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ERT, GPR, and magnetic surveying: the case study of Khayrabadtepa settlement (Southern Uzbekistan)

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ABSTRACT
The use of geophysical methods has become an integral part of the work at all stages of archaeological research. Geophysics contribute to the efficient and rapid detection of buried objects. One of the effective methods for mapping archaeological sites is the magnetic survey that reveals anomalies associated with the residual magnetization of such objects. To study the deep structure of complex objects in conditions of variable relief, the method of electrical tomography (ERT) has been well recommended. Ground Penetrating Radar (GPR) measurements delineate buried structures in soil strata. Geophysical work was carried out within the boundaries of the settlement of Khayrabadtepa, which is a monument of the Kushan period in the territory of Northern Bactria. The settlement is located 1 km southwest of the city of Angor, 30 km northwest of the city of Termez.

Section: RESEARCH PAPER

Keywords: Geophysics; archaeology; ERT; GPR; magnetic surveying

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1. INTRODUCTION

Khayrabadtepa is an ancient settlement located in the Surkhandarya region of the Republic of Uzbekistan. It was founded in the 4th-3rd centuries BC and is one of the most ancient archaeological sites in the region (Figure 1). The settlement is located on a high hill, which is surrounded by a wall 800 m long, circa. Inside the walls are the ruins of ancient structures such as buildings, baths, temples and other features.

Archaeological research has shown that Khayrabadtepa was a large and prosperous city that played an important role in the trade and culture of the region. Various items have been found in the city, such as pottery, metalwork, jewellery, and ancient coins. Today, the ancient settlement of Khayrabadtepa is a popular tourist attraction.

The first studies of the fortress were carried out in 1953 by the staff of the Institute of History and Archaeology of the Academy of Sciences of the Republic of Uzbekistan L. I. Albaum and V. D. Zhukov, who studied the citadel and Shahristan. Shahristan is part of Iranian and Central Asian cities, located inside the city walls, but outside the citadel. Usually, it had geometrically correct outlines of city walls and sometimes the layout of streets [1]. In 1975 the wall section was made to clarify the construction of the fortress walls. This study further revealed four construction periods [2].

Figure 1. Overview of the site and measurement area. (A) Location of the ancient settlement Khayrabadtepa (basemap: Map data ©2023 GeoBasis-DE/BKG (©2009), Google, Mapa GISrael); (B) Google Earth image of the site (basemap: Imagery ©2023 CNES / Airbus, Maxar Technologies, Map data ©2023). The area of interest is visible inside the squares.

The settlement is rectangular in plan, oriented from north to south with some deviation from north to west; its length in this direction is 280 m, and from west to east - 120 m. The walls in the form of deteriorated ramparts are preserved at a height of 6-9 m. On the outer side they rise at an angle from 35° to 45°, and on the inner side they are at the same level of the surface of the settlement [3]. The shahristan, a characteristic feature of a site from this period, is divided into two parts: a southern and a northern section. The wall separating these two parts runs approximately down the middle of the settlement and remains in the form of a low rampart which can be seen even today, with an average height of 1 m.

Early research indicates that the southern part of the hill fort may have contained several large structures, while the northern part contained traces of pottery, which can still be traced today by ceramic slags in the north-eastern part of the settlement. Unfortunately, the entire surface of the settlement is covered by a layer of loose soil making such visual detection difficult today. This degradation is mainly connected with agricultural works and irrigation of vegetable gardens of residents located to the south and west from the site [3].

For an extended duration, archaeologists were unwavering in their belief that geophysical prospecting outcomes on their own would provide limited contributions to solving intricate archaeological puzzles. However, contemporary consensus underscores the routine integration of some form of geophysical exploration as an essential precursor to initiating modern archaeological excavations [4], [5], [6], [7], marking a shift in perspective where geophysical prospecting has seamlessly evolved into an indispensable foundation of standard excavation protocols.

The primary purpose of using geophysical methods to address archaeological tasks is to predict the spatial distribution of anomalies within the research site and to identify signs of anthropogenic influence. During the investigations at the archaeological site, a series of geophysical methods was employed, including magnetic surveying, ERT and GPR. The overall methods are widely used in modern archaeological geophysics and yield promising results. It is worth noting that a comprehensive interpretation of the data allows for more detailed investigation, which is a crucial advantage when mapping and studying cultural heritage objects [8].

ERT enables the detection of structural disruptions in the upper layers of the soil, identified by zones of localized changes in resistivity (in comparison to the surrounding section). Such anomalies can indicate the presence of archaeological features and even help refine their dimensions. Local increases in resistivity may suggest the existence of stone structures. Such enhancements are often observed in areas where stones were used in the construction of buildings [9]. Magnetic surveying often detects abrupt changes in the magnetic field in areas of main and entrance pits, and localized changes in the magnetic field signify the presence of large metallic objects. Local increases in the magnetic field are frequently registered in locations with accumulations of burnt stones and stone structures. Finally, GPR allows one to scan and detect underground utilities by changes in the dielectric constant of the soil structure and the objects inside [10], [11], [12].

Geophysical work has focused on studying a hill fort, where early research, as mentioned above, suggests that there may be significant differences in the types of structures present in the southern and northern parts of the site. While pottery traces have been identified in the north-eastern part of the settlement, loose

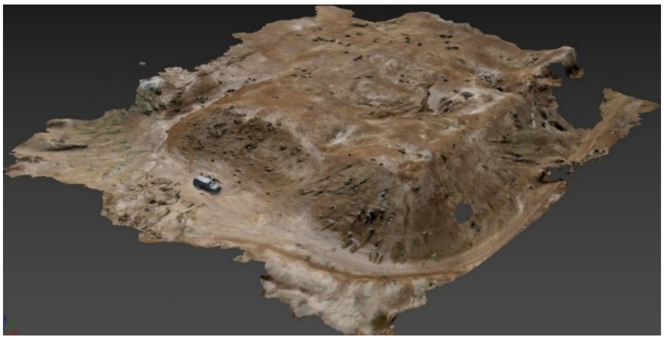

Figure 2. Orthophoto of the work area (A. Zakirov).

soil has covered the entire surface of the site, making such investigations challenging.

2. METHODS AND METHODOLOGY

Investigations using geophysical methods at Khayrabadtepa were concentrated in the north-eastern corner of the fortress, to study the modes of defence, namely fortifications - walls, towers, as well as the adjacent inner-city development. Photogrammetric survey was carried out to create an orthophoto model of the work area (Figure 2).

The area of the geophysical magnetic survey was 50 × 50 m and located in North corner of the settlement (red square in Figure 1). The magnetic survey was carried out using two Geometrics 856AX proton magnetometers. Two sensors connected to one magnetometer were used for field measurements, which allowed us to measure two profiles at once to increase the efficiency of the work. The distance between the sensors was 50 cm, so that the step between the measurement points and the profiles was 50 cm (Figure 3). Another magnetometer was also employed to measure the daily changes of magnetic field.

However, it is worth pointing out that for the detection of archaeological objects, conducting fieldwork with a

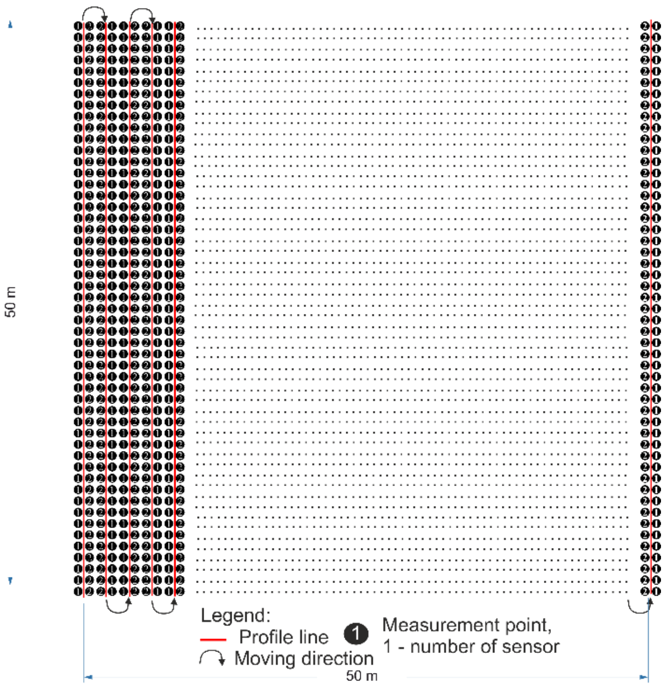

Figure 3. Scheme of magnetometry measurements.

magnetometer of this type was quite a labor-intensive process. The proton magnetometer produces discrete data records only at the observation point; not allowing for continuous data recording between observation points. Despite this fact, various objects are clearly distinguished on the map of magnetic anomalies even without serious processing of the field data.

ERT was carried out to detect large objects close to the surface, as well as to detect objects located at a deeper level for future detailed work. Electrical prospecting was carried out along two profiles (the blue lines in Figure 1). The first profile crossed the settlement diagonally in the direction from northeast to southwest; the second was carried out along the northeast wall, in the direction from northwest to southeast. ERT was conducted with a 72 electrode georesistivimeter M.A.E. X-612EM, with 5 m electrode spacing, using “Dipole-Dipole”, “Schlumberger” and “Pole-Dipole” measurements array. The distance of 5 m between each electrode was chosen to explore the change in electrical resistivity over the area of the settlement and to identify anomalies associated with buried structures.

GPR measurements with 250 MHz antenna were carried out 70 m to the southeast from magnetic field measurement area (yellow square on Figure 1). These measurements were carried out by 1x1 m grid, total area of GPR investigation was 30x30 m.

2.1. Processing of magnetic survey data.

Data processing was carried out using standard procedures, which included: the subtraction of the daily geomagnetic background, the binding of the results obtained, and the construction of maps of geomagnetic field anomalies (Figure 4).

In Figure 4, anomalies caused by metallic objects (debris) on the surface can be observed, which are often considered to be false anomalies. Additionally, the "banding" seen in the profiles, was most likely caused by a zero-shift during the measurements due to an increase of the temperature of the device.

2.2. Processing of ERT data.

The software package x2ipi was used to assign elevation values to each survey point and to edit the data. Data editing included the elimination of anomalous measurement results and

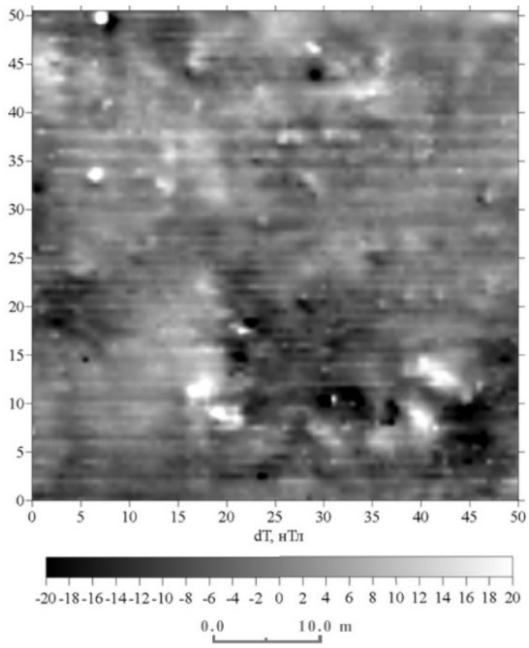

Figure 4. Map of magnetic anomalies.

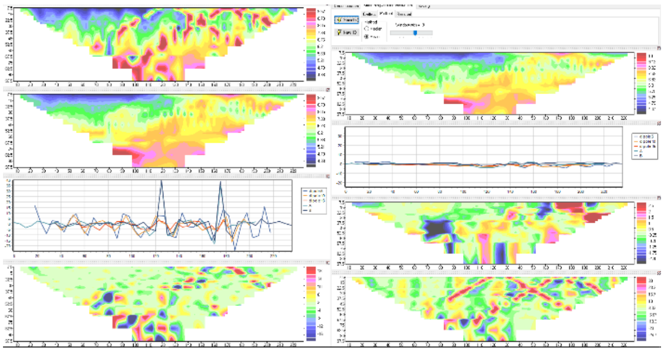
Figure 5. ERT field data filtering in X2IPI software.

the elimination of P- and C-effects caused by potential weak grounding of the supply and receiving electrodes (Figure 5). These procedures are conducted to produce a stabile inversion procedure to get more informative resistivity sections.

Further processing was carried out to calculate an inversion based on the model in the software package Res2DInv [13], [14]. The algorithm for calculating the inversion consists of fitting the model of the apparent resistances to the measured data with the calculation of the degree of inconsistency.

Various filtering, smoothing, and correction procedures were used during this process. Different methods of model calculation were based on the specificity of each profile, i.e. the length and the corresponding number of electrodes and, therefore, the depth of the study. Considering the trapezoidal shape of the obtained resistivity section, the maximum number of iterations in model calculation was used to obtain the most effective and reliable result. As a result of field data processing, the ERT method, resistivity sections and inversion models were obtained for dipole-dipole, pole-dipole and Schlumberger arrays (Figure 6, Figure 7).

From what can be seen, data obtained by dipole-dipole array has more significant resolution of near surface anomalies of resistivity while Schlumberger and pole-dipole arrays gives more information about the deep geological structure of settlement. To identify anomaly zones, the first derivative of resistivity in the vertical direction was calculated (Figure 8). This shows that most anomalies of resistivity lie 1.5-2 m under soil. To justify this further, the ERT and magnetics data were compared.

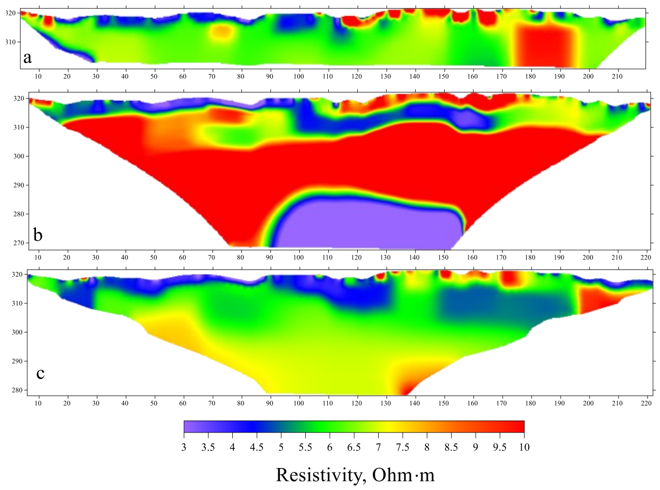

Figure 6. Resistivity section along the profile I. a) dipole-dipole, b) pole-dipole, c) Schlumberger array.

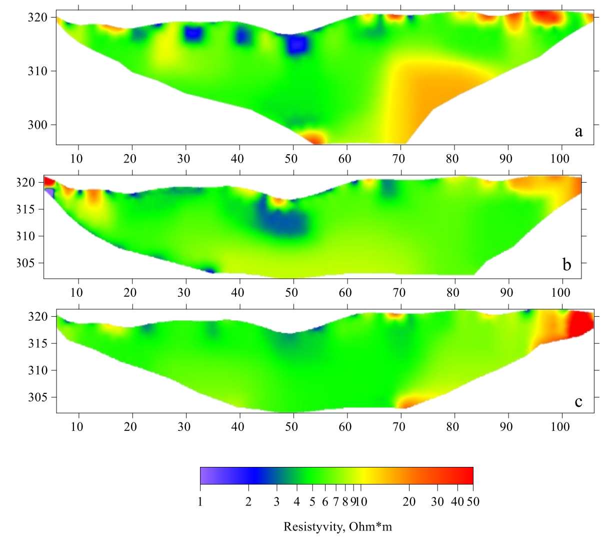

Figure 7. Resistivity section along the profile II. a) dipole-dipole, b) pole-dipole, c) Schlumberger array.

As a result of the interpretation of magnetic and electrical survey data, the most pronounced areas were identified (Figure 9).

The magnetic field anomalies forming various geometric shapes of regular form are clearly visible in Figure 9. They are probably associated with objects hidden by sediments. Objects of round and rectangular shapes are visible in the northeastern part of the magnetic anomaly map. Presumably these anomalies were related to the base of the watchtower and the part of the drainage system. Comparing the results of magnetic survey and electrical tomography, we can note that the area of elevated magnetic field values, identified by the data of magnetic survey, correlates well with the results of ERT. Geometric forms of these

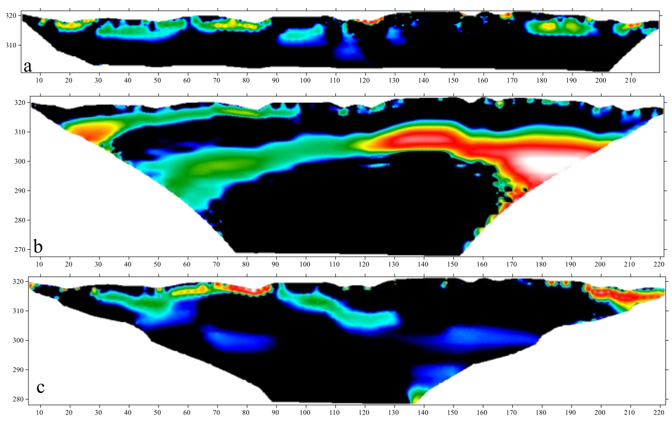

Figure 8. First derivative of resistivity in Z direction, a) pole-dipole, b) pole-pole, c) Wenner-Schlumberger.

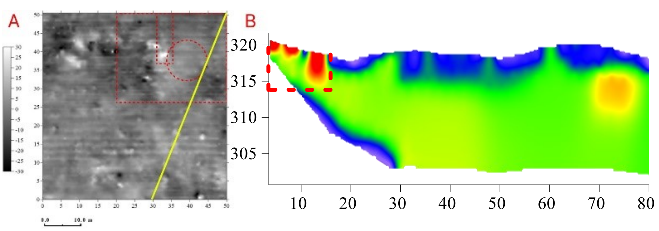

Figure 9. Comparison of magnetic survey and ERT results (profile 1): A - map of magnetic anomalies in the area (yellow color indicates profile 1 ERT); B - fragment of the ERT (pole-dipole) section.

anomalies, i.e. angularity, length or roundness, distinguish them from the background of others [4]. Such a manifestation of anomalies may correspond to structures or other objects of life activity in the past. According to archaeologists, in the north-eastern part of the wall it is assumed the presence of a defensive tower, which may correspond to the highlighted anomalies in the form of a circle.

2.3. GPR data processing

Processing of field material was carried out using the Pulse EKKO Project software package and consisted of the following procedures: average subtraction; gain; background subtraction, velocity correction, FK migration, envelope extraction. As a result, depth slices of reflected electromagnetic wave envelope were obtained (Figure 10).

Anomalies on GPR section can be assembled to objects of linear and rectangular forms, which can be associated with possible buried and/or destroyed foundations of building walls. A joint analysis of GPR and ERT data allows us to assume that a linear anomaly manifested throughout the entire GPR research area and extending from east to west appears on the section along profile I at a distance of 140-150 m from the beginning of the profile and has a resistivity value of 10 Ω·m. This anomaly is also expressed in the relief of the settlement in the form of a hill (Figure 11).

3. CONCLUSION

The reliability of the results of geophysical methods can be confirmed only after the excavations. In the area, excavations were carried out after careful processing of magnetic survey and ERT data using a priori archaeological information about the geometry (shape, depth of occurrence, orientation, etc.) of the object of interest. Four 8 × 8 m squares were laid down. A comparison of the geophysical data with the results of the excavation is shown in Figure 6.

Figure 12. shows that through the excavations two features were found. The first is the base of the tower, the contour of which spatially coincides with the position of the magnetic anomaly on the map. In addition, this area can be traced on the orthophoto model created by photogrammetry. The second feature in the form of a rectangular, elongated shape, identified on the magnetic survey data, most likely, is a drainage structure for water diversion. At the 11th and 15th m of the profile I of ERT observed high resistivity anomalies relative to the surrounding rocks. When excavating in this area, it was found that the profile ran along the edge of the base of the tower.

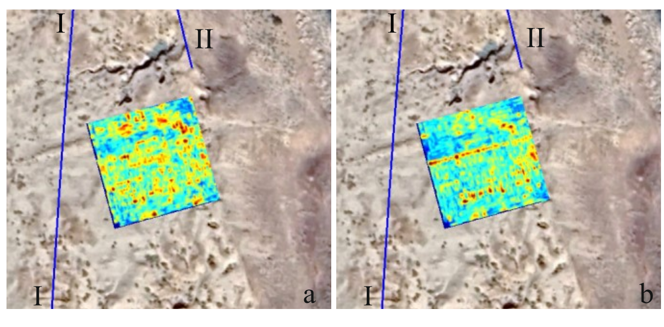

Figure 10. GPR depth slices (basemap: Map data ©2024 GeoBasis-DE/BKG (©2009), Google, Mapa GISrael); (B) Google Earth image of the site (basemap: Imagery ©2024 CNES / Airbus, Maxar Technologies, Map data ©2024): a) 1.25-1.5 m; b) 1.5-1.75 m depth slice.

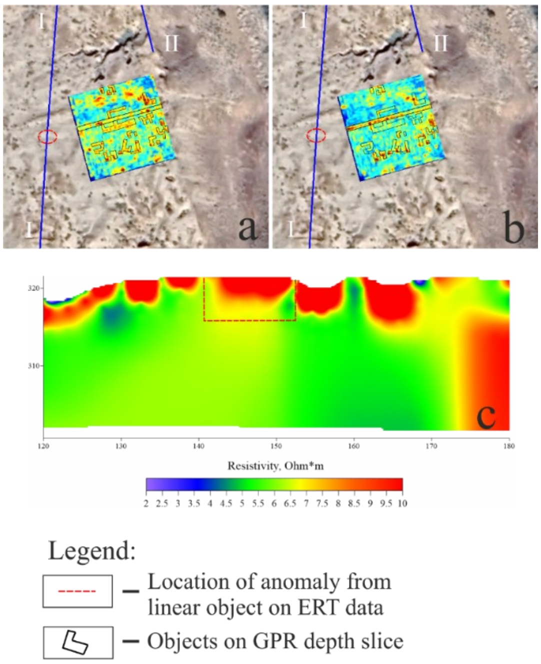

Figure 11. Result of joint analysis of GPR and ERT data with indication of anomalies (basemap: Map data ©2024 GeoBasis-DE/BKG (©2009), Google, Mapa GISrael); (B) Google Earth image of the site (basemap: Imagery ©2024 CNES / Airbus, Maxar Technologies, Map data ©2024): a) 1.25-1.5 m; b) 1.5-1.75 m depth slice; c) part of profile I section.

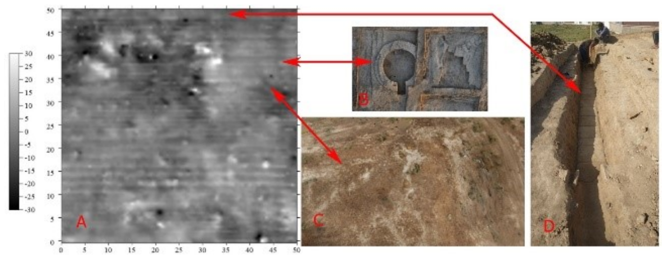

Figure 12. Joint analysis of the results of excavations and geophysical methods of the studied area: A - map of the geomagnetic field anomaly; B - supposed base of the defensive tower; C - result of photogrammetry on the surface of the area; D - supposedly a drainage structure.

The excavations of the upper horizon of the corner tower showed that the last period of its habitation can be dated to the late Middle Ages by the presence of the remains of a hearth. The hearth was found literally on the surface, lined with fragments of burnt bricks measuring 28x28x6 cm. Several small fragments of glazed pottery (mostly corolla) with white glaze and blue color on the corolla were found near the hearth. In addition, slag from ceramic production was found in this layer. Note that according to preliminary work and analysis of the materials found, this tower, and possibly the rooms where traces of short-lived inhabitation were found, date back to the X-XII centuries. In addition, this structure was cut into the wall of Kushan period and was erected of raw material measuring 32x32x12 cm; the traces of which were recorded to the left of the entrance to the room.

The magnetic properties of archaeological objects depend on the composition of the material from which they are made of. If the walls contain magnetic minerals such as magnetite or hematite, then they will have magnetic properties. However, if the walls are made of non-magnetic materials, then they will not have magnetic properties.

If objects have magnetic properties, then they can create magnetic anomalies on the surface of the earth. On the magnetic anomaly map, walls will appear as areas of higher or lower magnetic strength than the surrounding area. In addition, the shape and size of the anomalies may indicate the location of the walls and their geometry. However, the main problem in interpreting geophysical data may be the insufficient amount of a priori archaeological information about the object. In addition, in this area there are objects identical in composition to the covering soil, which makes their detection difficult. In addition, before starting magnetic survey, it is desirable to measure soil indicators with a kappameter. Similar studies were presented in [15].

Thus, we can conclude that methods of exploratory geophysics, such as magnetic surveying, ERT and GPR can effectively solve the most complex archaeological problems.

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