Instrumental Surveys Related to the Siege of Zrínyi-Újvár

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Due to the development processes in the scientific world, an interesting phenomenon can be observed today. As a result of this, there is a tendency to the specialisation of various disciplines and separation caused by that. However, an increasing interdisciplinary character (the merge of disciplines) can also be observed, which is normally reflected by the application of various scientific results in different fields of study. Computer-aided data processing and visualisation, the information sharing possibilities offered by telecommunication, as well as sophisticated remote sensing and signal processing technologies have created new approaches in almost every field of life. As a result, research areas in the social sciences with centuries-old traditions and well-established research methods, such as archaeology, as well as the more recent interdisciplinary battlefield research seem to be equally striving to make the most of the technical achievements of our time.

One of the primary aims of our paper is to introduce techniques and methods based on different measurement principles and their potential fields of applications, which can provide us with information without disturbing the ground for detecting, investigating, evaluating and interpreting underground anomalies of archaeological interest. Along these lines, we present procedures based on metal detectors used in practice, as well as magnetometer, radar and soil resistivity measuring, together with their limitations and some alternatives for solving the problems that may arise.

We illustrate the above in practice, through presenting the investigations carried out by our research team in recent years, as well as our experience and findings obtained during the engineering and technical support of the archaeological works conducted at the site of the siege of Zrínyi-Újvár. By the targeted handling of the arising anomalies, we managed to increase the efficiency of our archaeological work. Nevertheless, during the research, we were able to pinpoint a number of other areas where our findings may also come useful, such as soil surveying before engineering earthworks, the control of public roads and utilities, or the assessment of the condition of embankments and dams in connection with flood defence works.

Before turning to the examination of each method, it is worth presenting some data about the background and circumstances of the surveys undertaken. Since 2005, our research team – the members of which are basically former and current lecturers at the Faculty of Military Sciences and Officer Training of the National University of Public Service, and its predecessor, the Zrínyi Miklós University of National Defence – has been conducting battlefield investigations in the territory of the fortress built by Miklós Zrínyi, poet and military leader, to defend his estate in Muraköz. It is located in the close vicinity of the current border between Croatia and Hungary. The excavations of the remains

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of Zrínyi-Újvár (the rammed clay fortification of strategic importance built by taking advantage of the favourable terrain and other natural features of the area) and the traces of the 1664 Ottoman siege have been explored in many phases over several years. By now, we have had the possibility to try out a number of non-destructive methods that have offered us with enough experience to test their applicability and effectiveness. Due to the geographical conditions of the area, the necessary surveys and measurements had to be carried out mainly on hillsides covered with dense undergrowth. The speciality of the investigation was that – based on historical data – there were fights in this area only during the Ottoman siege of the fortress, so the finds could be dated with great certainty. Nevertheless, the ground was disturbed in several places by military engineering works (border fortification) in the 1950s. Additionally, the territory of the battlefield has been subjected to agricultural cultivation (viticulture) for decades. That is why, we also discovered objects and tools dated to these periods.

Analytical methods

Stabbing and cutting arms, firearms, artillery and other fighting tools, projectiles, as well as protective equipment used in the history of warfare have continuously evolved in accordance with the technological level of the given era in order to increase the effectiveness of their offensive and defensive functions. One of their most important common properties is the material they were made of. During their manufacture, specialists have always strived to use materials that were mechanically resistant, hard and relatively easy to form, which requirements were mostly met by metals. As a result, the various types of metal detectors are among the most essential instruments used in battlefield research. Besides old weaponry, they are, certainly, suitable for detecting the position of all other metal objects, such as jewellery, decorative objects, coins, tools and household utensils, depending on their settings.

However, there are many further ways for detecting artefacts, rocks, or other ‘anomalies’ hidden in the ground. The applicable methods and tools can be grouped, among other things, according to the material properties (e.g. conductivity), physical dimensions and the depth that the sought feature is found at. In terms of material structure, we can differentiate among artefacts or geological formations with detectable metal content that can be localised with metal detectors, magnetisable objects that can be detected with magnetometers, as well as non-magnetisable metal artefacts that can be identified with electrical soil resistivity measuring. In case of non-metallic features or structures, we can carry out ground-penetrating radar measuring in addition to ground resistivity testing. Furthermore, seismic and LIDAR[1] surveys, as well as aerial orthophotographs can also be employed, which are suitable for photogrammetry-based 3D modelling, vegetation analysis, thermal mapping[2] and many other purposes.

[1] Light Detection and Ranging.

[2] It can be used to identify strips of soil of different composition and disturbed ground, because they warm up or cool down at different speeds. In this way, we can demonstrate the presence of any different substance in the soil and the fact of earthmoving in the past.

Further evaluation criteria may be the speed of the surveying (that is, the size of the area that can be surveyed in one day), the size of the territory or soil depth that can be explored during each survey, as well as the accuracy and – horizontal and vertical – resolution of the measurement. Additionally, important aspects can be the level of expertise required for the measuring (for the use of the device and the evaluation of the results), the speed of evaluation (in situ or requiring lengthy post-processing), various factors affecting/limiting the use,[3] the possibility of sensor integration (joint analysis of multiple sensor results), the possibilities of post-processing by software programmes (e.g. filtering, statistical evaluation), and, during each measuring, the platform and manufacturer independence of the technology employed.

Various geophysical surveys can be ordered in Hungary as a service, so one does not have to purchase the special tools and software required by them that are often very pricey. Archaeological application, however, means much more than the professional use of the instruments. Effective collaboration between experts in different disciplines is fundamentally important, because determining the range of instrumental surveys that are needed for the successful solution of a certain archaeological question is a complex task. After formulating the question, the purpose of the survey should be clearly defined and the technologies to be used must be determined. It is important to note here that these methods of surveying alone cannot identify unambiguously the object hidden in the ground and the feature causing the anomaly. In other words, we cannot "see" into the ground with them, instruments can typically detect only one or more physical properties. During a surveying process, we can perform statistical analyses using the results of repeated tests, which can be used to determine the cause of the anomaly. In order to improve the efficiency of the evaluation of the tests and to avoid erroneous measurements, it is advisable to carry out reference tests beforehand in areas with known parameters or target objects. In the course of these tests, it is worth identifying the characteristics of the examined area and the properties of the sought objects (e.g. artefacts, structures, remains) by means of known properties under controlled conditions. Reference tests can be done on previously explored or excavated sites, or on a "test area" designed by us. It is advisable to simulate the implications of various possible interferences (e.g. radio frequency disturbances, utility lines) and how metal waste scattered on the ground, various soil composition, as well as objects placed in different depths affect the results of the measurements. As a rule, one should adapt the principles of measuring to the given survey and measure the probability parameters of "false positive" and "false negative" test results, and the correct detection of an object/feature. Preliminary investigations can also be carried out to determine the depth of detection, the size of the objects, the material and selectivity (that is, the distinguishability of underground features), as well as their relationship, the results of which can later be used to optimise the calibration of instruments.

In the following, we present the tools, technologies and methods that we used in our research in the territory of Zrínyi-Újvár.

[3] Weather, terrain, vegetation, etc.

Surveying with metal detectors

Following the early pioneers (Alexander Graham Bell, Gerhard Fischer), metal detectors began to be developed primarily for military use during World War II, and it was only later that – similarly to many other technologies – the possibilities of their civilian utilisation were considered. At the beginning, military instruments were used in archaeology. It was due to the expanding demand (requirements) that later more and more companies specialised themselves in developing such devices.

Today, possibilities offered by metal detectors are utilised in many fields of life, including preliminary surveys in the construction industry (e.g. for finding metal wires, utilities and substructures), or exploration in metal mining, security technology, law enforcement and many other areas. Depending on the financial resources available, both professional and home-made tools can be used for metal search and detection. In terms of their design and functionality, these instruments are available optimised for a specific purpose, but there are also universal devices with greater degrees of freedom to be used by experts.

According to their operational principles, metal detectors[4] can be instruments based on secondary induction (VLF[5]), pulse induction (PI[6]), and interference measurment (BFO[7]). Their operational principles will be summarised below without any in-depth technical analysis.

In case of metal detectors using the *VLF technology,*[8] two coils found in the instrument head and the associated circuits provide the physical background for operation. The outer coil loop[9] is an excited coil carrying alternating current. This (according to the Biot–Savart law) creates an alternating magnetic field around the coil, and the lines of electric field and induction surround the coil in a closed loop. When the detector head is held parallel to the ground, these lines penetrate the ground perpendicularly. If the path of this primary magnetic field is crossed by a metal object with electrical conductivity while the head of metal detector is moved parallel to the ground, (according to the Faraday–Lenz law) a voltage is induced in it due to the alternating magnetic field. It causes an electric current[10] in the target object, which tries to block the induction process above. As a result of this alternating current, a secondary magnetic field develops around the target object, the lines of which are crossed by the secondary coil[11] as the head of the detector is moved, in which a current starts to flow due to the induced voltage. That is how the metal object is detected. If we calibrate the detector before beginning the survey, we can obtain additional information about the material and physical dimensions of the target object and its relative vertical position below the ground surface by examining the characteristics of the secondary circuit, that is, by an analysis using different processing circuits. Since the material of the target object determines its electrical properties and conductivity, which in turn affects

4 *Gee:* Metal detectors.
5 Very Low Frequency, 3–30 kHz.
6 Pulse Induction.
7 Beat-Frequency Oscillation.
8 *Neice* 2016.
9 Transmitter Coil.
10 Eddy Current.
11 Receiver Coil.

the magnitude of the excited secondary magnetic field and induction, it is possible to determine (discriminate) the types of metals based on the rate of electric current generated in the secondary coil before removing them from the ground.[12]

In case of *pulse induction*[13] detectors, we generate hundreds of current pulses per second using two or more loops in the transmitter coil. We are able to detect the secondary induction generated by the impulses in the target object with the receiver coil. Since the magnetic properties of various metals and, therefore, the duration of secondary magnetic excitation field around them differ (e.g. it lasts longer in case of highly magnetisable materials), it is possible to deduce from the temporal distribution of the collapsed magnetic field the material of the target object, whereas the delay of the "response impulses" indicates their depth. In practice, by detecting the "echo" of substances, we can perceive and identify different target objects.

Detectors based on interference measurment[14] represent the cheapest, but, at the same time, the least reliable and least efficient solution. In this case, two separate antennas of different lengths are placed in the detector head. The smaller one is connected to the analyser input and the larger one serves as a transmitter. The coils of both antennas are excited at the same frequency from a common oscillator, as a result of which hundreds of current pulses are emitted per second through the transmitter coil, similarly to the pulse induction metal detectors. However, in this case, due to excitation at the same frequency, the magnetic field generated by the transmitter and analyser coils will interfere with each other, the magnitude of which will change in the proximity of a metallic target object found in the ground. The receiver can detect this change of interference and will signal it to the operator with an audible signal or an indicator. Using a more sophisticated digital processing unit, the indicator will infer from the extent and nature of the change the material properties or even the size of the target object.

The range of devices operating on the basis of secondary magnetic induction detection, that is, the depth at which the target object can be detected depend on the frequency of induction and collapse of the alternating magnetic field,[15] the physical dimensions of the detecting probe (the size of the transmitter/receiver antenna), and the field strength (magnitude) of the excited magnetic field.

In terms of the size and transmit power, we distinguish between short, medium and long range deep seeking detectors. These devices are not interchangeable during a complex field surveying task because of their operational features and properties. They are used in different phases of the surveying process, depending on which layer of the soil is being investigated. The increase of transmit power does not necessarily mean the enhancement of efficiency, since due to a higher transmit power, the metal content or inhomogeneous distributions of salt in the soil, as well as metal waste and pollution of different size in the upper layers or on the surface of the ground can also cause secondary induction of such extent that may lead to false detection, or – in the case of an overload saturation in

[12] Due to this property, we can either limit the amount of metals we discover in a targeted investigation, or, by proper calibration, prevent the detection of metal waste found near the ground surface.

[13] *Neice* 2016.

[14] Ibid.

[15] The extent of soil damping increases as frequency gets higher, while the depth of penetration decreases.

the receiver – it can cause excitement and malfunction. Larger probes do not necessarily result in efficiency enhancement, either. In proportion to the enhancement of the receiver antenna gain, there is a growing likelihood of receiving interference signals, the exact position (direction and distance) of the detected target object becomes more difficult to determine, and the differentiation (induced magnetic field separation) of target objects found next to each other becomes harder.

Our practical experience shows that it is advisable to use detectors of different sizes for complex investigations and for the most thorough exploration of a site. Instruments with a large seeking head or frame antenna can provide an extensive survey of a given area and detect the position of larger anomalies with an accuracy of half to one metre. It can be a particularly effective tool when looking for larger metal objects (e.g. cannonballs, body armour) found deeper underground. Devices with a smaller seeking head can be used to determine the direction and depth of a specific target object with an accuracy of 5 to 30 cm. These instruments can be used effectively to locate small artefacts (e.g. musket bullets, arrowheads, coins) close to the ground surface. Hand-held detectors and pointers can help us determine the exact position of smaller artefacts in an already excavated "research pit" from a distance of a few centimetres.

Figure 1.
Surveying with metal detectors
Source: picture made by the authors

In the case of a target object, the depth in which the detection can be effective is influenced by its properties and condition, as well as by many environmental parameters and circumstances. These may include the instantaneous conductivity of the soil (e.g. composition, water and salt content), the existence of electromagnetic interference (e.g. mobile base stations, radio transmitters, high-voltage wires, vehicles), as well as the presence of highly conductive materials (metal waste) in the soil. Concerning the sought object, its material, physical dimensions, geometry, homogeneity, degree of corrosion (oxide layer), and its orientation in relation to the power lines of the magnetic field generated by the metal detector equally influence the results.

From metal detectors applied in the investigation of the site of the siege of Zrínyi-Újvár, we used primarily the various measuring devices of the *Deepmax*[16] family of instruments manufactured by the company called *Lorenz* to survey extensive areas and to locate large artefacts and tools at great depths. The Deepmax X6 metal detector is an advanced, pulse induction deep seeking detector supported by digital signal processing (PGBS[17]), which is less sensitive to local changes in the composition, temperature and mineral content of the soil. The possibility to change the transmitter frequency offers protection against interference generated by equipment operating at the same frequency or generating harmonics there; thus, we are able to minimise harmful interference in a given test environment while undertaking the survey. Pulse mode allows measurements to be carried out at different depths by activating the receiver circuit after a certain time after radiation. In this way, the device does not detect secondary induction generated by objects found near the ground surface, but only signals arriving from a greater depth, after a longer delay. This function proved to be particularly useful during battlefield investigations, at places where – due to subsequent agricultural cultivation or other human activities – we expected the occurrence of metal waste near the ground surface, so the topsoil could be excluded from the survey.[18] At the same time, the device is also able to classify target objects according to their composition (discrimination) by determining their electrical conductivity. We concluded from the measurement carried out in practice that during the A/D conversion, the device automatically adjusts the quantisation steps to a range of values between the signal maximum and the signal minimum thereby enhancing its capacity of target object discrimination.

The results shown by *Figure 2* were obtained by surveying an area of 6 × 8 m with a large frame detector. In the case of the group of six images on the left, there was no target object in the soil, so there was only a slight difference between the maximum and minimum signal levels. That is the reason why the instrument indicated even the slightest differences with striking colouring (red areas), but it also showed during the evaluation of the data that – based on the results – the target object was unlikely to be in the soil. In the case of the group of images on the right, there were real target objects below the ground surface, the conductivity of which significantly exceeded that of their surroundings. Therefore,

16 www.metaldetectors.de/download/deepmax_x5_x6_manual_uk.pdf (Accessed: 25 July 2017.)

17 Pulse Ground Balancing System.

18 On the basis of soil structure surveys conducted during previous investigations (a test trench was dug in 2006), the rammed clay walls of the fortress are found below the 20–30 cm thick layer of soil, so the upper layer should be considered to be of no archaeological interest.

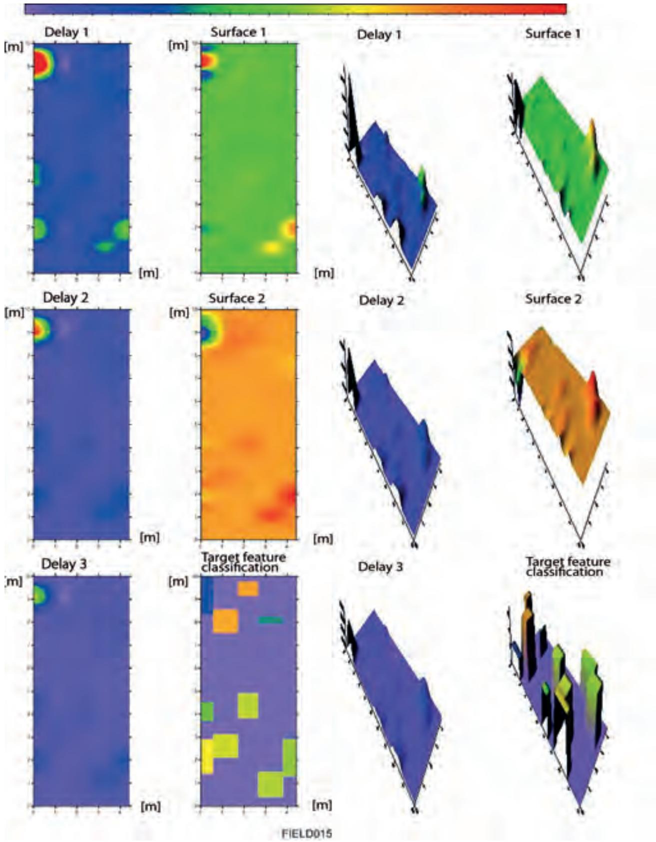

Figure 2.

2D and 3D representation of the results of the survey

Source: compiled by the authors

the instrument compensated for small conductivity fluctuations and strongly differentiated the sought objects from their background. Subsequently, it identified the material of these objects and represented them on the area on the basis of a colour code.

In addition to the frame, the instruments can be fitted with coils of various sizes and types. This allows us to scan the area with a coil that is the most suitable for the nature of the survey task. The size of the seeking head defines the magnitude of the excited magnetic field and, therefore, the theoretical limit of the scanning depth. Antennas in the seeking head can be targeted less or more, depending on the character of the research, that is, whether the primary goal is the scanning of a large area or accurate detecting in a given site.

The instrument can be used in both reconnaissance and "mapping" modes. The latter is possible only if a special measuring frame is used, since we need to identify the position and orientation of the area to draw the "map". In *reconnaissance mode,* the device can equally be used with a conventional double "D" search coil and with a deep seeking frame. In this case, we identify the horizontal position, as well as the estimated depth and

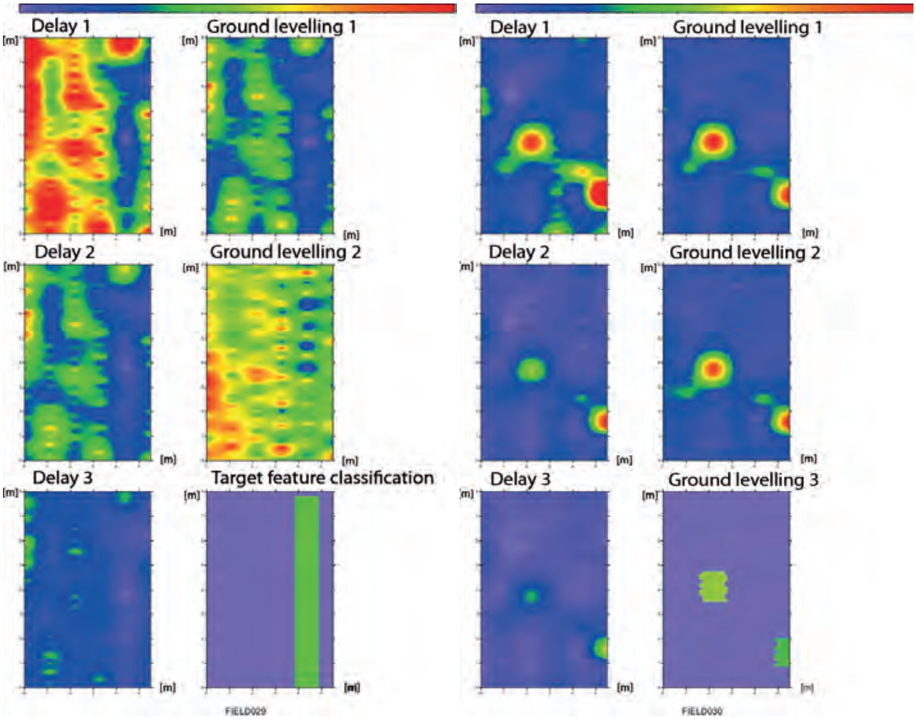

Figure 3.
The results of surveying at a site without any target object (left) and with a target object (right)
Source: compiled by the authors

material of the artefacts. By contrast, in *mapping mode,* the instrument offers the systematic examination of a pre-defined area. It records the results of the survey (measured values) and the coordinates of the surveyed site (when a GPS unit is connected), analyses them with the help of a computer data processing application, and displays them visually, in the form of colour 2D or 3D images *(Figure 3).* In this mode, the instrument automatically adjusts its parameters (receiver sensitivity, ground levelling and delay) according to a sequence of measuring.

During the use of the device, we sought effective answers to questions related to the management and analysis of the results, such as increasing the efficiency of surveying procedures and instruments, the planning and preparation of the surveying, the non-perturbed operation of different metal detectors at the same time, improving the accuracy of target object recognition, as well as the methods of analysing the measurement results and displaying the processed data.

From the aspect of the accuracy of the measurement results, it is important to delineate precisely the area to be surveyed and also to maintain the direction and speed of detection throughout the survey. If these conditions are met, whether the survey is performed with a hand-held metal detector head or with a deep seeking frame supplied with a carrying strap, the errors resulting from the management can be significantly reduced. In the case of our survey conducted in the area of Zrínyi-Újvár, we examined the applicability of the following methods: marking out the site with laser, the use of a conventional, hand-held GPS device, the application of a built-in solution (GPS module), recording the coordinates of the site corner points with a GPS, as well as indicating strips of the area with signal poles or cordons.

The disadvantage of marking out the borders of the site with laser was that the visibility of the light source was often poor when working at daylight. The GPS receiver offered precise and reliable navigation, but because the receiver itself contains electronic parts and circuits, as well as other metal components, it can be considered an external source of interference from the aspect of the survey. At the same time, the device has its own GPS unit designed for this purpose that can be optionally connected. In practice, however, it often proved to be insufficient as its horizontal accuracy was below three metres, even when the sky was almost completely visible. In addition, it was supposed to record the position of the operator, instead of the position of the frame, but it could only be attached to the carrying strap of the frame.

Although marking out the survey area with "traditional" methods was the most time-consuming and labour-intensive process, due to its accuracy, the use of signal poles and cordons proved to be the most effective solution.

Practical experience has shown that the pre-use calibration of the receiver of the detecting instruments and the removal of perturbing signals and the metal content of the soil by setting the device are important, as well (also for the accuracy of the measuring). The setting must be done over a flat area that does not contain any target objects and metal waste, which can be pre-checked with a hand-held device. Before the survey, it is also worth checking the settings for acoustic and visual signals – sound effect and displayed values – for target objects (e.g. keys, pocket knives, musket balls and other formerly discovered artefacts) with known wave forms to prevent the need for a repeated measuring due to the application of incorrect configuration. The accuracy of the measurement can be greatly enhanced if we make sure that the detecting frame is held parallel to the ground surface and that its distance from the ground is constant while we walk through the area.

When planning the measuring, the following points are worth to be considered to minimise the risk of errors resulting from incorrect handling by the operator, even when using multiple instruments at the same time. One of the most crucial issues in this case is to allow enough space – that is, minimum interference protection distance – between the individual instruments so that their detection processes would not be affected by the primary magnetic fields of other metal detectors used next to them. It is also important to consider in advance what types of objects we seek and how the ground surface looks like, because the detector head needs to be selected accordingly. Furthermore, if the site requires it, it is advisable to "clean up" the ground before the survey (that is, to remove the undergrowth, fallen leaves, waste and debris). It is important to make sure that there is no physical obstruction or restraint when swinging the instrument parallel to the ground surface, because it would result in skipping a small area and thus pose risk that some target objects in the ground remain undetected. In case of uneven ground surface, it is advisable to change the orientation of the head of the metal detector several times during the survey, and thus examine a given place from multiple directions, since the responses to induction vectors arriving from different directions may differ depending on the location of the target object. Consequently, it may occur in some cases that the receiver is not able to undertake the detection from every direction.

In order to *improve the reliability and accuracy of our measurements and the detection of target objects,* we went beyond the automated execution of the points listed in the operation manual of the device and by interpreting the responses of the instrument as closely as possible and paying careful attention to the operational principles, we carried out test measurements under controlled circumstances. During this, we placed control objects of known composition (electrical conductivity), and of various sizes and geometries on a pre-defined and cleaned "field", at different depths and distances (distributions). Afterwards, we passed over them several times at different speeds, using different head positions, and recorded the data collected in this way. We have also conducted these tests at different places with different types of soil in order to have as much information as possible about the actual operation of the device. For example, the slime pit of Lake Velence at Gárdony was selected as the site of such a validation measurement. During our first measurements conducted there, we observed the automatic scaling system of the device, which has already been shown, illustrated by the images above. The types of survey to be presented below can be used effectively to learn about the characteristics of other instruments, as well. In modern metal detectors, the *operating frequency* can be changed to avoid interference caused by the simultaneous use of multiple devices or other sources, and to minimise their effects. According to our experience, the probability of detecting metal objects of different conductivity and the extent of secondary induction may depend significantly on the relation between the wavelength of the frequency applied and the physical size of the target object, which also influences, among other things, the depth of detection. During the analysis of the *travel speed,* we have gained experience that is also logically foreseeable, namely that the resolution decreases in proportion to the horizontal velocity of the detector head, while the likelihood of measurement error increases. Slower speed allows for more accurate and reliable measurements, but it considerably restricts the size of the area that can be scanned over a given period of time. In case of hand-held instruments, the *oscillation speed* (that is, the velocity of swinging movement perpendicular to the direction of travel), also has a major effect on the detection of the target object. If the excitation and collapse of the secondary magnetic field in the vicinity of the target is too fast or too slow, the detection of the object may become uncertain or completely impossible. Depending on the relation between the spatial orientation of the target object and the vector of the primary magnetic induction, *the angle formed by the plane of the detector head and the ground surface* defines the magnitude of the secondary magnetic field in the soil and, consequently, the probability of detection. On hilly terrain and where dense undergrowth makes movement difficult, measurement errors are also likely to occur.

In case of hand-held instruments, the degree of overlap between swings fundamentally defines the resolution of the measurement. The lower the travel speed in relation to the oscillation speed, the greater the overlap (that is, the more often the detector head passes over the target object), which thus increases the probability of detecting smaller metal objects (e.g. coins). Consequently, the operator must try to achieve a higher oscillation speed than the travel speed so that the target object would cross the path of the magnetic field more often. This will, of course, also restrict the size of the area that can be scanned over a given unit of time. *Scanning depth* refers to the depth at which a target object can be still reliably and unambiguously detected. Besides the orientation of the target object and the frequency used, this also depends greatly on the physical size and material of the object. In case of equal excitation, materials with good magnetic conductivity and large metallic objects create a larger secondary magnetic field around them and can, therefore, be detected at greater depths. Modern digital instruments, with almost no exceptions, have *filtering functions* of different extent. When activated, these functions can constrain the detection of metals that are considered irrelevant. However, when using such a function, it should be borne in mind that this filtering will also reduce sensitivity towards the sought metal type in each case, and thus the probability of detecting these will also decrease. *Discrimination* can refer to differentiation by material type, as mentioned above, but this term can also be used for spatial separation. In the latter case, we studied the distinguishability of objects found close to one another in space, at different depths and distances. This may be significant, for example, to recognise the phenomenon of "artefact shielding", when a small metal object near the surface reflects a stronger signal leaving another artefact lying deeper in the ground undiscovered. This test is also advisable to be performed with the same and different types of metal finds (and "metal waste"). A single instrument used in a single mode of operation is unlikely to solve this problem, but using multiple instruments with different properties and sensitivities, we may draw conclusions about this question, as well.

In addition to the circumstances under which the measurements are performed, it may also be significant to consider how we can *process and visualise the results* available to us. The deep seeking metal detector we used was capable of capturing the data during a continuous measurement process and geo-referencing them, which made possible the non-destructive investigation of extensive areas and subsequent systematic analysis of the measurement data. Although archaeological investigations carried out with metal detectors my offer relevant information locally by themselves, statistical data obtained from a database comprising the data of a large number of artefacts with their exact location coordinates and characteristics (size, intactness, soil composition, depth) allow us to draw more complex conclusions, whether about the siege or the position of the fortification walls.

Since the incidental measurement errors can only be spotted after the completion of a surveying cycle, during data processing, it is not advisable to scan areas in dimensions of hundreds of metres in a single survey. It is worth dividing the entire survey area into grids of 20 × 20 m or 25 × 25 m size and merging the results later. It is also advisable to adopt this solution if the resources of the processing computer (laptop) are limited. Planning a survey with a hand-held instrument after deep seeking metal detecting is also easier if we need to scan a site divided into smaller parts beforehand. The Deepmax deep seeking metal detector creates 80–100 bytes of data in a single discrete measurement, on average. Since it takes samples sixteen times per second, a ten-minute surveying[19] can produce a data file up to 3–4 MB. In cases of files significantly exceeding this size, software processing and visualisation may tie up significant resources (CPU usage, memory allocation, etc.). The processing of data directly after the working in the field is fundamentally important for verification, because we can determine only in this way whether the survey was conducted

[19] Depending on the conditions of the terrain and the qualifications of the operators, an area of 16 × 12 m can be surveyed during this period of time, in general.

correctly and all data needed for the analysis of the results were recorded.[20] It may also turn out whether the surveying needs to be repeated, using a different configuration setting.

When we need to integrate (merge) the results of several surveys conducted over an extensive area, we will find that *Surfer 9* data processing software offered for the instrument is not capable of performing this task. We have worked out two methods to solve the problem in such cases. In the first case, the raw data of the survey must be joined in a semantically correct form before processing, as a result of which we receive a large input file. It will take a long time to process this file, but if this procedure is carried out correctly, the result will be accurate. The other solution is to match the images obtained after processing similarly to map sheets. If it is performed with due diligence, this procedure is hardly perceptible in the end result, and we can expect only minor inaccuracies where the pieces meet.

Although the first solution is not documented by the manufacturer, the analysis of raw data of the survey demonstrated that the instrument captures the GPS coordinates of the site together with the discrete survey data (x, y, z coordinates, magnetic field strength, electrical conductivity of the target object), and records the number of the given strip as shown in *Figure 4.*

A	B	C	D	E	F	G	H	I	J	K	L
0	0	8389234	8398645	2098756	8377461	8399268	0	4729.5601	N	1906.7491	E

Figure 4.

The structure of the recorded measurement data

Source: compiled by the authors

When visualising data collected over large areas, the need may also arise to show the results on maps (e.g. old map sheets, orthophotographs, satellite imagery, digital maps). This cannot be a problem, because the data records above include the latitude and longitude coordinates recorded by the GPS. Nevertheless, during the development of the software, the application was not prepared to use these data.

During the examination of the structure and format of the records, the format of the coordinates could be determined. Thus, after conversion, they can be used in other GIS applications, as well. *Figure 5* shows the transformation of the coordinates of a target object stored in a measurement record, which is then placed on an online GIS background as shown in *Figure 6.* (The image shows one of the sites chosen for validation tests; namely, a detail of the sports field of the Zrínyi Miklós Barracks and University Campus.) We used the free online Google Maps application for representation, but in knowledge of the format, it is also easy to depict it with any other mapping platform.

[20] If, due to the inaccuracies of the surveying, there are larger than 0.5 to 1 m wide "holes" between the surveyed strips of land, the software cannot process the data of the measurement. It leads to inconsistencies in the database, and the software cannot add a spectrum of colours corresponding to the data records of the incomplete parts of the area, which makes the software stop running.

Latitude	N47°29.5601'
Longitude	E19°6.7491'

Calculated Values - based on Degrees Lat Long to seven decimal places.

Position Type	Lat Lon
Degrees Lat Long	47.4926683°, 019.1124850°
Degrees Minutes	47°29.56010', 019°06.74910'
Degrees Minutes Seconds	47°29'33.6059", 019°06'44.9460"
UTM	34T 357827mE 5261642mN
MGRS	34TCT5782761642
Grid North	-1.4°
GEOREF	PKEC06742956

Figure 5.

Conversion of the coordinates stored in a measurement record

Note: We used the Earth Point online application to carry out the conversion: www.earthpoint.us/Convert.aspx (Accessed: 25 July 2018.)

Source: compiled by the authors

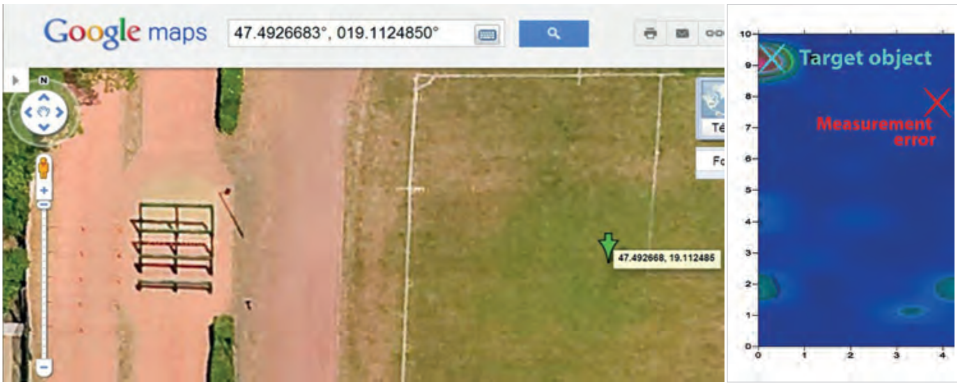

Figure 6.

Representation of coordinates obtained from the measurement data (left) and the result of superposing the information layers (delay, target classification) of the images (right)

Source: http://maps.google.hu (Accessed: 30 July 2018.)

Another advantage of the post-processing of images is that the target objects observed in the same area with different settings (delay, ground levelling) can be assessed by the interpolation of the images, and objects detected incorrectly due to measurement error can be filtered out statistically *(Figure 6).*

The excavations conducted on the territory of Zrínyi-Újvár and along the walls of the fortification imposed considerable strain on our instruments, since the terrain and the undergrowth often made it very difficult to work with them. Under such unfavourable circumstances, many measurements had to be repeated because of the erroneous or incomplete results. We are positive that there are still a great number of undiscovered metal artefacts hidden in the ground that are connected to the siege. However, due to the systematic investigations carried out over the past nearly one and a half decades, we have found hundreds of musket bullets, pieces of shrapnel, cannonballs and other metal objects, which provided us with a great deal of valuable information concerning the events of 1664. What is more, it is fundamentally thanks to these tools that we could confirm positively the existence of a stronghold near Belezna and Őrtilos.

Soil resistivity testing

If we need more information about the sub-surface soil structure in order to determine the position of former ditches, wells and other artificial structures, as well as natural formations, without digging long and deep trial trenches with physically demanding work or carrying out test drilling, soil resistivity testing can offer one of the most effective solutions. In the case of Zrínyi-Újvár, this method was used to prove our assumption that, in addition to the well discovered in 2017, there was another possibility to draw water in the fortress courtyard.

The use of soil resistivity testing (also known as geoelectrical measurement) makes possible the identification of geological formations and features above and below the ground surface by measuring their electrical conductivity. The measuring is normally conducted by placing electrodes at selected points along parallel or sometimes perpendicular lines, and excitation can be performed using either direct or alternating current. The principle and outline of the measurement are shown in *Figure 7.*

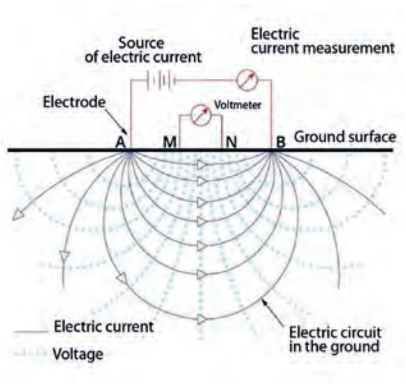

Figure 7.

The principle of geoelectrical measurement (left) and its implementation on the site in practice (right)

Source: www.researchgate.net/publication/322367522_Using_Electrical_Resistance_Tomography_to_Detect_Leaks_in_Landfills (Accessed: 30 July 2018), as well as picture made by the authors

The resistivity of soils of different composition is different, which can be calculated with the help of Ohm's law, in knowledge of the difference of electrical potential caused by the excitation current in the soil. The degree of electrical resistivity[21] of the soil depends on the electrical resistivity of its components (e.g. rocks, soil), the morphological properties of the soil particles and rocks, the structural properties of the ground and rocks, the porosity of the soil, the moisture content of the soil, the quality and concentration of the dissolved salts and minerals, as well as the temperature of the ground and rocks. The characteristic resistivity values[22] of some soil types, the arrangement of the electrodes used for the measuring, and the results of the surveying carried out in the courtyard of Zrínyi-Újvár in the spring of 2018 are shown in *Figure 8*.

Table 1.
The soil resistivity of different materials

Material	Soil resistivity (Ohmm)
granite	200–10,000
limestone, dolomite	100–5,000
basalt, andesite	200–10,000
tertiary limestone	100–1,000
sandstone	100–2,000
dry/wet gravel	100–10,000/50–1,000
dry/wet sand	50–1,000/15–100
clay marl, marl	5–50
clay	5–30
bentonite, kaolin	1–10

Note: Ohmm = Ohm-metre.

Source: compiled by the authors

Figure 8 shows a characteristic vertically oriented anomaly with low resistivity (in colour blue). It may as well indicate the site of another hypothetical well, but the results of the subsequent test drillings suggested that we discovered the remains of a natural geological formation rather than a filled-up well. Consequently, we have not yet been able to prove our assumption. *Figure 9* shows the results of parallel measuring lines projected onto a LIDAR image after matching.

21 The electrical resistivity of the ground depends on the different soil types of the studied area. It was measured between two opposing faces of a cube with edges one metre in length. www.kbfi-triasz.hu/Meresi-modszer/8/ (Accessed: 3 August 2018.)

22 www.kbfi-triasz.hu/Meresi-modszer/8/ (Accessed: 3 August 2018.)

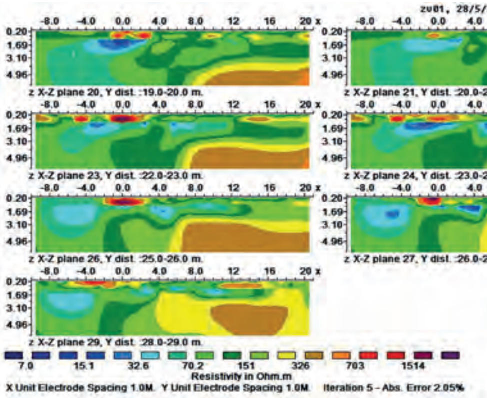

Figure 8.

Characteristic values of soil resistivity (top left) and the arrangement of measuring electrodes (below)

Source: compiled and picture made by the authors

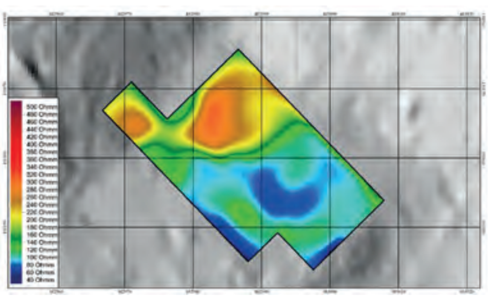

Figure 9.

The results of parallel geoelectrical measurement lines joined together

Source: compiled by the authors

Measuring with a ground penetrating radar

Another important method of geophysical surveying is measuring with ground penetrating radars (GPR[23]), which can be effective instruments of sub-surface investigations. During their operation, they normally use radio frequencies of the electromagnetic spectrum in the range 25 MHz to 2 GHz. The system comprises a transmitter and a receiver, as well as antennas connected to them, the geometric parameters of which determine the dominant operating frequency. The typically pulse-like signal generated by the transmitter penetrates deep into the ground, which is reflected at boundaries between materials having different permittivities, and the significantly weakened return signal is recorded by the receiving antenna *(Figure 10).* The processing and imaging module connected to the receiver is able to display underground features, cavities, cracks, traces of previous human activities, soil disturbances, as well as various geological anomalies by analysing the relationship between the transmitted and return signals.[24] The depth of effective surveying, as well as the physical size and extent of detectable anomalies are determined by the operating frequency selected. Due to the damping properties of the soil as a transfer medium, in case of archaeological and geological surveys, the lower 20–25% of the electromagnetic spectrum (that is, the range 25 to 400 MHz) can be used, which usually allows surveying to a depth of 10–25 m. For the survey of the top 1–2 m thick layer and for various concrete structures, constructions and support structures (building-related applications), the range between 500 MHz and 2 GHz can be used effectively. The results of the surveying can be evaluated or displayed in 2D (using a single horizontal measured strip) or in 3D (matching multiple measured strips).

Figure 10.
The operational principle of ground penetrating radars[25] (left) and their use in practice (right)
Source: compiled and picture made by the authors

23 Ground Penetrating Radar.
24 Ground Penetrating Radar Theory 2009.
25 www.geomega.hu/mergeo/?page_id=29&lang=en (Accessed: 17 August 2018.)

Ground penetrating radar surveys were conducted several times in the area of Zrínyi-Újvár to detect the burnt remains of the fortress wall, as well as to find the "dark gate" and the well of the fortress. This method proved to be successful in detecting sections of the fortress wall and in identifying the site of the well *(Figure 11).* However, we still need to demonstrate the existence of the hypothesised "dark gate" and identify its location.[26]

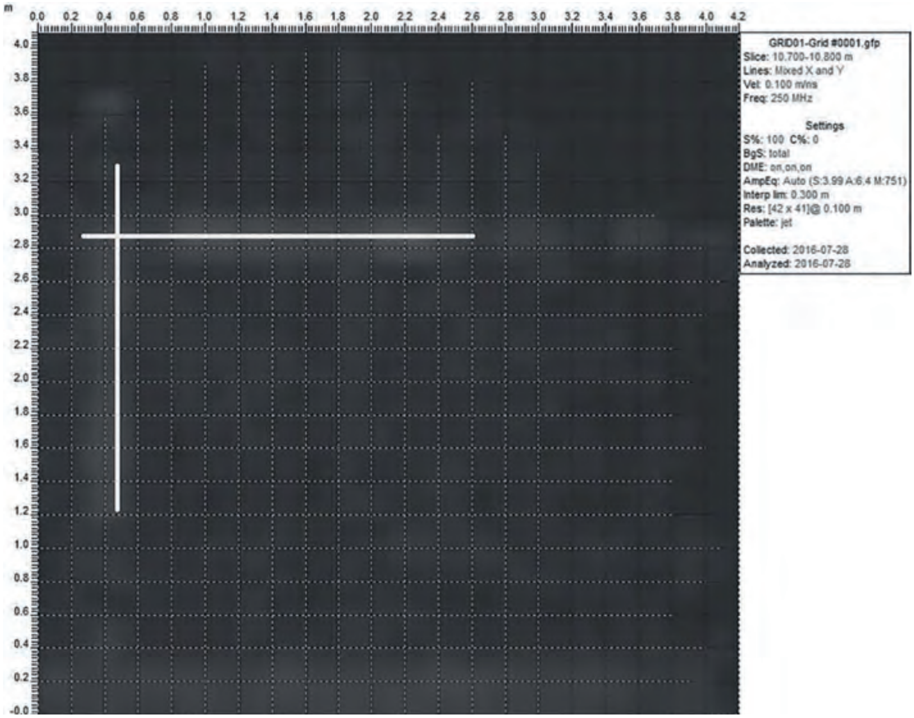

Figure 11.
Image produced by a ground penetrating radar about the well at a depth of 10.7 metre
Source: Padányi 2016. 103.

Measuring with a magnetometer

In contrast with the above, magnetometer surveying is a passive sensing method. Applying this, we can map local anomalies of natural or cultural origin in the magnetic field of the Earth, due to the fact that every material has magnetic properties. We can differentiate between inductive magnetisation, which develops in the presence of an external magnetic field and collapses when it terminates, and remanent magnetisation, which is caused by the magnetic moment of the material. Thermoremanent magnetisation (TRM) is the most common form of natural remanent magnetisation (NRM), where the magnetisation of

[26] *Padányi* 2016. 94–104.

magnetic minerals depends on their temperature. Above the Curie Temperature, they lose their magnetic properties, but when they cool below this temperature, their dipoles align themselves so that their moments point in the direction of the external magnetic field. Below the blocking temperature, the magnetic field "freezes" in the rocks. At the level of the atoms, the source of the magnetic moment of materials can be the spin of the electrons, the orbital movement of the electrons around the nucleus, as well as the number of electrons on the unfilled shells.[27]

Soil layers containing various materials, geological anomalies and objects made of different types of metal can be detected or distinguished by their magnetic properties. In case of diamagnetic substances (e.g. quartz), we cannot speak of spontaneous magnetisation because they have no uncompensated spin. Paramagnetic materials (e.g. olivine) have this, but their orientation is disordered. In case of ferromagnets (e.g. iron, nickel, cobalt), due to the uncompensated spins, the magnetic moments generated in the atoms are coupled in the domains.[28] In addition to the above, there are also antiferromagnets (e.g. hematite) and ferrimagnets (e.g. magnetite, ilmenite).

In terms of the operational principle, there are several types of instruments that can detect anomalies caused by the magnetic properties of substances in the magnetic field of the Earth, such as fluxgate (with an accuracy of 1 nT[29]), proton precession, overhauser (0.1 nT) and alkali vapour (0.01 nT) magnetometer.[30] During gradient measuring, we assess the composition of the studied area or its deviation from its surroundings reflected by the local changes in the magnetic field. With this method, we can detect materials with induced magnetisation (e.g. ductile iron, certain volcanic and metamorphic rocks, bricks) and remanent magnetisation (e.g. steel, certain volcanic rocks, bricks, daub), and – due to the decreasing magnetisation – various changes (e.g. earthmoving, backfilling) in the composition of the soil.[31] One can also measure the difference in the values of the magnetic fields by placing two probes above one another, which, divided by the distance of the probes, shows the magnitude of the vertical gradient of the magnetic field. This method is inexpensive and makes possible significantly faster surveying than others. It is often used for delineating various underground features (e.g. pits, trenches, ditches, sunken houses, ovens, fireplaces).

We also conducted such surveys several times at the site of the siege of Zrínyi-Újvár and along the fortress walls, seeking the Ottoman siege trenches and the "dark gate". The process of the survey and the analysed results of the magnetometer measuring are shown by *Figure 12.* It clearly displays a buried ditch and various pieces of metal waste appearing as spot-like noise in the area.

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27 http://geophysics.elte.hu/magneses1.pdf (Accessed: 26 August 2018.)

28 www.fke.bme.hu/oktatas/Hudson_Nelson/Fizika33_Anyag_magneses_tulajdonsagai.pdf (Accessed: 30 August 2018.)

29 Nanotesla.

30 http://geophysics.elte.hu/magneses1.pdf (Accessed: 30 August 2018.)

31 *Lenkey:* Measurements.

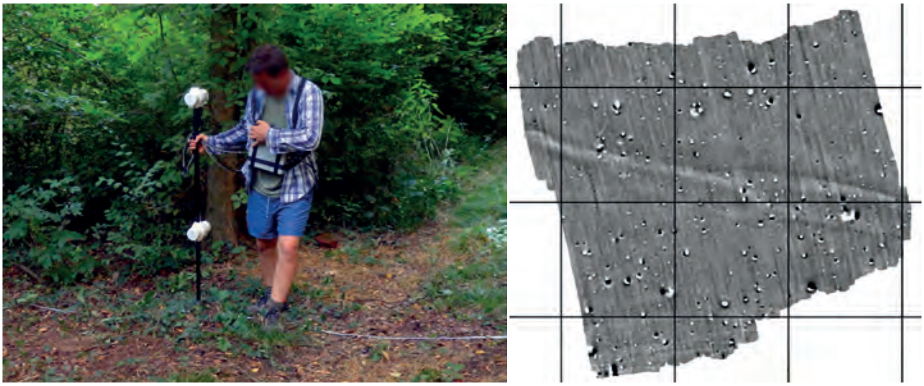

Figure 12.
The process of measuring (left) and the result obtained by merging the data of several measurements (right)
Source: compiled and picture made by the authors

Summary

Over the past one and a half decades, we used numerous state-of-the-art technical solutions, instruments and research methods for the investigation of Zrínyi-Újvár to obtain as comprehensive and accurate a picture of the fortress, its surroundings and the 1664 siege as possible. In the present study, we have mainly introduced those non-destructive testing methods, with the help of which we can conduct a preliminary survey of the sub-surface "world" without long and laborious physical work in order to answer research questions (raised in scholarly literature and in the field) and to prepare and plan the necessary earthmoving and archaeological work effectively. One of the most outstanding examples of this is the exact location of the well of the fortress *(Figure 13)* with the help of a ground penetrating radar. Thanks to this, in 2017, we could completely excavate[32] this specially constructed and strategically important water drawing place. Although the remains and weapons of soldiers defending the fortress – who are also mentioned in stories related to the well – were not found in large numbers, the discovered finds still added new, important pieces of information to the expansion of the "legacy of Zrínyi".

Nevertheless, the greatest help was provided by the use of metal detectors. Their use in archaeology and battlefield investigations offered us a wealth of knowledge and important practical experience that could be incorporated in our excavations, and thus gradually enhance the efficiency of our activity. As a result of this, we managed to demonstrate the existence of Zrínyi-Újvár, to find its exact location and identify typical features in the battlefield (gun emplacements, siege trenches, etc.), and to obtain plenty of data to prepare a miniature and complex 3D model of the area. At the same time, the huge amount of information we have today about the fortress and the siege has been yielded by several technical-based research methods, which have been assessed in a complex way, based on collective knowledge. The experience gained during the research process will be transferable

[32] *Költő–Vándor–Varga* 2018.

to other similar projects in the future. Additionally, the efficiency of the applied methods may further increase due to the development of technology and technical equipment.

Figure 13.
The well of the fortress in Zrínyi-Újvár during its excavation from the upper perspective (left) and from the lower perspective (right)
Source: pictures made by the authors