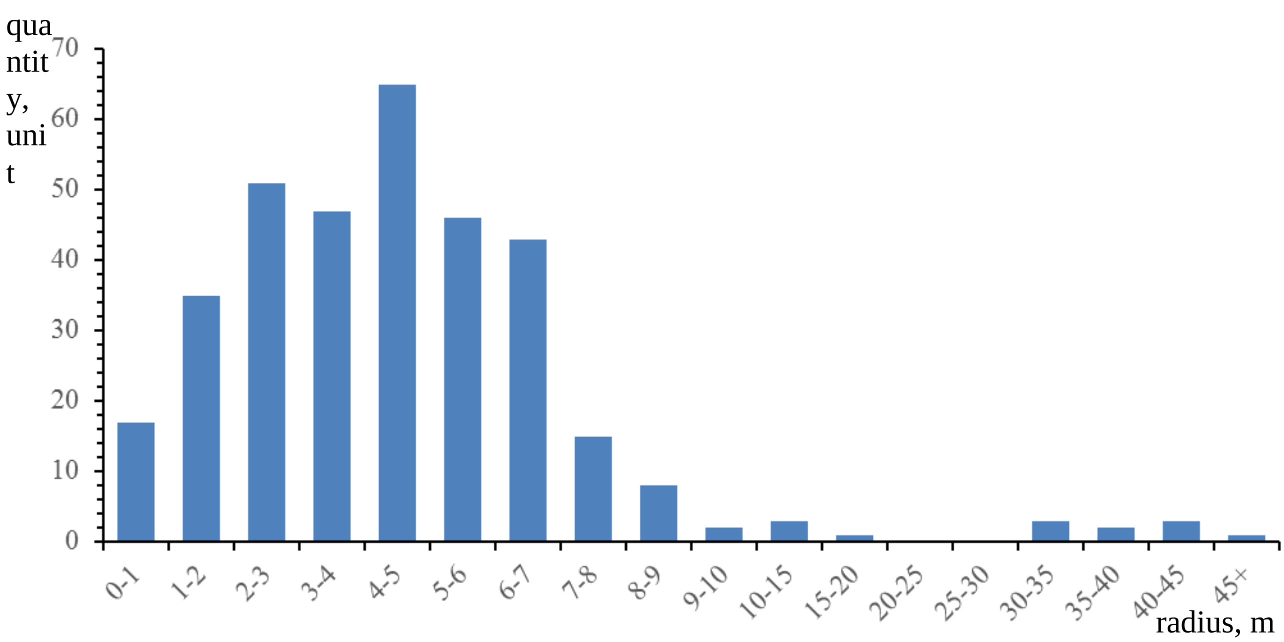

Fig. 4. Frequency distribution of the number of craters by their radius

The total area of the damaged top layer of the soil on the test land plot was 1.18 ha, which is 5,8% of the entire arable land. The area of the craters varies in the range from 2,7 to 304,8 m^2, average – 34,2 m^2. Depth – from 0.3 to 17.8 m, the average is 2.6 m. The calculated total TNT equivalent of the explosions within the area was approximately 11 tons.

The total volume of damaged (displaced) soil was 278.8 thousand m^3. The volume of craters varies from 0.1 m3 to 37,296 m^3, with an average value of 810.5 m^3 of soil. Visualization of soil damage is shown in fig. 5. Spatial distribution of craters and soil damage within the area is not uniform.

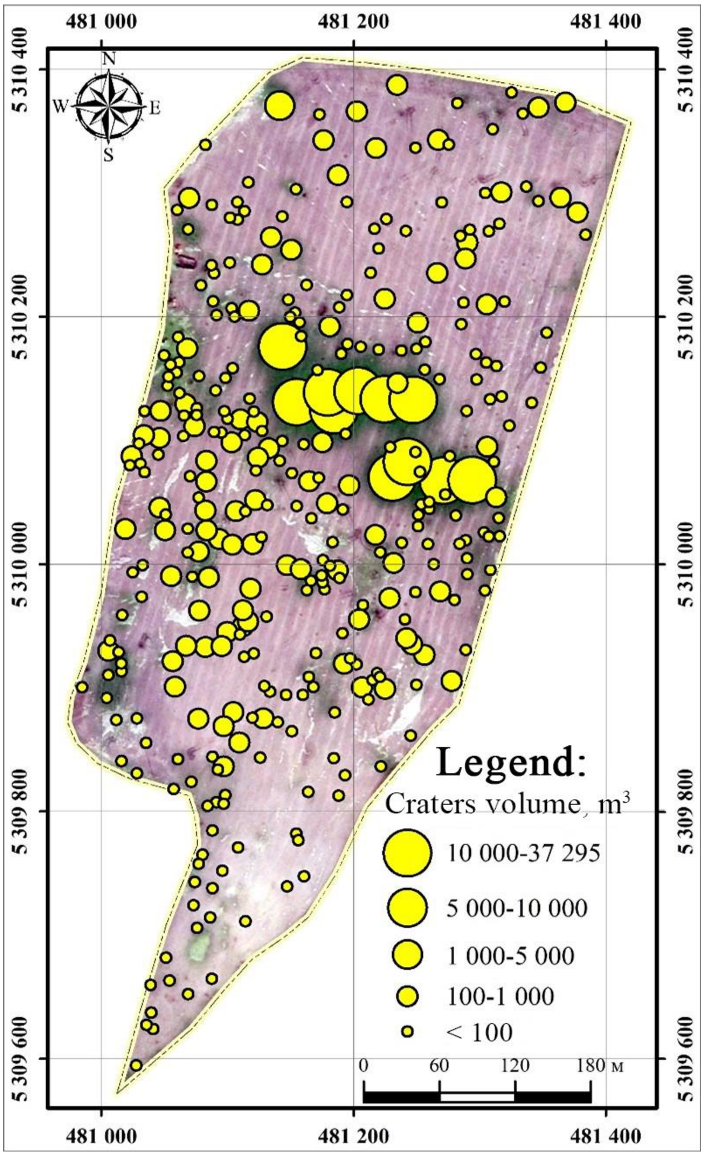

Fig. 5. Cartographic model of the distribution of blast holes by volume within the test area

The average number of pits per unit area is 17 units per hectare. At the same time, the highest density is more than 60 craters per hectare and is concentrated in the western part of the site, and the lowest is less than 5 craters per hectare in the northern and southeastern parts (Fig. 6). These data can be used in the prediction of explosive areas.

The concentration of craters in terms of size within the test area is quite heterogeneous. With a more or less uniform distribution of craters up to 10-15 m in size throughout the test area, a zone in the central and eastern part with a concentration of holes with a radius of more than 25 m is clearly distinguished (Fig. 6).

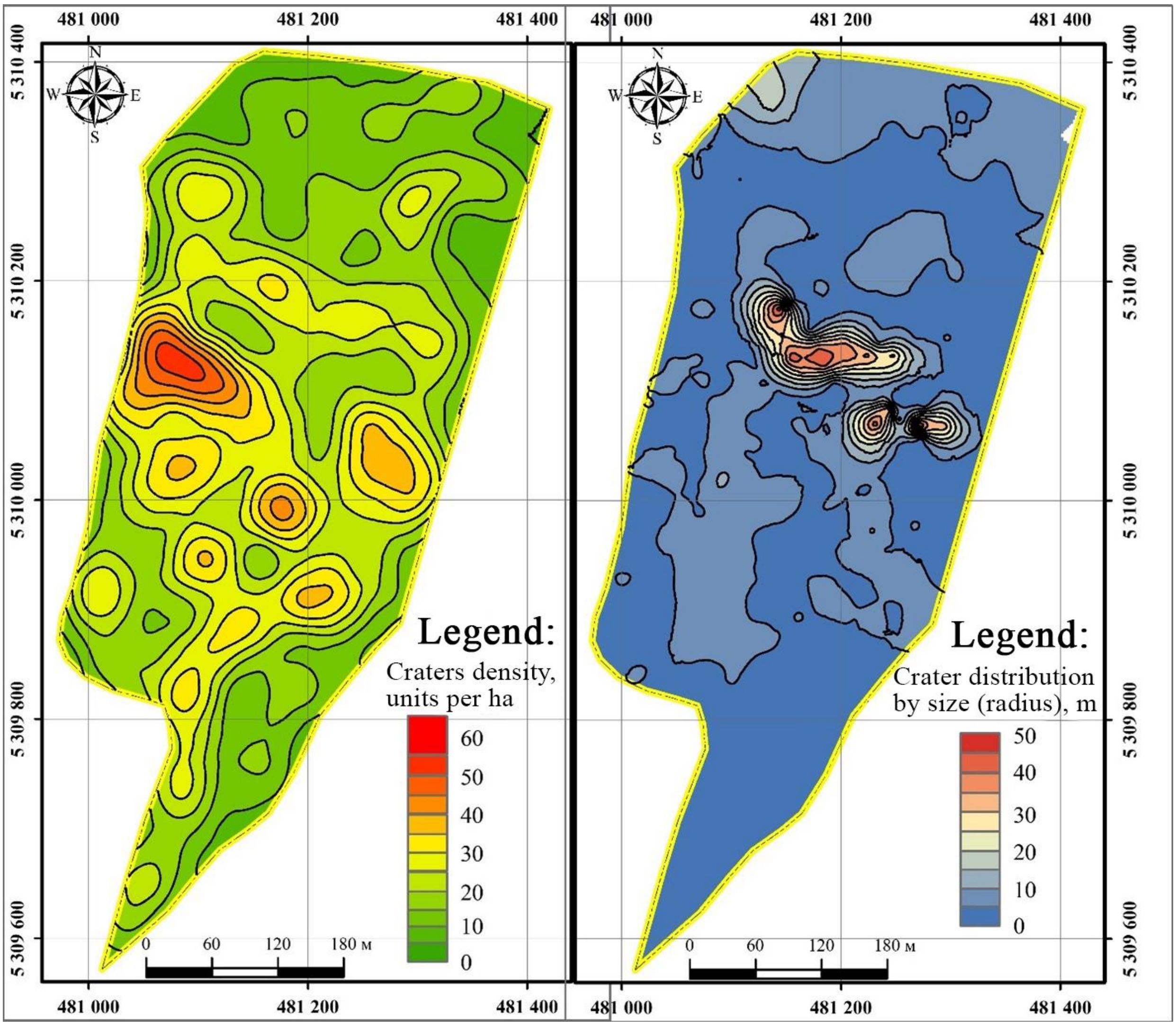

Fig. 6. Map of density (on the left) and distribution of explosive craters by size (on the right)

The analysis of the created geomodels showed that there is almost no correlation between the density of landslides and the volume of the damaged area. This is confirmed by the fact that 7 craters larger than 30 m account for 89.9% of the volume of damaged soil (the central part of the studied area), while the density of craters in this area is 15-30 units per hectare.

Conclusions and perspectives.

The analysis of existing methods for determining the volume of damaged soil showed that field geodetic methods are suitable for accurate determination of the geometric characteristics of explosion craters, but require significant material and time costs and are impossible during hostilities, in turn, remote methods are effective for prompt establishment and identification of these areas, but due to limited access to data, they are ineligible for the volume of excavation calculation. Therefore, the complex use of contact and remote data allows to quickly detect craters and calculate their geometric characteristics.

The developed technique allows to quickly and safely calculate the geometric characteristics of craters based on remote and contact data on agricultural lands. The built geomodels made it possible to assess the degree of damage to agricultural soils and to determine the most dangerous areas. According to the obtained data, it was established that there is no correlation between the density of craters and their radius in the presence of craters larger than 25 m.

Assessment of damage to agricultural land as a result of military operations in Ukraine requires the use of images from UAVs and satellites with ultra-high spatial resolution. In the future, it is necessary to check the adequacy of the developed methodology by field geodetic methods.

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ВИЗНАЧЕННЯ ГЕОМЕТРИЧНИХ ХАРАКТЕРИСТИК ВИБУХОВИХ ВИРВ НА ЗЕМЛЯХ СІЛЬСЬКОГОСПОДАРСЬКОГО ПРИЗНАЧЕННЯ ДИСТАНЦІЙНИМИ МЕТОДАМИ

Анотація. Збройна агресія Російської Федерації проти України призвела до значного пошкодження родючого шару ґрунтів на тимчасово окупованих територіях. Оцінка збитків для земель сільськогосподарського призначення пошкоджених вирвами потребує визначення їх геометричних характеристик. Існує дві групи методів для знаходження площі та об’єму вирв. Перша група – контактні геодезичні дослідження, які дозволяють точно визначити параметри вирв, але їх не можливо застосувати із-за вибухонебезпечності території й великої кількості ушкоджених ділянок. Інші методи пов’язані з визначенням геометричних характеристик за даними дистанційного зондування Землі (ДЗЗ). Вони дозволяють оперативно виявляти місцезнаходження вибухових вирв, але у військовий час не доступні у повному обсязі. Тому, комплексне використання даних дистанційного зондування та контактних досліджень дозволить швидко то безпечно визначати місцезнаходження й геометричні характеристики вибухових вирв.

Метою дослідження є розроблення методики визначення геометричних характеристик вибухових вирв за рахунок комплексного використання контактних і дистанційних геодезичних даних в умовах ведення бойових дій. Головні завдання дослідження: аналіз існуючих методів визначення геометричних характеристик вибухових вирв; визначення залежності між силою вибуху та геометричними характеристиками вирви; розробка методики визначення пошкодження родючого шару сільськогосподарських угідь від військових дій з використанням Геоінформайних технологій (ГІС-технологій); практична реалізація розробленої методики на прикладі тестової ділянки сільськогосподарського угіддя.

Розроблена методика полягає у використанні геоінформаційних технологій та даних ДЗЗ для визначення місцезнаходження та площі вибухових вирв. За існуючими статистичними залежностями між тротиловим еквівалентом вибуху та геометричними характеристиками отримані нові функції взаємозв'язку між радіусом вирви і об'ємом, глибиною та тротиловим еквівалентом вибуху.

У геоінформаційному програмному забезпеченні ArcGIS побудовані картографічні моделі розподілу вирв за об'ємом, щільності вибухових вирв та їх розподілом за радіусом.

Побудовані геомоделі дозволили оцінити ступінь пошкодження ґрунтів сільськогосподарського призначення й визначити найбільш вибухонебезпечні ділянки. За отриманими даними встановлено, що між щільністю вирв й їх радіусом при наявності вирв розміром більше 25 м відсутній кореляційних зв'язок.

Оцінки збитків для сільськогосподарських угідь внаслідок військових дій в Україні потребує використання знімків з БПЛА та супутників з надвисоким просторовим розрізненням. У подальшому необхідно перевірити адекватність розробленої методики польовими геодезичними методами.

Ключові слова: вибухові вирви, пошкодження ґрунту, ГІС-технології, космічні знімки, ДЗЗ, ArcGIS.