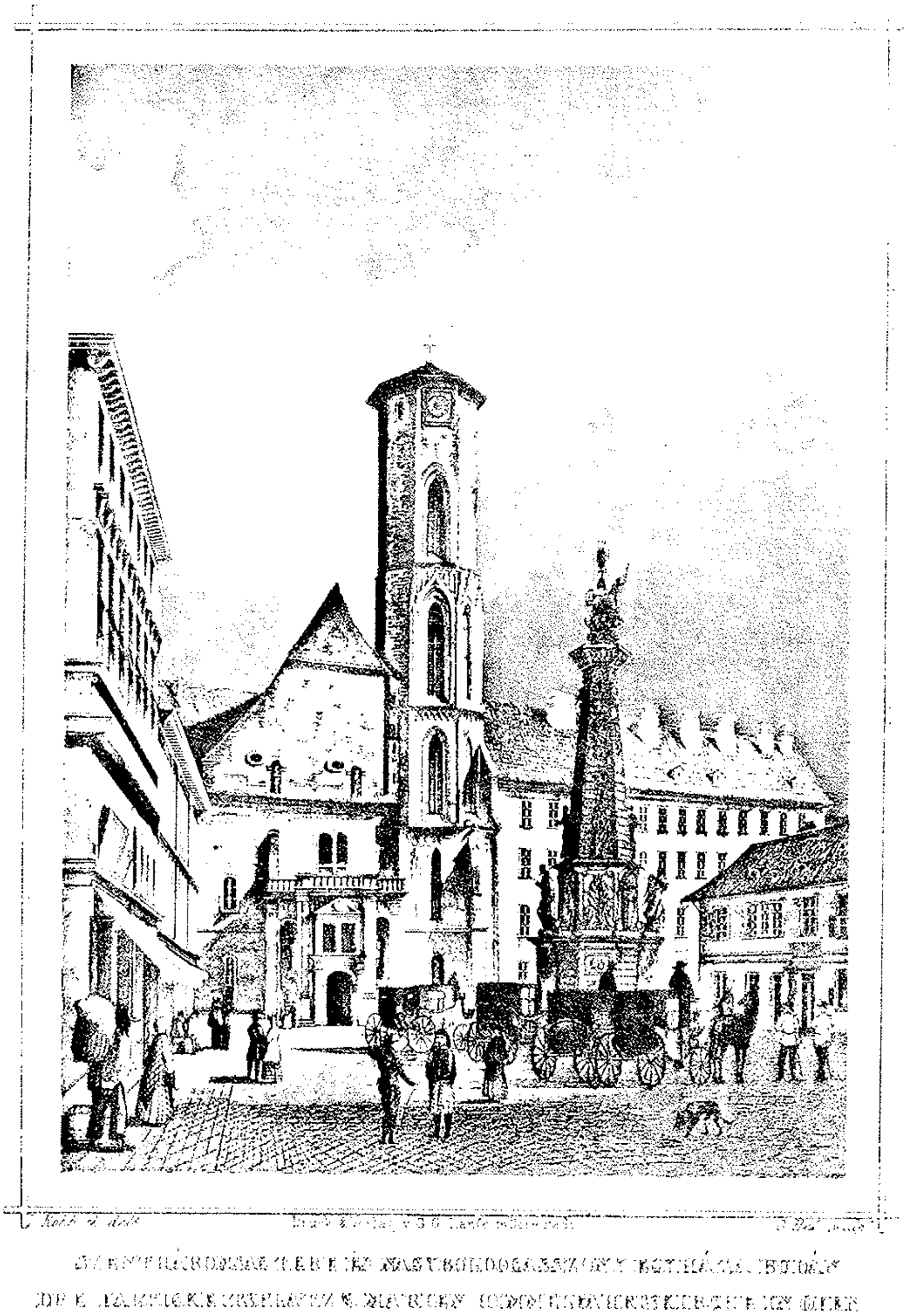
COMBINED GEOPHYSICAL INVESTIGATION ON BUDA CASTLE HILL



** This paper was presented in the poster session at the 56th EAEG Meeting in Vienna, in 1994.*

M.Pattantyús-Á., L.Hermann, Zs.Prónay, E.Törös
Eötvös Loránd Geophysical Institute of Hungary
Budapest, POB.35, H-1445, HUNGARY

Combined geophysical investigation on Buda Castle Hill*

Pattantyús-Á.,M., Hermann,L., Prónay,Zs., Törös,E.**

Abstract

Castle Hill in Budapest is formed of marl covered by limestone and topsoil. Many of the caves and cellars in the area were deepened and excavated into this soft material during historical times. Nowadays, a complex, three-level labyrinth exists under the ancient buildings - sometimes it is said that there is an underground town beneath the Castle. In many cases, the condition of these cellars is extremely poor. Some of the galleries are unexplored, many of them are closed off by walls built later, and/or filled with debris. Surface subsidence or collapse are frequent events at these places.

The task of geophysics is to investigate the unexplored cellars beneath the roads, pavements and parks in order to guide the underground excavation and reinforcing activities. Frequently, prospecting is needed for archaeological purposes, such as tracing the remains of ancient walls. Since the existing site maps of cellars tend to be incorrect and contradictory, identification of underground points (at a depth of more than 10 m) on the surface could also be a geophysical prospecting task.

Seismic reflection, refraction and tomography, ground penetrating radar (GPR) and electromagnetic measurements with several transmitter-receiver coil configurations are the geophysical methods utilized for these complex tasks. The relief of the limestone bedrock was prospected by seismic reflection profiles. Responses of cellars and caves were investigated by seismics and GPR but the reflections of the latter are superimposed on and interfered with the reflections of water pipes and other public utilities.

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1. Geology and history

Buda Castle Hill - together with its natural and artificial relics - is invaluable for both the city of Budapest and Hungary, and it forms part of the World's Heritage. Deep-cellars and caves, castle-walls and retaining walls, dwelling houses and palaces are the components that are in a tight relationship with each other and (of course) with the public works of the surroundings. This complexity is the most important aspect of the geotechnical study regarding the geophysical prospecting in the Castle.

The major part of this hill - that is built up from sedimentary layers - is Buda Marl dating from the Upper Eocene and, at several spots, clay was settled on it (Fig.1). The travertine (limestone) deposited by the hot-water springs welling up in the Pleistocene protected the hill from destruction. Under this "limestone cap" - at a depth of 7-11 m - numerous cave-cellars and cellar-systems exist being hollowed mainly in the marl.

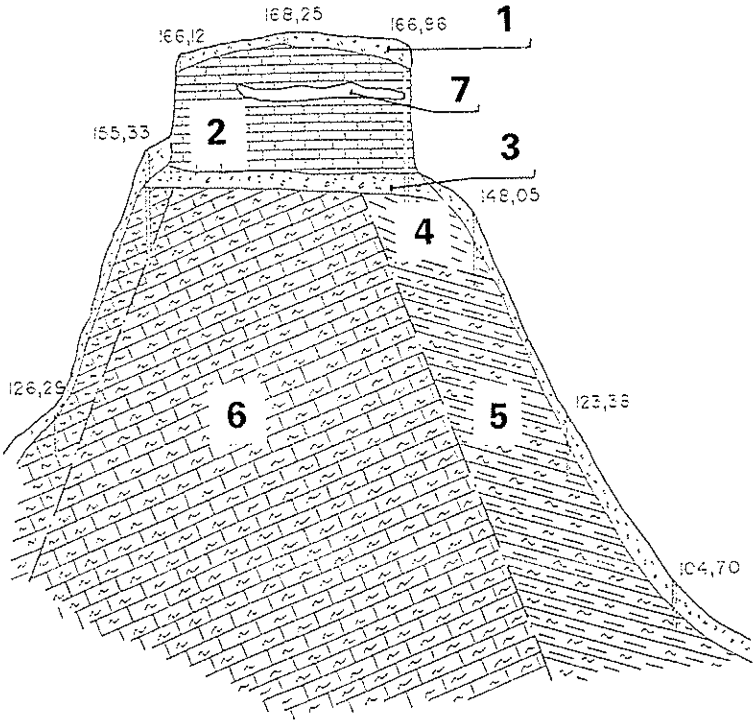


Fig.1. Geological structure of Buda Castle Hill.
1: debris, **2:** limestone (Pleistocene), **3:** alluvial deposit (Pleistocene), **4:** clay (Middle-Oligocene), **5:** argillaceous marl (Lower-Oligocene), **6:** marl (Upper-Eocene), **7:** cavity.

The caves were originally created by the thermal water at the lower part of the limestone. Later, these cavities were opened from the deep-cellars of the houses in the Middle Ages and, connecting them to each other, a complicated labyrinth of a length of some kilometres was created. Based on present knowledge, there are 52 small individual caves (or cellars), too, that have remained separate. The total area of the caves exceeds 18,000 m^2 and they form a three-level system (Fig.2).

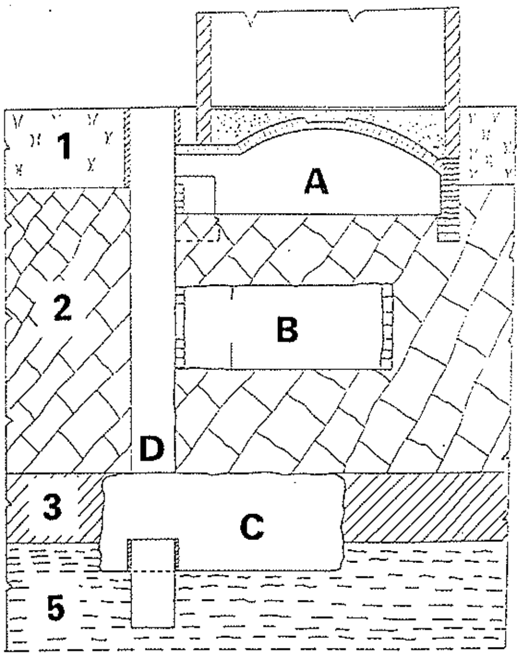


Fig.2. Location of cellars and caves.
1-5: see Fig.1. **A:** upper cellar of houses (built), **B:** lower cellar of houses (created by mining), **C:** cave-cellar (natural formation), **D:** well.

2. Challenge for geophysics

In the case of this type of prospecting many geophysical tools have to be utilized because of the complexity of the task, moreover; a great deal of preliminary information is needed for the exact solution (historical documents, one-time and contemporary maps of buildings, of known and supposed cellars, of public utilities, etc.). The challenge means carrying out field measurements in an urban area covered by paving-stones or asphalt, in a noisy environment with heavy pedestrian and car-traffic.

Problems to be solved by geophysics are:

- Forecasting the direction of empty or more-or-less backfilled cellars of the second level (see Fig.2) under the public area (streets, pavements, squares).
- Prospecting of a rondella (corner-bastion) down to a depth of 11 m in order to define the place of ancient walls or to search for supposed cavities.
- Identification of underground points on the surface since geodetic surveys could be almost impossible or could take too much time.

The geophysical methods utilized for these purposes - were seismics and certain kinds of electromagnetic (EM) measurements (for a short description of the methods, see annex):

- The relief of the bedrock could be defined by seismic reflection/refraction measurements.
- Caves were prospected by ground penetrating radar (GPR) profiling and by seismic surface tomography.
- Many of trials were carried out by EM measurements with different coil-configurations in order to locate on the surface the underground points.
- The inner construction of the rondella was prospected by cross-hole and "wall to hole" seismic tomography and by GPR on the surface.

It is emphasized that it was virtually impossible to apply normal geophysical methods under such rough and special conditions: in every case inventiveness was necessary, sometimes special tools and configurations had to be applied. The main part of the measurements had to be carried out at night. Particular skill was also required for data processing and interpretation; in many cases the development of new processing software was essential.

3. Seismic tomography - "Esztergomi Rondella"

Seismic tomography was used for prospecting one of Buda Castle's corner-bastions known as the "Esztergomi Rondella". This rondella has a diameter of about 40 m and extends downwards to a depth of 11 m. A thick brick-wall has been built around it and the surface is almost free: there are only some sitting-places and a high flag-pole with an enormous underground concrete basement. The aim of our measurements was to investigate the inner structure: ancient walls and cavities were assumed to be at a depth of 5 to 10 m.

A combined geophysical investigation was carried out here: GPR measurements for prospecting the near-surface zone, seismic refraction profiling for tracing the bedrock relief, and seismic tomographic measurements between boreholes, and between the wall-face and the boreholes in order to get information on the inner structure of the bastion (Fig.3 shows the sketch of this procedure). For these measurements two boreholes were drilled in the middle area of the bastion, the logs of which gave useful information on the subsurface conditions. Results of seismic tomography will be discussed here in detail.

Tomographic measurements were carried out in the following way: seismic receivers (geophones/hydrophones) were located in the boreholes one after the other, and the sources of the elastic waves were the hammer hits both on the surface and at every half meter along eight vertical lines on the outer part of the wall (Fig.3).

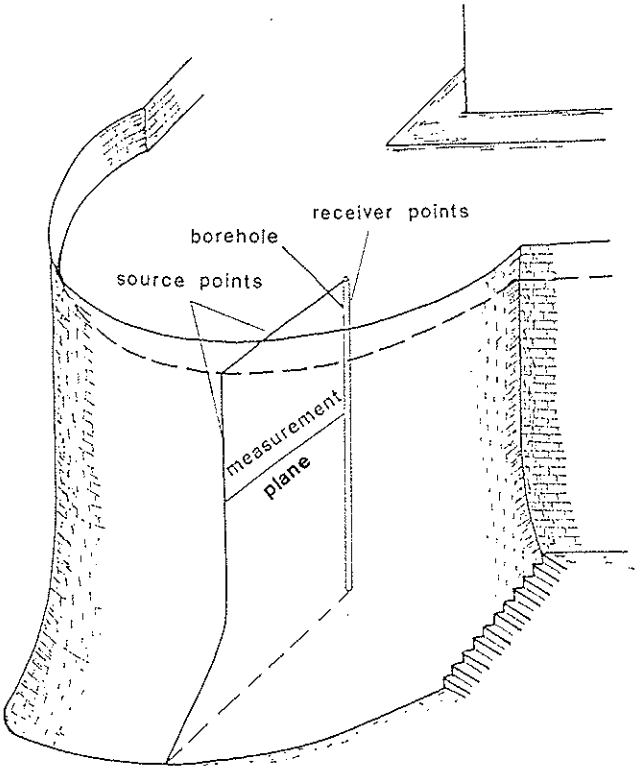


Fig 3. Sketch of the seismic transmission measurement carried out between the wall-face of the rondella and one of the boreholes.

For processing the acquired data we used our own, curved-ray velocity tomography software. The essence of this procedure is that the values of travel times calculated from the velocity field of an initial model are compared with the measured arrival times. As a next step, the algorithm makes a correction on the velocity field to decrease the differences in the time values. This procedure is repeated many times by iteration. Since this process is convergent, after some modifications, the calculated velocity field will be more and more similar to the real velocity distribution.

Fig.4 shows the ray tracing of the initial model (A) and the final velocity field (B) of a wall-borehole tomogram calculated by this type of iteration. The result of these measurements was that the velocity field of some planes shows a clearly distinguishable high velocity zone (see Fig.4.B) that could be due to a wall dating from the Middle Ages - whereas velocity maps of other planes do not contain this type of anomaly. In this way the presence of the wall could be demonstrated.

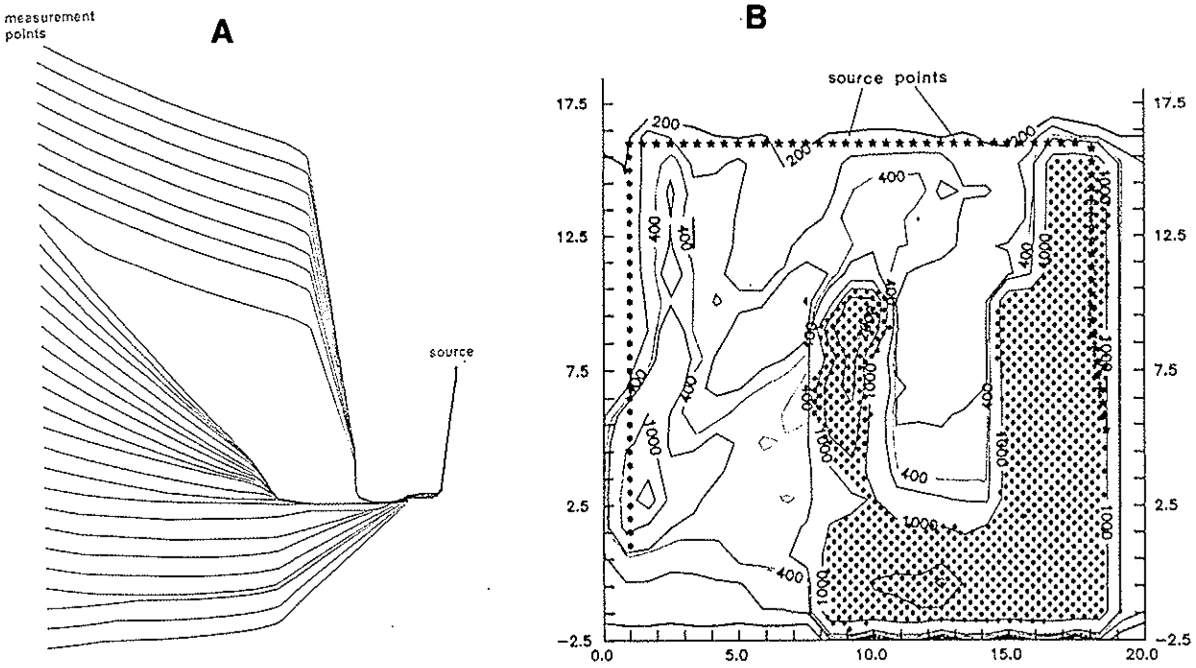
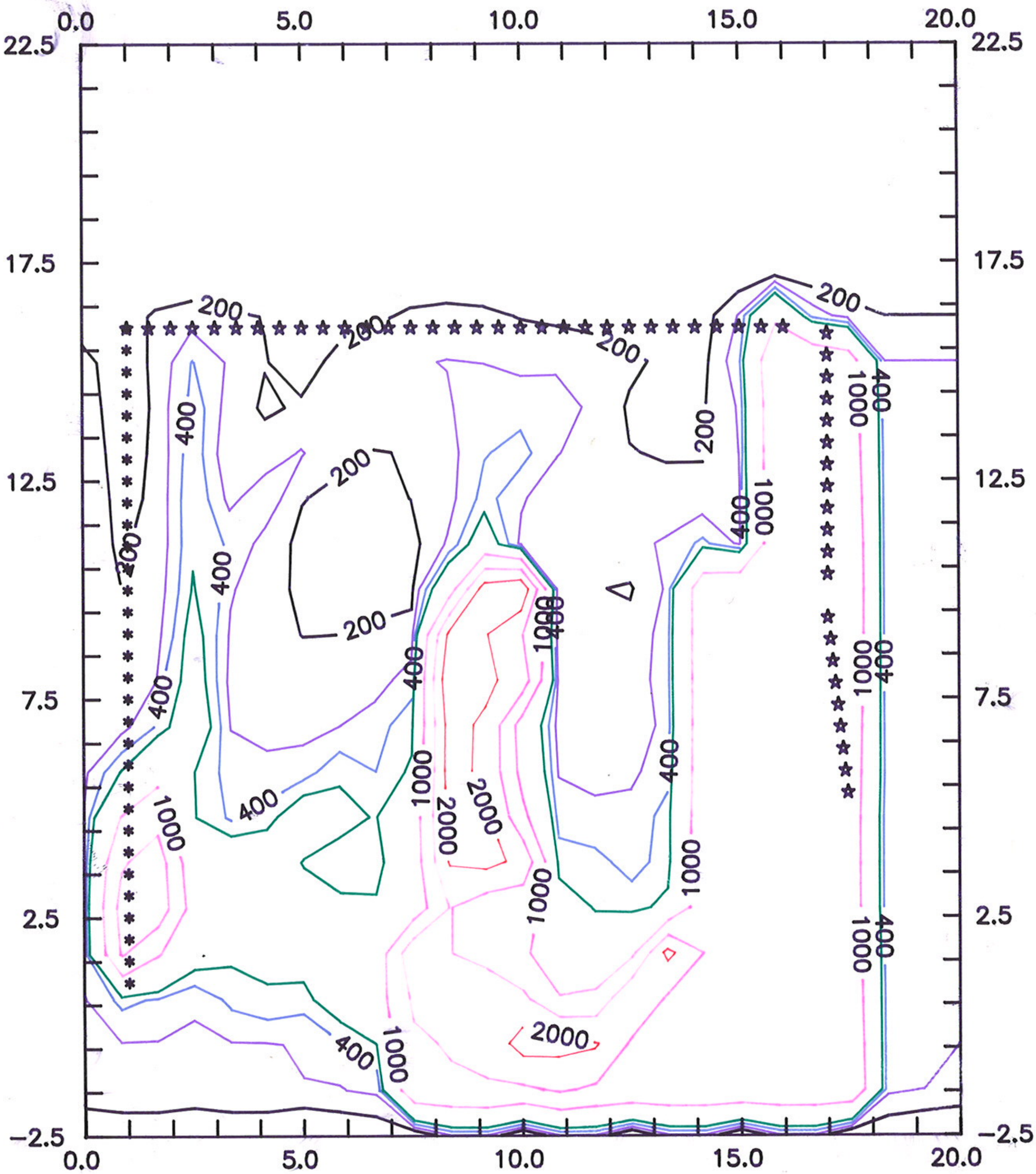


Fig.4. Initial ray tracing of seismic transmission measured between a borehole and the wall-face (**A**) and the final velocity field of the iteration (**B**).

Final result (velocity field) of the iteration



4. Ground Penetrating Radar measurements - searching for caves

The exploration and restoration of caves and cellars have been continuing in the Castle district for decades. The task of geophysical investigations was to detect the unexplored cellars under the streets and pavements or to define the exact location of uncertain or supposed cellars in order to direct underground exploration work.

GPR is a well-known method for tracing near surface geological structures and for detecting underground objects. Air-filled cavities such as caves and cellars usually cause a reflection with a characteristic shape on the radar sections. At the same time, the effects of other buried objects (e.g. manholes, pipes, cables, large rocks, etc.) also appear on the sections. All these effects are superimposed on (or better to say: interfered with) each other. Moreover - GPR being an electromagnetic instrument - the detected signal is also influenced by the disturbing effects of EM sources located in the vicinity.

The final result of GPR measurements is a time-section that contains all the reflections mentioned above. The amount of noise and undesired effects on the radar section could increase sometimes to an enormous extent in an urban area, due to improper shielding of the antennas. For this reason - besides GPR profiling - in most cases, we apply seismic reflection measurements too (sometimes seismic surface tomography) for investigating cellars.

Fig.5.A shows a typical radar section measured in the Castle. This section contains many disturbing effects but the response of two cellars crossing the measuring line could be separated and interpreted. Also shown is a characteristic seismogram (Fig.5.B) where the reflection of the cavity could also be recognized. During this prospecting, the result of these two methods confirmed each other. Often radar results could not be interpreted at all because of the strong outside effects. In these cases seismic reflection measurements gave the key to the solution.

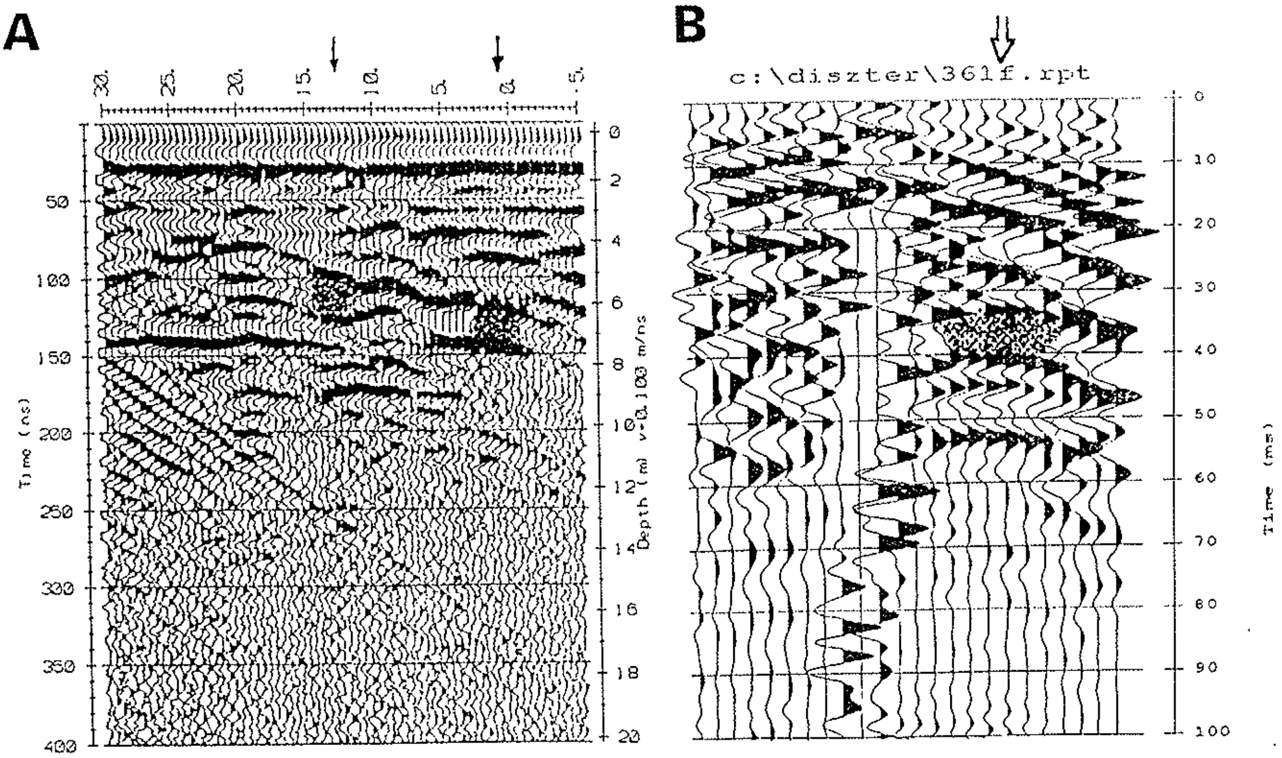


Fig.5. **A:** Radar record containing the reflections of two probable cellars.
B: Characteristic seismogram of the same profile with the indication of the cavity.

5. EM transmission - localization of possible collapsing point

A new problem arose in the period during which we carried out surface measurements for cellar-investigation. Subsidence occurred on the surface therefore work started on cleaning the cave-cellar (labyrinth) on the third level at the place assumed to be the cause of the accident. A partially filled chimney was found going obliquely upwards. Four meters of the filling material has already fallen. The depth of this gallery is about 11-13 m beneath the surface.

Excavation also started on the surface at the site of the accident but without any success: they could not reach each other. No reliable map existed about the exact location of this part of the labyrinth. It would have taken too much time to perform a geodetic survey because this part of the labyrinth is located about 80 m from the entrance and the more than 20 curves and corners make surveying difficult in total darkness. Our task was to indicate the exact spot where this chimney could reach the surface.

Some years ago, ELGI developed a special type of electromagnetic instrument that works with two coils (transmitter and receiver) with a diameter of 80 cm. The central frequency of this instrument is 2 MHz. This equipment is usually used for profiling on the surface in a so-called "zero-coupled" (perpendicular) orientation of coils to detect underground inhomogeneities of dielectric parameters with a separation of 5 to 30 m between the receiver and the transmitter coils. In this case, we put the transmitter coil at certain places in the labyrinth and tried to detect the transmitted signal on the surface along an appropriate grid in order to define the exact location of the transmitter coil.

Fig.6 represents a map of the labyrinth with an anomaly map of the received values on the surface (EM-field intensity). After some trials, we could point out the position of the transmitter with this procedure. Moreover, the shape of the anomaly gave information on the orientation of the loose zone of refilling material of the chimney. As a result of this prospecting it was strongly suggested that the bus-stop be moved and fence be built in this dangerous area. Within some days 5 m of soil subsided in the vicinity of the predicted place (fortunately in the area of the grassy park).

6. Seismic surface-tomography - prospecting on "Szentháromság tér"

"Szentháromság tér" (Holy Trinity Square) is the central area of the Castle: many tourists are usually to be found here. Recently, sinking of the pavement and the road occurred in some places therefore geophysical mapping of the locality became urgent. (The site of the subsidence described in the previous section also forms part of this square.)

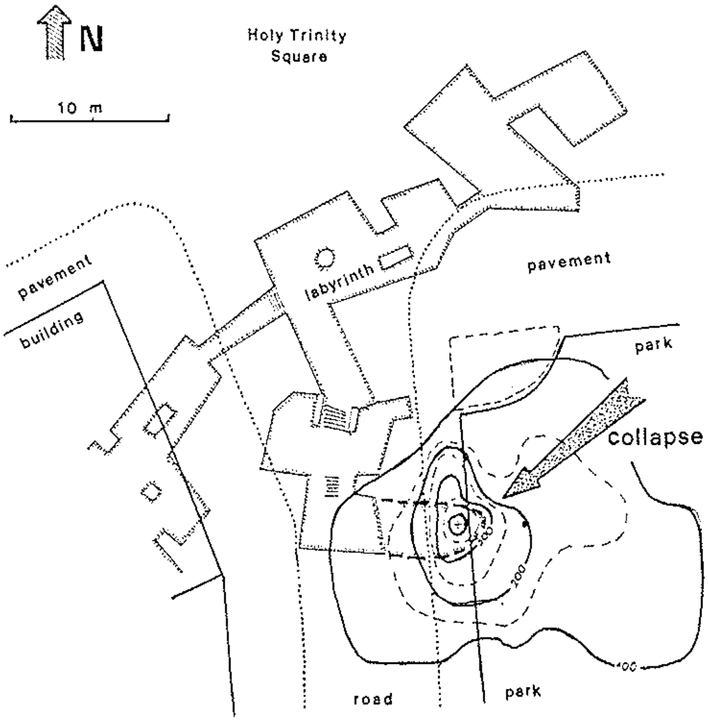


Fig.6. Localization of potential site of subsidence by EM mapping.

Preliminary information was found in the archives: some old maps of the Square and descriptions revealed one-time collapses. Some hundred years ago the Square was built up with houses, meaning many cellars might exist (nobody knows in what condition). The task of the geophysical investigations was to give information on loose, improperly backfilled zones that might subside.

A combined investigation needed to be planned here because there are many public utilities crossing the Square: heating and water pipes, cables and sewer pipes criss-cross beneath the surface. In such a difficult case there is no single geophysical method that could give acceptable and unambiguous results by itself - in view of this a number of methods needed to be applied.

These methods were GPR profiling, electromagnetic mapping (with the same coils used for localization but using a different arrangement) and seismic surface tomography. The results of the last of these proved to be the most acceptable - the interpretation of other methods could only support the anomalies of the velocity map resulting from the seismic tomographic measurements. The uncertainty of interpretation of EM methods is due to the complexity of the underground conditions together with the outside noise.

Seismic measurements were carried out along a grid of 2 m: each point of the grid was a source-point for the elastic waves induced by hammer-hits, and geophones were located at 46 points inside the grid. In this way we were able to measure along many ray-paths crossing each other, this was suitable for tomographic processing, to enable the near-surface velocity field to be precisely calculated.

Fig.7 shows the calculated velocity map resulting from the surface tomographic measurements. Only those anomalies of low velocity are marked that could indicate the places of loose (cavernous or improperly backfilled) zones. Anomalies caused by near surface objects (manholes, etc.) are also present on this map.

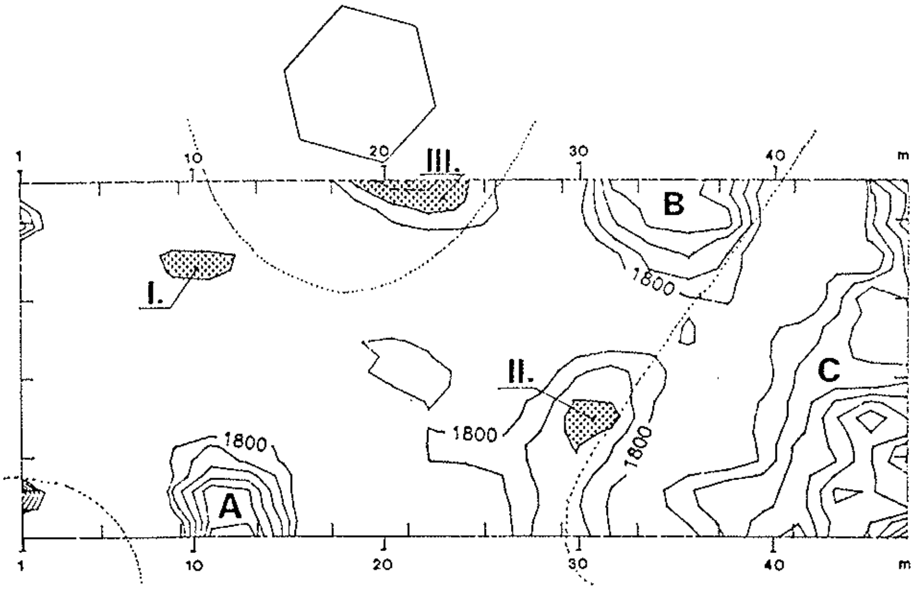


Fig.7. Velocity map of seismic tomographic measurements.
A, B: anomalies caused by manholes, **C:** anomalous zone due to the loose foundation of the pavement, **I., II., III.:** anomalies interpreted as loose backfilling of possible cellars.

7. Summary and the future

Although most of the prospecting problems that arose in connection with the restoration programme of the cellar systems in Buda Castle Hill could be solved by some of the well-known geophysical methods, we always had to apply some new or special techniques both in the field work and in the data processing.

In the prospecting of the rondella, cross-hole measurements had to be carried out not only between boreholes but between one of the boreholes and the wall face of the bastion too, in order to transilluminate the largest possible internal part of the bastion. To carry out hammering vertically up the wall, it was necessary to use a special hoist cradle. The trials using our radar system by letting the antennas down the wall were unsuccessful. Special software was developed for processing the seismic tomographic data.

In localizing underground points we applied our EM measuring system in a special way by separating the coils: the transmitter coil was located in a cave at a depth of 13 m and the receiver did the mapping on the surface. The execution of surface tomographic measurements also needed new elements such as a special array for the geophones and the source points. Despite the special iteration software processing of this large amount of data took a great deal of time.

Latterly, there is a pause in the geophysical prospecting because there are too many really dangerous cellars that have to be reinforced or filled in as soon as possible (some of the streets are totally closed for this reason). The whole amount of funds is being spent on the fast reinforcing activity but later a systematic geophysical project will start in this area.

8. Acknowledgements

Our prospecting was financed by Budapest's 1st district Local Government; funds are provided by the Government in the framework of the National Cellar Programme. The main technical coordinator of this Programme on Castle Hill is the Planning Engineering Office of the Capital (FÖMTERV). Thanks are due to all experts and representatives of these organizations who requested us to participate in this exciting work and helped us in the interpretation.

ANNEX 1.

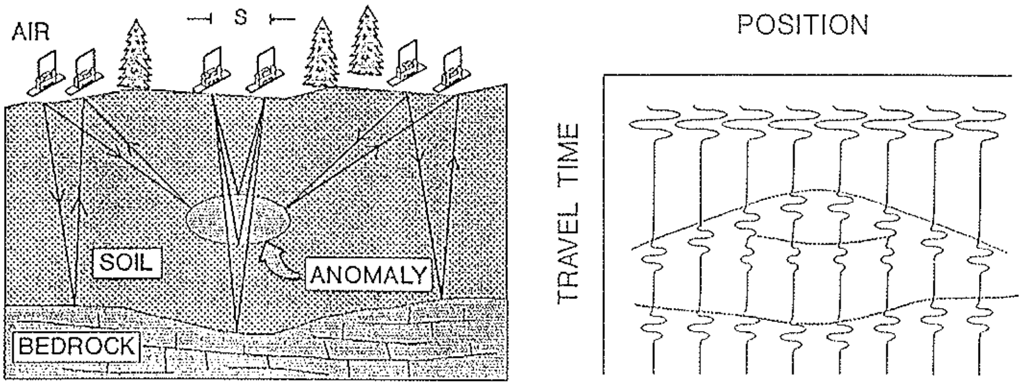
THE GPR METHOD

GPR works by radiating a series of high-frequency (20-1000 MHz) electromagnetic impulses into the ground via a surface contact transmitting antenna. As this signal passes through the earth it may encounter subsurface materials of varying electrical properties. At these electrical interfaces, the signal is reflected and diffracted, being more or less attenuated or dissipated in the material. The reflected signal is detected on the surface by the receiving antenna which is near to the transmitter. Reflections come back from all geological inhomogeneities so the effect of layers, geological structures and other buried objects can be recognised on the time-sections of radar profiling. The essence of the method is the exact measurement of the signal delay time (10-2000 nanoseconds), which depends on the velocity of the signal in the subsurface as it passes through the material, then it is reflected and travels back to the receiving antenna (two way travel time: TWT). The time-section of radar measurements can be converted into a depth-section by calculating this wave propagation velocity**[1].**

In GPR survey, soil conductivity and dielectric properties are the main parameters that influence the detectability of the subsurface features **[2]**. High conductivity causes high attenuation of the signals and therefore the penetration depth is smaller. Dielectric permittivity controls the wave propagation velocity, and the dielectric contrast between the target and its surroundings determines the reflectivity of the object. The investigation depth can be controlled by the frequency applied: lower frequency (25-100 MHz) results in a higher penetration (25-10 m) but poorer resolution, and the application of a higher frequency (300-1000 MHz) results in excellent resolution but only down to small depths (5-1 m).

The principle of the operation of the GPR is illustrated in the **figure** below **[3]**. The inhomogeneity can be detected as a characteristic reflection, and the boundary of a deeper layer can also be traced on the time/depth section.

As it was already mentioned, high conductivity is the most significant limiting factor in radar applications. Water saturation or the presence of highly conductive clay beds will cause high attenuation and a decrease in signal velocity and energy, consequently a decrease in depth penetration or observable reflections.



Schematic illustration of GPR field survey procedure and the resulting reflection section

Another disturbing factor may be the objects above the ground surface which cause reflections on the radar profile and interference with the subsurface reflections [4]. This latter problem can be lessened by careful planning of measuring lines and by thorough and accurate observation of such effects and taking them into account during the interpretation.

Instrumentation

The instrument we use with great success for near surface investigations is pulseEKKO 100 system, with frequencies of 25, 50, 100 and 200 MHz depending on the task to be solved. This system is a lightweight, modular and fully battery powered instrument, controlled by a computer. Operation is digital with data transfer by fibre optic cables thereby ensuring high performance and resolution and avoiding the noises picked up by wires. The multiple signal averaging effectively improves the signal/noise ratio. Computer based data acquisition makes possible the on-site presentation of the sections or pre-processing before interpretation. The digital data storage means that further (more complicated) processing can be carried out by applying special radar processing techniques [5].

Data processing

The original software package of pulseEKKO contains some simple processing procedure (gain, filtering, etc.). In many cases the presentation of data (radar section) handled only by these procedures gives satisfactory results for interpretation. In some cases, however, further processing is needed to enhance characteristic reflections and/or suppress or eliminate the undesired ones.

This further processing can be carried out by a special radar processing software which has been developed in ELGI. This software can perform the following procedures: normalization, direct wave elimination, smoothing, median filter, bandpass filter, deconvolution (spike, predictive), notch filter, dip filter, calculation of attributes, finite different migration. This software works under WINDOWS and can use its all displaying and graphical possibilities.

It should be mentioned that frequently it is not necessary to carry out all these processing steps. In every case, it should be decided in the course of interpretation which steps yield the best image of the target.

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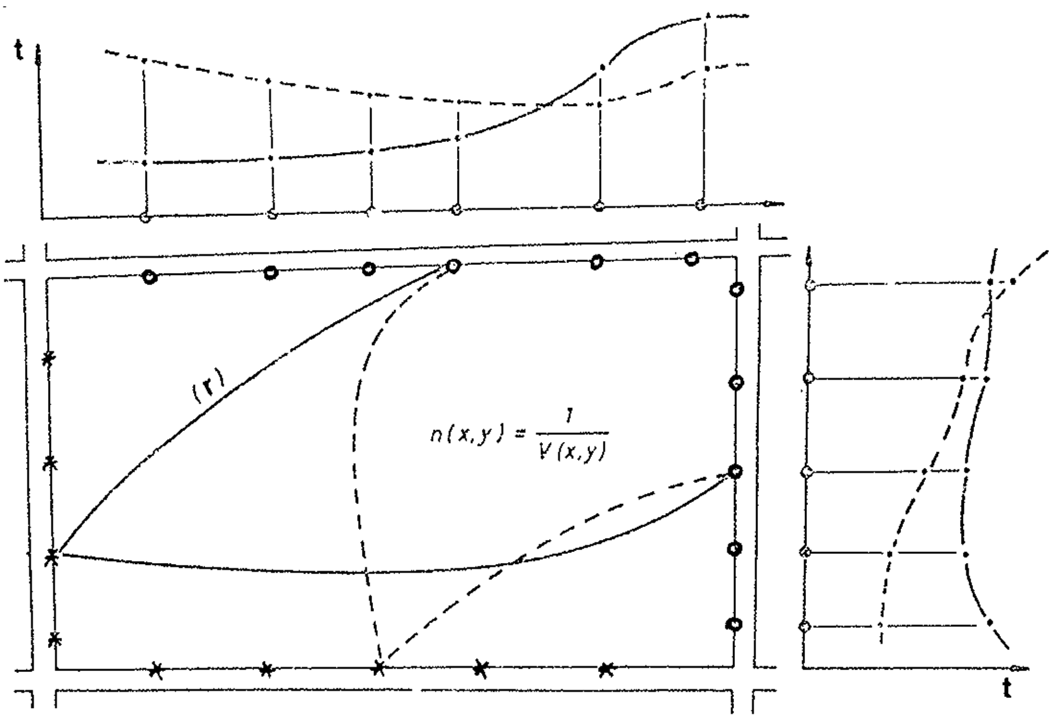
ANNEX 2.

METHOD OF SEISMIC TOMOGRAPHY

There are many areas of science in which the distribution of some physical quantity inside a "body" has to be determined from its line integrals measured on the perimeter of the body. These tasks can be solved by tomographic methods. The principles of the seismic transmission - as one type of tomography - can be found in *L.Hermann, L.Dianiska, J.Verbőci, 1982, Curved ray algebraic reconstruction technique applied in mining geophysics: Geophysical Transaction 28/1, pp.33-46.*

Applying the tomography in seismic prospecting we measure the travel times of elastic waves between the source points - located on one side of a body - and the receiver points - that are located on the other side. This method is called seismic transmission. The sketch of this procedure is illustrated in the **figure**. For determination of the wave propagation velocity map the input data are the geometry and arrival times, i.e. the first breaks picked out on the recorded time series.



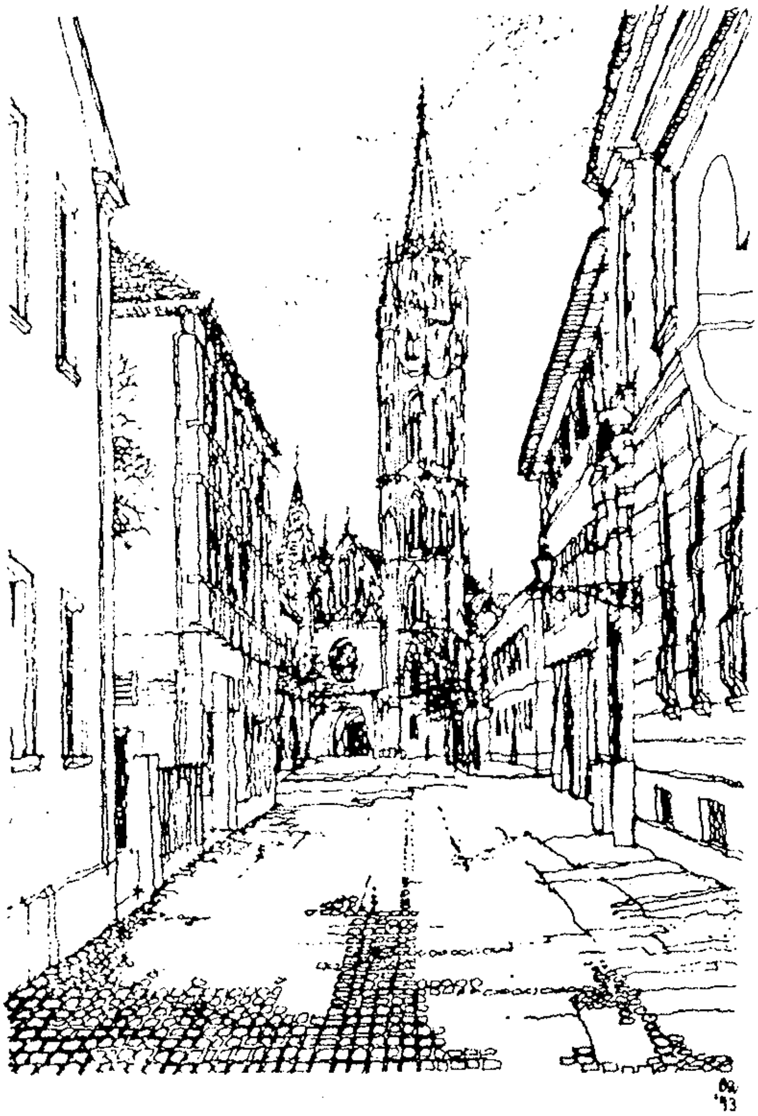
The sketch of the seismic tomographic measurements
*** source points** **O geophones**
(r) : wave propagation ray pathes
(t) : measured travel times

For processing of acquisited data we use our own, curved ray velocity tomography software. The essence of this procedure is that the values of travel-times calculated from the velocity field of an initial model are compared to the measured arrival times. As a next step, the algorithm makes a correction on the velocity field for decreasing the differences in the time values. This procedure is repeated many times by iteration. Since this process is convergent, after some modifications, the calculated velocity field will be more and more similar to the real velocity distribution.

The basis for the interpretation of the velocity maps is as follows: the loose (cavity) zones have lower seismic velocity but hardrock and consolidated formations have a high propagation velocity.

COVER PAGE:

Church of the Great Blessed Lady and
Holy Trinity Square in 1856
(contemporary engraving)



Matthias Church
- the same building now
(drawn by Attila Emődy, architecture)