Exploration and Stability Analysis of Underground Cavities of Urban Areas

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ABSTRACT: One of the main reasons for the instability of the terrain surface is the occurrence of natural and anthropogenic cavities and the development of a crack zone around them. The existence of voids and loosening at small depths in urbanized areas can cause damage to the infrastructure. Therefore, it is important to have a good geotechnical and geophysical recognition of the area where shallow natural and anthropogenic voids are located. Large urban centres such as Budapest and Krakow are located in such areas. Non-invasive geophysical investigations were conducted using the electrical resistivity tomography (ERT) method to determine the locations of cavities as well as recognizing the loosening zones. To obtain the input parameters for stability analyses the real geometry of the cavity was measured by terrestrial laser scanning (TLS) method and the strength parameters of rock masses were determined by in situ and laboratory analyses.

Keywords: TLS, ERT, stability analysis, strength properties, cavities, urban areas

1. Introduction

One of the main causes of terrain surface instability is an occurrence of natural and anthropogenic voids at small depths and developing zones of cracks and loosening of subsoil around them (and especially above them). As a result, continuous and discontinuous deformations appear on the surface e.g. subsidence zones and sinkholes, which cause damage to the subsurface infrastructure (gas pipelines, water supply systems, tanks, sewer networks etc.) and above ground (e.g. buildings, high voltage poles, roads, tracks). The emergence of subsidence zones threatens the life and health of residents, especially in areas where karst phenomena occur. Conditions directly or indirectly affecting the development of karst processes can generally be divided into three groups [1]:

1) lithological and petrographic features of the rock,
2) climatic conditions,
3) spatial situation of the limestone complex.

The lithological and petrographic features of the rock determine its susceptibility to krasification processes. The main role is played by the structure and texture of the rock, the thickness of the shoals, the presence of hewn cracks, fractures and tectonic cracks, and finally, the quantity and type of pollution [2] The second group of conditions determining the progress of karst processes are climatic conditions [3]. Not only the amount of rainwater but also its temperature, climate-related rock weathering, the presence of vegetation, etc. is crucial here. The effect of the water saturation and freeze on physical properties on limestone is described by [4] and [5]. The spatial situation of the limestone complex, its thickness, borders with impermeable layers, and finally the relation to the surface morphology of the area is also of great importance.

Natural voids occurring in Krakow and Budapest in the form of caves, fossil aven cave and pits along with the accompanying zones of cracks and loosening are the result of, among others, the rock's karstification. Anthropogenic voids related to human activities were created mainly as cellars for storing and storage products. [6]. In Kraków and Budapest area [7] you can find cellars, even of historical origin, bored from the Middle Ages to the 19th century, for various purposes. Many of them are still standing and are used e.g. for growing mushrooms, wine production, storage of products or they are converted into restaurants. However, some of the cellars are not used and have even been forgotten. The condition of such cellars is often very bad, which can pose a serious threat to people as well as difficulties in planning and developing the area. Therefore, due to the development of cities and the expansion of their borders, weak porous limestone rocks with developed karst phenomena in which there are natural voids or hollow cellars [7], which can be additionally affected by loads they threaten the surface by creating subsidence and collapse.

The purpose of this work is a geotechnical and geophysical reconnaissance of the area with shallow natural and anthropogenic voids and presentation of the possibilities of the methods used. The area of Kraków is partly located on a calcareous, limestone base in which active karst processes contributed to the formation of caves (Smocza Jama, Twardowski, Jasna etc.). To determine the location of karst caves occurring shallow below the surface and the recognition of loosening zones were performed non-invasively geophysical examination by electrical resistivity tomography (ERT). In addition, research focused on the stability of the cellars in Budapest. To get input parameters for stability analyzes, real cavity geometry measured by terrestrial laser scanning (TLS), and strength parameters of rock masses determined by in situ and laboratory analyzes.

2. Location and Geology

Jasna Cave is located on the right bank of Krakow in the Podgórze district in the Vistula valley. Its coordinates WGS84 are λ: 19°54′05,88″, φ: 50°02′21,59″. In the direct neighbourhood the cave there are three other larger caves: Twardowski, with Kulki, and Niska Fig. 1.

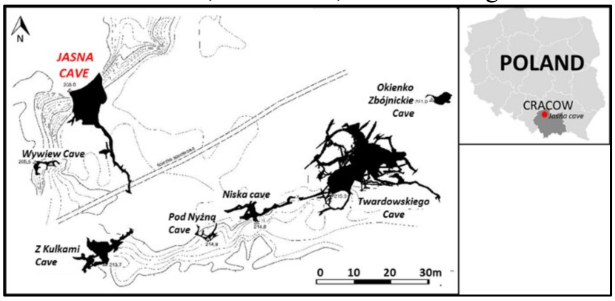

Figure 1. Location of the caves

The caves are located in the northern part of the logging hill Krzemionki Zakrzowskie, built of Jurassic limestone. On the surface, numerous karst forms are visible. They arose in places of increased water infiltration. They can also arise as a result of the collapse of the ceiling of underground vacuums. The funnels are covered with weathered grass and vegetation Fig. 2.

Figure 2. Surface karst forms as sinkholes and funnels

The Jasna Cave was formed in pampered (shoal) limestone Upper Jury like most of the caves found in Kraków and the surrounding area, it dates from the Cretaceous period, and its largest cave systems were built at the end of the Tertiary [8]. According to explorers, the cave has a depth of 3.2 m, length 82 m, and the hole is located at the height of about 210 m above sea level. The entrance has 13 m wide and 5 m high Fig. 3.

Figure 3. Entrance and morphological profiles of the Jasna Cave (foto: B. Pasierb)

Directly behind the hole, there is a chamber leading towards the end into a tunnel with low ceiling height, from which they lead from side to side small branches ending inaccessible slits and fractures. The chamber is destroyed by the exploitation of limestone, which was mined here before World War I [9]. In the background, the chamber goes into a narrow channel about 40 m long, running deep towards SE. In part near the entrance and in a considerable space of the corridor, the bottom is covered with rock debris, and large limestone blocks fell off the ceiling. The end of the main corridor is a chimney, blocked by large limestone blocks. Jasna Cave connects to the network of karst canals fed with Vistula waters. During the floods in 1997, the bottom of the chamber was flooded with considerable water. In the years 1997–1999, several obstructions were observed in the chamber and at the beginning of the corridor running deep into the cave. The next huge rock falls took place in 2000 and 2006 years. The largest of the previous ones occurred in 2007 when a layer about 3 meters thick broke in the central part of the chambering, partially blocking the entrance into the massif. The rock falls still take place, which threatens to completely collapse the ceiling in the main chamber.

In Budapest and the surrounding of Budapest (Törökbálint, Diósd, Sóskút) Miocene limestone formed, which is soft limestone. As it is highly porous and easy to work with, therefore, these stones became one of the key construction materials of the 18th and 19th centuries [10]. Limestone used as a construction material, famous buildings of Budapest, such as the Parliament building, Citadella and Mathias Church was built from this stone [11]. The quarries were around Budapest until the early 20th century and resulted several huge underground cellar systems. Nowadays, the areas of the quarrying activity are inside residential area. The underground cavities can cause hazards and make the building developments of the area difficult. The layout of the cellars mainly different of the site plane above them, therefore roads, buildings can be found above the cavities. Many times there are forgotten cellars which can cause several problems because nobody can count with them. A collapse of a forgotten cellar happened in Törökbálint, fortunately not inside residential area Fig. 4.

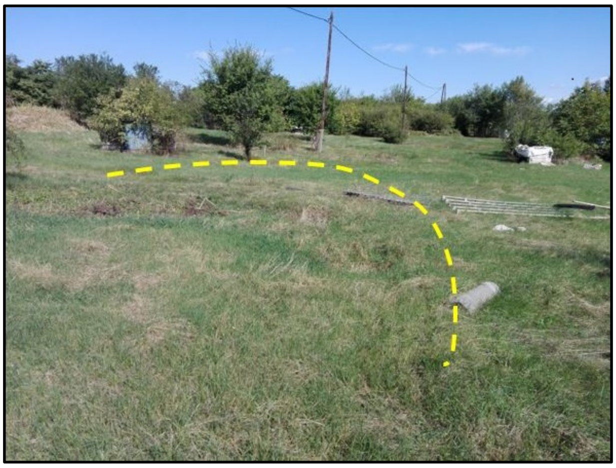

Figure 4. Sinkhole above forgotten cellars (foto: P. Görög)

The investigated cellars are in Budatétény Fig. 5. which is part of a huge cellar system.

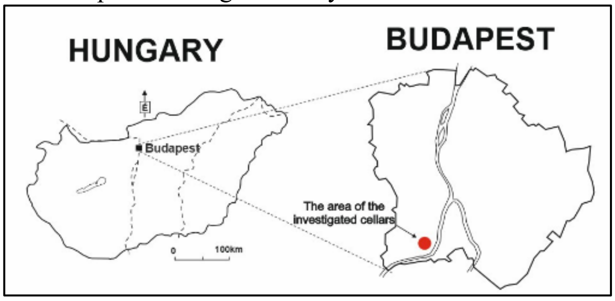

Figure 5. Location of the investigated cellars

The cross-section of the cellars is mainly rectangular, and there are only a few discontinuities in the rock mass of the porous limestone since it is a soft rock. The cellars are sometimes supported by masonry arches Fig. 6, which are mainly against roof failure.

Figure 6. A photo of the rectangular cross-sectioned cellar with masonry arches (foto: P. Görög)

The porous limestone around the cellars mainly massive with only a few joints, but many times it is layered. Sometimes these layers are thick, and there are stronger and weaker layers deposited above each other, and sometimes there are thin layers above each other with almost the same quality of rock. There are some cellars where this stratification is not determinative, but there are somewhere this layered structure controls the instability mechanism Fig. 7. It is almost the same mechanism, which showed on Fig. 3.

Figure 7. Failed roof of a cellar in Törökbálint (foto: P. Görög)

3. Methodology

Ground reconnaissance research is most often carried out by the methods of point drilling and geotechnical probing, whose negative side is the invasiveness and random nature of the information obtained. Thanks to the development of research techniques are becoming commonplace the use of geophysical (e.g. Electrical Resistivity Tomography) and geodetic (e.g. Terrestrial Laser Scanner) methods as a complement to geological and engineering works, especially in areas threatened by the occurrence of weak soil and discontinuous deformations resulting from the presence of e.g. undocumented anthropogenic and karst voids.

3.1. Terrestrial Laser Scanner (TLS).

Terrestrial Laser Scanner (TLS) is a useful and effective method for measuring geometry of buildings [12], rock slopes [13,14,15] the 3D geometry of the cellars [16]. The primary end-products of this technology is a high-density point cloud (1-5 cm point spacing) which was merged and used to create cross sections and 3D view of the cellars and convert to dxf format. The obtained geometry and section was the geometrical input parameters for stability calculations. In this case, the TLS output cannot be coloured because there was not enough light for using the built-in camera of the laser scanner. Therefore, the obtained information was not proper for engineering geological description, for example, for detecting joints. For measuring the geometry, a Faro Focus 3D S120 terrestrial laser scanner and for data processing the Faro Scene software was used.

3.2. Electrical Resistivity Tomography

The applied geophysical studies are based on the variability of the electrical parameters of the medium [17]. In the presented work, the ERT method was used to locate the cave and possible karst voids and chambers that have not yet been discovered during exploration. A system of parallel profiles was planned for data interpretation by 3D inversion method according to the basics of 3D ERT measurement methodology presented in the works of [18]. For this purpose, over the cave, 5 parallel profiles with a length of 94 meters were laid, at intervals 4 meters and an electrode spacing of 2 meters. The profiles were run NE-SW perpendicular to the axis of the cave. The measurements were offset over the cave entrance by 7 meters. The ERT research was carried out using Ares measuring apparatus by GF Instruments with a dipole array [19]. The processing used the Res2Dinv and Res3Dinv programs from Geotomo Software based on nonlinear optimization technique [20,21]. The 3D image visualization was made using the Voxler program (Golden Software Company).

3.3. Laboratory work

The goal of the laboratory investigation of the host rock of the cellars is to obtain the necessary data for stability calculations. The specimen has been obtained by investigatory drillings from the cellars and by the laboratory drilling machine from blocks which collected from the cellar. The obtained specimens were between 37 and 50 mm in diameter, according to L/D of the specimens was in the range of 1.46-2.03. The correction of this values to (L/D = 2, D = 50 mm) have been done [22].

The density of both dry and water-saturated samples was calculated by mass volume ratio according to EN 1936:2007. The procedure for strength measurements uniaxial compressive strength (UCS) and indirect tensile strength (Brazilian) was performed according to the code no. ASTM D7012-14e1 and ASTM D 3967 respectively. Water absorption test of the specimen was done based on EN 13755:2008. P-wave velocities were determined from measured travel times through the specimens according to the methodology described in EN 14579:2005. For each type, the mean, minimum and maximum values and also standard deviations were calculated.

The generalized Hoek-Brown failure criterion [23] was used to determine the strength parameters of the rock mass.

3.4. Modelling work

The stability calculations had been done by Rocscience software package, for 2D calculation, the RS2 finite elements code were used. The used software is a hybrid finite element code, which makes possible the slipping through joints elements. They can apply the Hoek-Brown material model, so in the modelling, the most important input parameters are the uniaxial compressive strength, the Young modulus, the Hoek-Brown constant (mi) of the rock and the geological strength index of the rock masses. According to these values, the software calculates the Hoek-Brown parameters of the rock masses [23]. The software is able to run statistical calculation when the input parameters are the mean and standard deviation of the strength parameters. After this calculation, the result is the probability of failure instead of a deterministic safety factor. The geometrical input parameters for 2D calculations are the cross-sections generated from the TLS measurement results. Where it was necessary, the measured joint parameters were also used in the software. The geometry was imported from dxf files; the mesh generation is automatic.

4. Results

Interpretation of ERT results presented in the form of 2D cross-sections indicates the presence of local zones with very high and low resistivity values. High resistivity anomalies above 12,000Ωm are associated with the main chamber of Jasna Cave (I) and its branches (side corridors), as well as with chambers not identified by exploratory research (II and III), due to their lack of connections and patency with the main chamber of Jasna Cave Fig. 8. Based on the ERT cross-section, the cave is located at a depth between 210-218 m a.s.l., under a 2-meter overburden. Based on geological data and obtained for overburden deposits, resistivity values around 250-2500Ωm can be concluded as loess and weathered, as well as locally protruding limestone rocks [24,25]. Zones with low resistivity in the surface layer are probably karst forms that can be filled with weathering mainly clay, silt, or they may be associated with water infiltration zones. The substrate consists of formations with resistivity values in the range of 550-4000Ωm according to literature data [24] are sandstones and conglomerates.

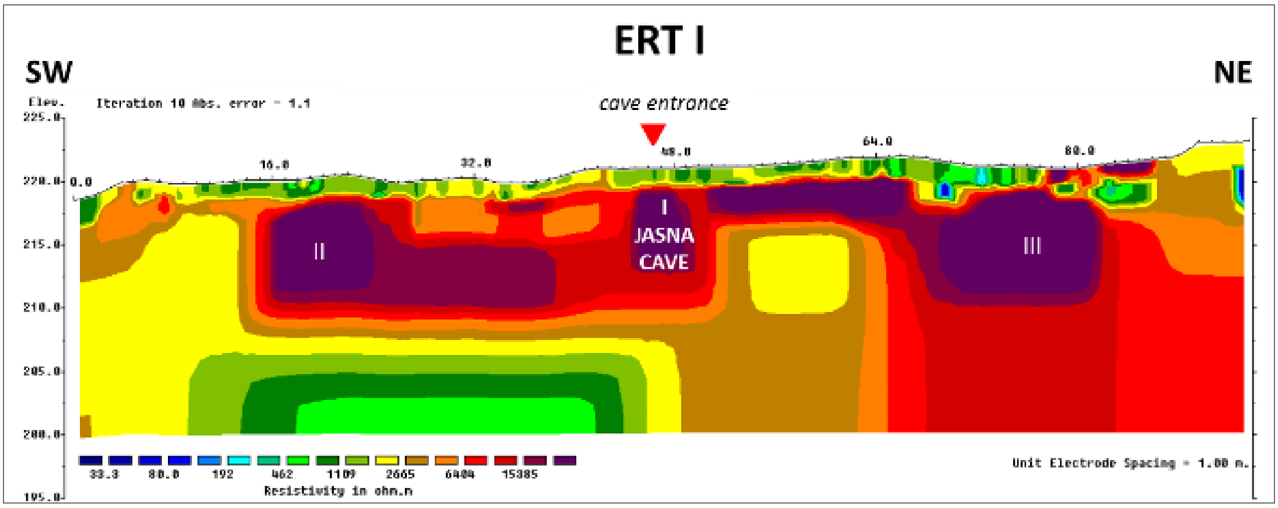

Figure 8. ERT I cross-section for Jasna Cave

The 3D inversion results show a three-dimensional image of the cave in the examined area Fig.9. In the presented work, very readable images were obtained in which the main chamber of the cave together with the left side is the clearly visible branch (southern), which explorers examined only in the initial part. Also visible is the more extensive right (northern) part of the cave, which can be seen in both the 2D ERT cross-section and the 3D ERT image. The hypothesis that the cave is part of the Zakrzówek Structure vacuum system and can be connected to other caves located in the study area Fig. 1 is therefore very likely.

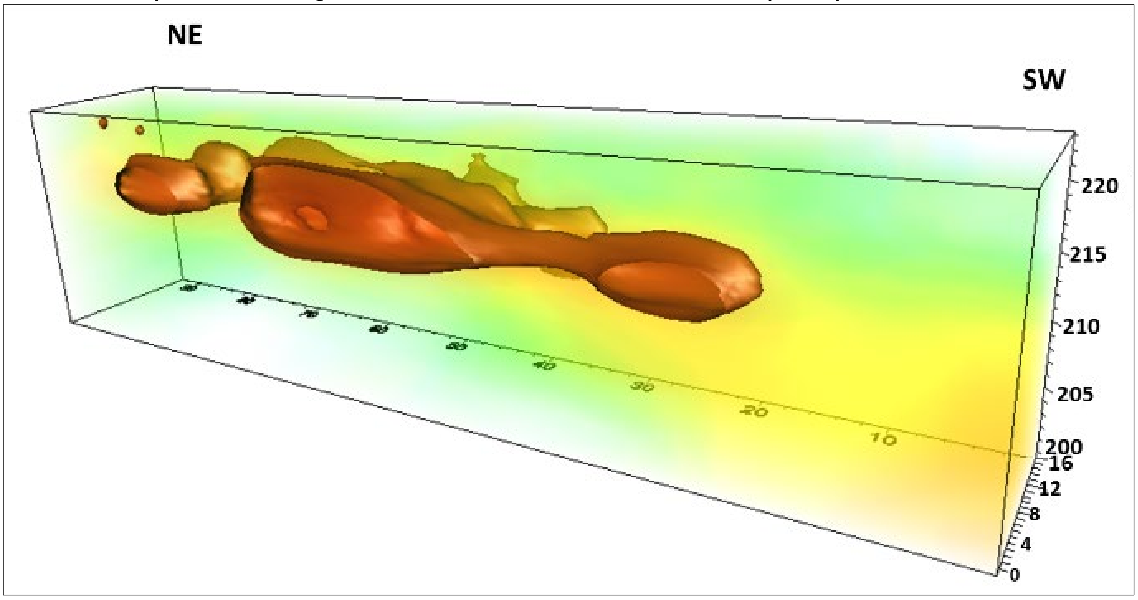

Figure 9. Three-dimensional 3D image of anomalies showing the distribution of Jasna Cave obtained in the ERT surveys

The studies show the results only for a fragment of the area where the cave is located Fig. 9 - but they are very promising. By means of electrical resistivity tomography, it was possible to locate, apart from the main chamber of the Jasna Cave, its additional branches (side corridors) as well as larger chambers which were unexplored before. Accurate analysis of 3D images allows determining their location and dimensions. In addition, as shown by the results of the research, the electrical resistivity tomography method gives the opportunity to determine: boundaries between lithologically differentiated layers, watered zones, places separating zones of different weathering conditions, e.g. between the ground and overburden, as well as the location of zones of weakness caused by karst processes and the development of fracture and loosening zones.

The geophysical ERT method described above helps to find the unknown parts of cave and cellar systems from surface surveys. At the same time, the TLS measurements taken inside the object gives precise results of the geometry, which can use for stability calculations. The TLS measurements usually measured in high resolution, but in this case, later was converted to a smaller resolution to handle easier with geotechnical software. The converted 3D view of the measured part of the cellar is on Fig. 10, and there are the main corridor and several other branches. The link between the cellar system and the surface was the several ventilation shafts, one of them is clearly visible in the Fig. 10. The 3D image of the cellars shows the place of the masonry arches as well, that is way the roof of the cellars is not horizontal on the figure.

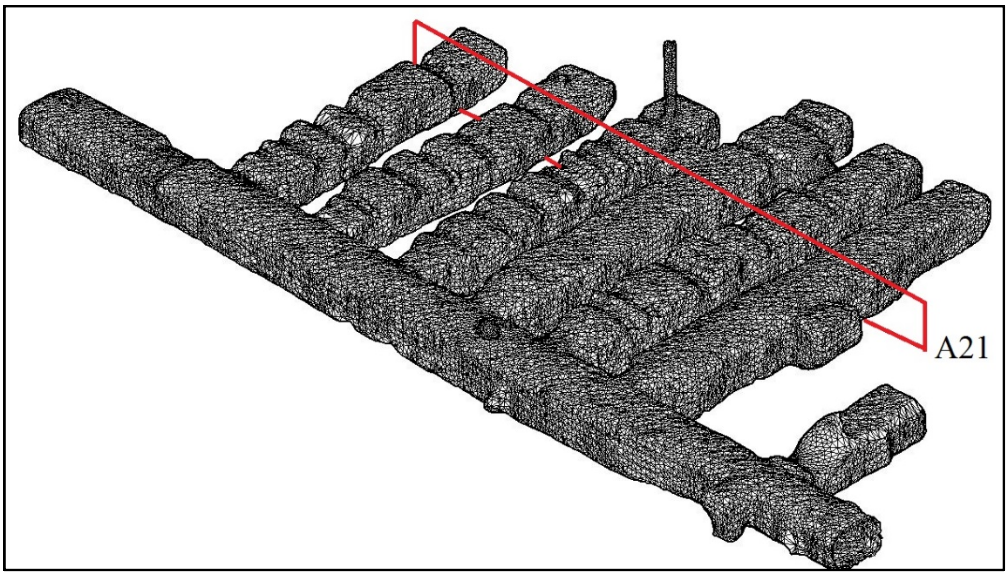

Figure 10. Three-dimensional 3D view of the investigated part of the cellar system, result of the TLS measurements with the location of the cross section A21

In the investigation area, there are more different cellars, which are close to each other with different entrances. Two of them was investigated, the distance between them around 300 m, but they are part of the same system. The reason for stability analysis is the development of the area in both cases; buildings are planned above them. But the bellow described stability analysis contains only the model one part of the cellar system, which is on Fig. 10. The stability calculation of the other parts of it is under progress such as the 3D calculations.

The average cover of the cellar system is around 5 m. In this case, there are only two layers in the model: the above layer of the porous limestone, which is weathered and jointed, and the rest of them which is massive with only some joints. The FEM model of it is on Fig. 11.

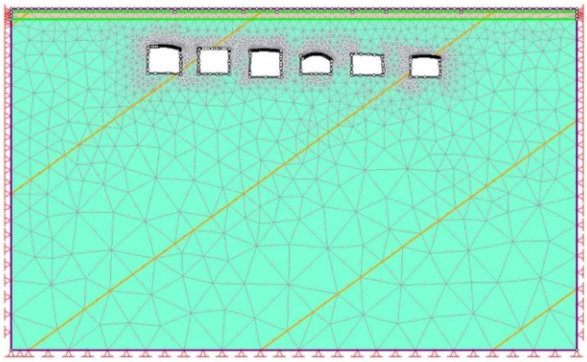

Figure 11. The FEM model of the cellars – cross-section A21

The calculation had been done using a deterministic and statistical method as well. For probabilistic calculation, the uniaxial compressive strength of the rock mass was given with mean (14.35 MPa) and standard deviation (6.8). The software made several calculations to have the probability of failure. For section A21 (located by 21m from the axis of the main corridor) Fig. 11 with the load of the buildings above the cellars, in a deterministic way three different calculations were made with minimum, maximum and average compressive strength parameters. The total displacement result of the average is on Fig. 12, while the safety factors are in Table 1 for all the calculated cases (Min, Ave and Max UCS values of laboratory results). It shows that the minimum safety factor in dry conditions is 2.32 and in saturated conditions is 1.37. Fig. 12 shows the joints also which measured in the cellar.

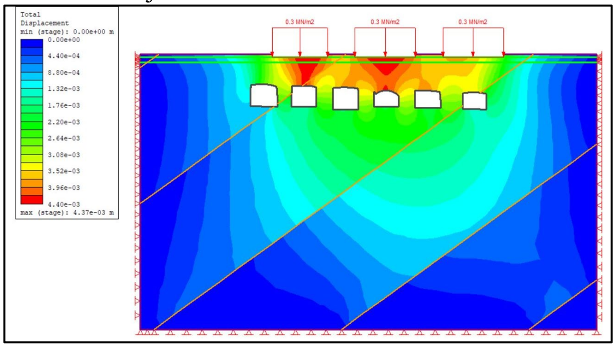

Figure 12. The total displacement of the section A21

Table 1. The max. displacement results and the factor of safety for the section A21 for different input parameters

		Max displacement (m)	FoS
Dry	Min	3.2*10-3	2,32
	Ave	4.4*10-3	3,37
	Max	1.67*10-3	5,39
Sat	Min	8*10-3	1,37

The probabilistic calculations were done only for dry conditions; it resulted average safety factor of 3.74 with standard deviation of 0.82. The probability of failure is 0.04%, which means that in 10000 cases only 4 can cause failure. And the probability that the factor of safety will be under 1.35 is 0.19%. The reliability index (RI) represents the number of standard deviations which separate the MEAN Factor of Safety, from the critical Factor of Safety (=1), RI number should be 3 or greater to have reasonable assurance [26]. and it can be calculated by $(RI)=\beta = (\mu_{FS}-1)/\sigma_{FS}$ [26,27].The RI of this calculation is RI=3.34 which is bigger than 3 so the calculation is reliable

5. Conclusions

The use of comprehensive methods; geophysical (ERT), geodetic (TLS), geotechnical supported by numerical simulations and laboratory tests enables the determination of complicated geological structure, in particular places of discontinuous deformations that may propagate towards the surface of the terrain, as well as karst and anthropogenic voids that pose a huge threat to surface infrastructure and public safety. Furthermore, these technologies are necessary for appropriate decision of building developments in such areas.

The geophysical (ERT) method helps to find the unknown underground cavities such as caves forgotten cellars. With this method, unexplored parts of the Jasna Cave was described. At the introduced investigation area of Budapest, the most parts of the cellars are known, but there were some parts of the site, where geophysical investigations were done to prove that there is no underground cavities can be found. The TLS method was used to obtain the geometrical input parameters for the calculations. Finally, both the deterministic and probabilistic calculation results showed that the cellars are stable at their current state with the planned buildings above them.

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