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Research paper

From legend to discovery – historical and geotechnical conditions related to the discovery of tunnels under The Castle Hill in Szczecin

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Abstract: The historical past of a building has a key influence on the variability of geotechnical conditions. These conditions change with a modification of the structural system, a change in function or only architectural elements (fashionable in a given period). In the article, various geotechnical and geophysical surveys are described, which led to a discovery of potential causes of a structural failure at historical Castle of Dukes of Pomerania in Szczecin. The investigation resulted in a discovery of an underground tunnel system constructed under the Castle, which existence was only suspected. The tunnels were constructed primarily during II World War, but also before that period. The article summarizes facts discovered due to investigation as well as historical and geological background related to the execution of the reinforced concrete and masonry tunnels. The lesson learned resulting from this discovery is that great care should be taken when historical areas are considered, even if the structure seems to be massive and robust.

Keywords: geotechnical research, geophysical methods, tunnels, historical object

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1. Introduction

The Castle of Dukes of Pomerania is considered as one of the most interesting locations in Szczecin and it is the most recognized monument of this city. Its beginnings can be traced back to 1346, when Prince Barnim III started the construction of a small castle and a chapel of St. Otton [1]. In mid XV century, the Castle was enlarged. In years 1573–1582, Prince Jan Fryderyk converted the late gothic structure into a renaissance residence. The northern wing of the Castle was built in years 1575–1577 at the location of the old court of Barnim III, collegiate of St. Otton, and a medieval defensive wall. The Castle was renovated and rebuilt multiple times, and as a result of air raids at the end of the II World War, it was seriously damaged. It was renovated over some years after the war, and it was made available to the visitors in the 1970s. The last renovation of the north wind has been conducted in 2014–2015 [2].

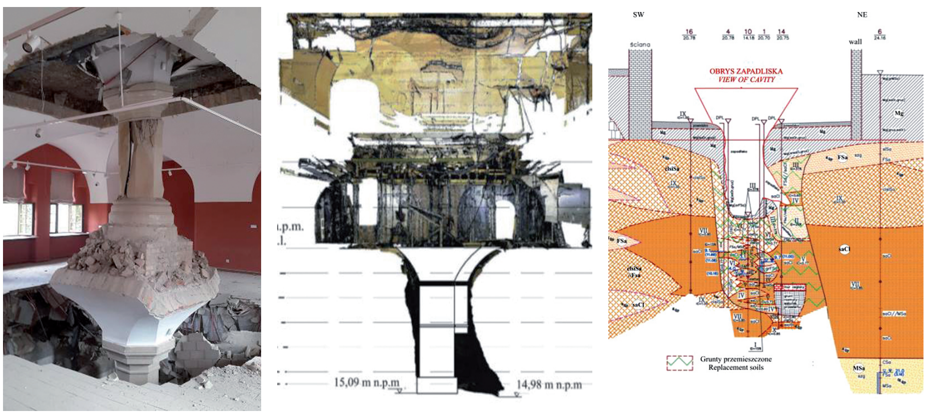
In terms of the morphology, the analyzed area is located in the area of Szczecin hill, i.e. within the moraine plateau, limited by erosive slopes, in the immediate vicinity of the Lower Odra Valley. The natural edge of the slope underwent significant anthropogenic transformations in connection with the settlement in this place and the construction of the Castle. The surface of the land was built up with a layer of fill grounds, and the surface of the slope was cut by the construction of houses. A slope on the side of the northern range, with a significant inclination with an upper level at the ordinate of about 24.0 m a.s.l., rests on the ravine of the former city moat. Its bottom is currently at an elevation of 10.0 m a.s.l., at Panieńska street, up to 17.3 m a.s.l. at the western part [25].

Due to the colonization lasting in this area from around the 9th century, in particular due to the construction in the 13th century of the first brick castle in the place of the former stronghold, and the construction of brick residential houses along Panieńska street (13–15th centuries), the natural edge of the valley has undergone far-reaching anthropogenic transformations. These transformations consisted, on the one hand, in adding to the natural surface of the land with a thick cover of fill grounds, and on the other hand, in digging into the slope with the rear parts of buildings at the back of the houses. Subsequent changes to the topography took place after 1945, after demolishing the ruins of the houses at Panieńska street, and then in recent years, in connection with the construction of new houses on the foundations of the former buildings, and with the clearing up of the area in their backyards. The slope, as indicated by the numerous geological and archaeological studies conducted to date, in its upper zone (the area of the terrace and the crest of the slope), is composed of fill grounds (mainly medieval) with a thickness of approx. 3÷6 m, based on native soil below. The slope is dominated by post-war non-engineering fill composed of rubble, built in the form of alternating layers consistently arranged in relation to the slope. The thickness of these embankments reaches 5÷6 m in the northern part and 7÷8 m in the eastern part (due to the remains of old buildings).

The Castle became famous after the failure, which occured on 11th of May 2017. The failure was very sudden, lasting just few seconds. Its occurence was registered by the surveillance cameras, with a sudden collapse of a column. The rooms in which the failure occured are adjacent to a staircase (as well as the entrance B and C) of the northern wind of the Castle.

In the central part of each room, i.e. in the basement, as well as at the ground, first and second floors, a massive column supporting the ceilling of a given level was located. Investigation conducted after the collapse indicated that the pillar has dropped down by one level, without rotating (Fig. 1a), while the basement part collapsed under the ground (Fig. 1b).Most of the rubble fallen down into the basement, which became partially buried and not accessible for a time. A significant inclination of the bottom of the cavity towards western direction and a niche inside, probably of antropogenic origin, were documented (Fig. 1c).

Fortunately, besides the material losses, there were no casulties. However, this event started a three-year long investigation into the causes of the failure. It also aimed to answer a question whether the rest of the structure founded on the Castle hill is safe.



(a) (b) (c)

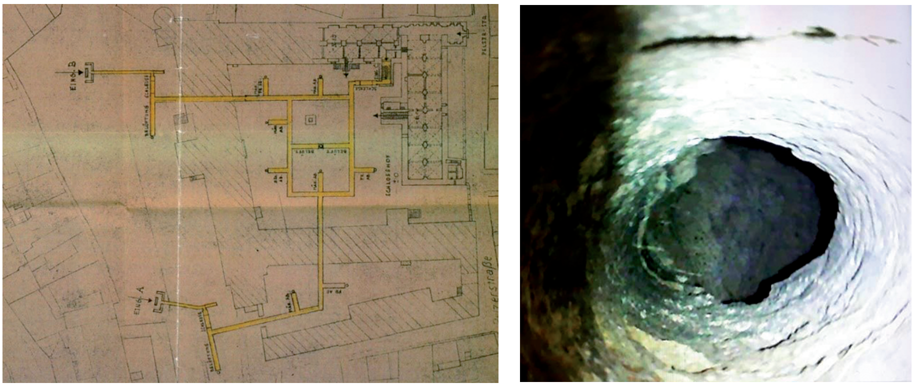
Fig. 1. a) Pillar condition after the failure [4]; b) simulation of the position of the column after the disaster based on laser scanning [2], c) part of the geological cross-section below the column [5]

2. Methods of geophisical and geotechnical investigation

Described mode of failure (collapse of the columns at a significant depth) and the conclusions of experts suggested (despite a large number of tests conducted so far) the possibility of existance of some structures or openings in the ground under the Castle [6]. Those speculations were based on the number of anomalies registered in geophysical tests, which were compared to the maps of planned bunkers from the times of the war (Fig. 2a).

Despite numerous boreholes, this hypothesis could not have been confirmed directly. At the same time, historical conditions and numerous renovations of the Castle added erroneous clues. In order to minimize the risk of conducting construction works associated with renovation, the administration of the Castle decided to conduct additional geotechnical and geophysical investigations.

First tests (boreholes) were conducted in May 2020, in orded to fulfill the recommendations of an expert opinion [2], stating the need to verify the ground conditions along the line between the failure location and a collapsed cavity that occured in the 1970s on the northern terrace. A cavity was found (Fig. 2b) along the borehole, at a depth between 12.5 m to 16.0 m b.g.l. [7].



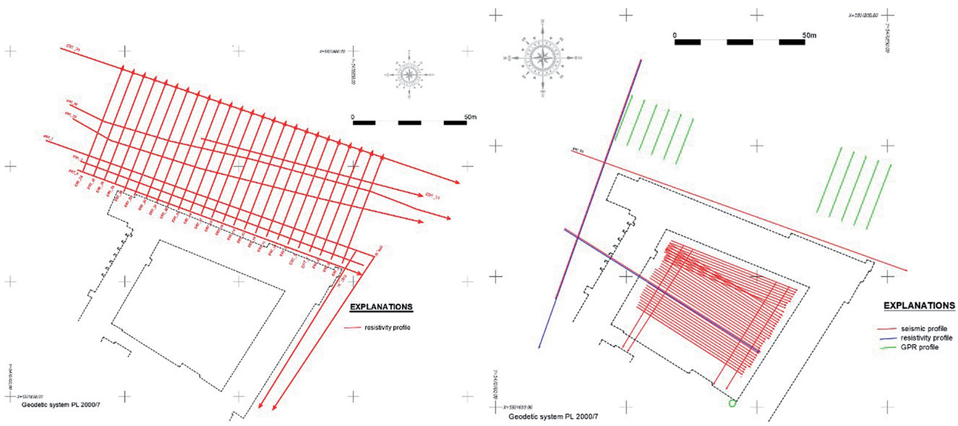
(a) (b)

Fig. 2. (a) Plans from 1943 for shelters with tunnels under the Castle – construction of a shelter, for max. 1480 people, under the Castle's coutryard, with tunnels of total length approx. 760 m with two entrences at the foot of the slope and an entrence from the Castle [3]; (b) the view on the void in the borehole at a depth of approx. 13.5 m b.g.l. [8]

This discovery justified the need for conducting additional works related to investigation of the conditions. Additional tests were conducted in July 2020 [8] and September 2020 [9]. Their scope was aimed at detection or exclusion of underground cavities, which might have influenced the failure of the column in the northern wing of the Castle. As a part of both stages of the investigation, a total of 30 boreholes and 30 dynamic soundings were executed, up to the depth of max. 19.5 m b.g.l., with total length of the boreholes of approx. 475 m and approx. 345 m of dynamic soundings. The test were planned in the locations of anomalies noticed in geophysical investigation.

The ERT method was developed at the end of the 20th century and is widely described e.g. in the works of Zhadov and Keller (1994), Loke and Barker (1996), Mościcki and Antoniuk (1998), Samouelian et al. (2005), (after [10]). In the ERT method, the distribution of electrical resistance of a medium is modeled in 2D blocks. Such modeling makes it possible to determine the differentiation of the resistivity of the medium in the vertical and horizontal directions on the cross-sectional surface along the lines of the measurement system [10, 11]. The final result of the series of measurements is the apparent resistance distributions on the apparent depth scale. The set of results obtained in this way can then be visualized, processed, and interpreted qualitatively and quantitatively in order to investigate the substrate [12]. Historical objects usually appear in the results of ERT tests as anomalies with increased electrical resistances (in the order of several hundred or several thousand µm), e.g. thick sedimentary layers, debris, walls, embankments, voids.

The scope of geophysical investigation included 36 ERT profiles (Fig. 3a), with total length of over 3000 m. Assumed methodology included a spacing of 2 m, 1 m and 5 m for the electrodes, using a measuring system 4×21 and 2×21, which resulted in high accuracy and investigation up to $15 \div 17$ m b.g.l., depending on the length of the profile.



(a) (b)

Fig. 3. Schematic of geophysical profiles at the Castle of Dukes of Pomerania in Szczecin: (a) ERT profiles during the I stage (along the terrace and the slope) [8]; (b) SRT profiles and additional ERT profiles stage II [9]

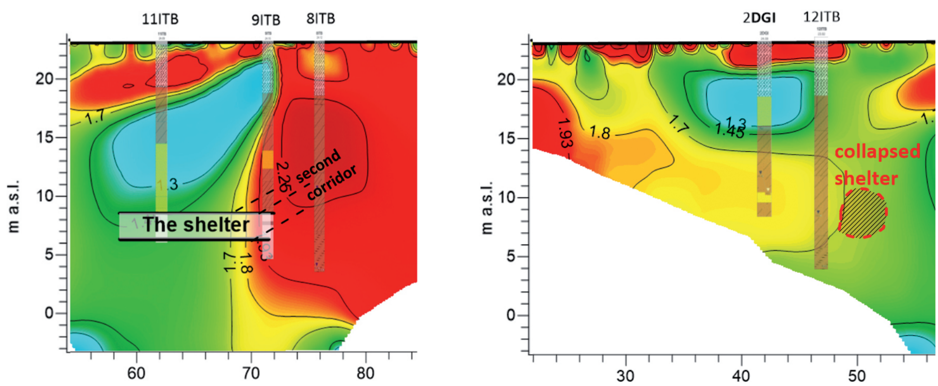
The idea of seismic refraction tomography is based on the assumption that wave velocity spreads spherically in the ground from the point of vibration induction, spreading to refractive border, where it breaks down and slides along the its surface, and then goes back to the ground surface, where it is registered by geophones. The seismic devices automatically registers the time of wave pass from the moment of its induction to the registration by the geophone [13–15].

In terms of SRT seismic profiling, a total of 44 profiles (Fig. 3b) were conducted with the total length of approx. 2400 m, mostly in the area of the Castle's courtyard; tests were conducted using parallel system of profiles every 1 m, with geophones spaced every 2 m. It allowed for obtaining a prospection up to approx. 20 m b.g.l. In the courtyard area, the measurements were taken as parallel profiles every 1 m. The distance between geophones was 2 m. The signal was generated with a 10 kg hammer at every other geophon (every 4 m). 10 Hz geophones were used (registering >10 Hz). The investigation was done using 2D method. Measurements were difficult due to car traffic vibrations nearby. In order to improve the quality of the signal, multiple seismic excitation (up to 15 times) was implemented.

3. Results

3.1. Geophisical and geotechnical investigation results

Geophysical (ERT and SRT profiles: own and archival) and geotechnical (boreholes and soundings) tests executed methodically and comprehensively (successive ground profiling with verification of encountered anomalies) revealed the existence of previously unknown underground structures (tunnels, bunkers), from the times of German Szczecin, under the Castle hill. In few boreholes at the depth of approx. 15.4÷17.3 m b.g.l. (8.4÷6.5 m a.s.l.), presence of described structures was confirmed. With the use of inspection camera, their type and state were confirmed and documented (photos, movies). Obtained distributions of electrical resistivity of the ground were very disturbed. It was a result of the presence of technical infrastructure (electrical cables), few meters thick fill layer, and underground structures (reinforced concrete tunnels constructed for shelter). In the profile ERT_3, a noticeable, vertical border between the zones of low (< 50 Ωm) and high (> 200 Ωm) electrical resistivities at the distance of 70 m (Fig. 4a) is present. This border resulted from the strong shielding of the tunnel structure – reinforced precast concrete. This was an important discovery (confirmed by the borehole) from the point of view of further research. Borehole (9ITB) performed in this area showed at a depth of approx. 15.4÷17.3 m b.g.l. a void in the ground. After inserting the camera into the hole, it was found that the drilled cavern was a fragment of reinforced concrete tunnels – German shelters from the period of the World War II.



(a) (b)

Fig. 4. Fragment of the profile ERT_3 along the terrace: (a) anomaly due to buried shelter, (b) anomaly with included outline of a tunnel/shelter [8]

Similar to the border described earlier, the boundary between the anomalies was also encountered at the ERT_3 profile, along the length of 50 meters. Borehole (12ITB) made in this place showed the presence of a collapsed corridor of the shelter (Fig. 4b). It was also confirmed in profile SRT (Fig. 5).

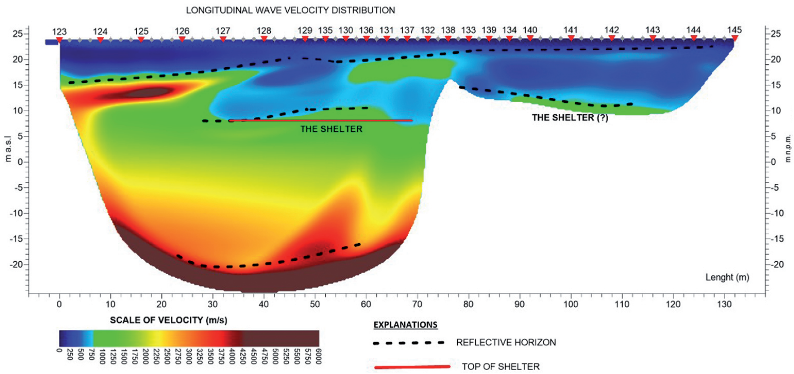


Fig. 5. Profile SRT_D3, along NE terrace, west – east direction [9]

28 ERT profiles were made in the slope area (25 down the slope, 3 along the slope). The variability of the electrical resistance is significant here: from several dozen Ωm to over 500 Ωm. The visualization of the electrical resistance distribution was prepared in the form of 2D sections and 3D models. The kriging method was used for the interpolation of ERT data. It was assumed that in the X direction there are 100 nodes and in the Y direction are 45 knots, so as to get spacing of about 0.4 m.

In 2D sections, several anomalies with very high resistances were distinguished, which may indicate the presence of an underground shelter under the slope. The high resistance of the subsurface zone may also indicate a significant share of brick rubble fill building the slope in these places. The electric resistivity anomaly caused by the influence of the underground shelter was indicated. At this height (on a layout), an underground tunnel structure was found on the terrace through the 9ITB borehole (Fig. 6).

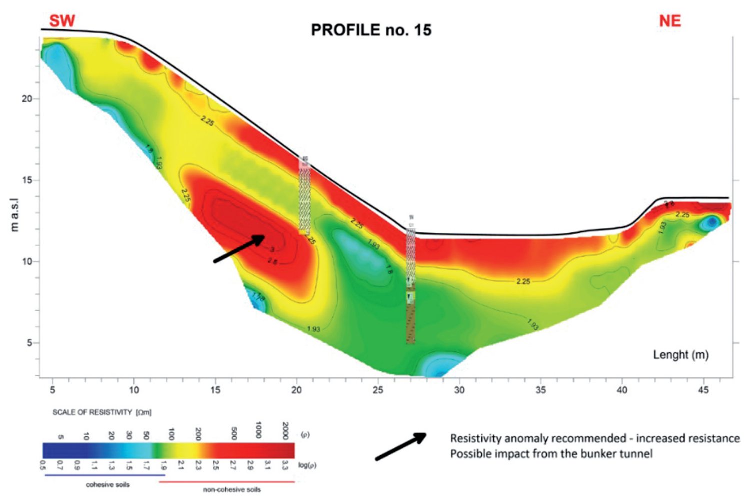


Fig. 6. ERT_7, approx. 17 m west from the NE corner of the terrace [8]

The compilation of all ERT profiles (supported by GPR profile – in terms of potential voids) allowed for the development of a three-dimensional image within the slope. The 3D visualization (Fig. 7) allowed for the separation of two distinct electrofusion anomalies in the slope foot area, which are most likely caused by the presence of two buried exits from the shelter or, according to the preserved documentation, of ventilation shafts. The two anomalies on the left side, indicated in Fig. 9, occur approx. 12÷17 m to the west of the stairs built in the NE corner of the terrace. On the other hand, the indicated anomaly in the middle of the slope correlates with the underground bunker that was identified by the 9ITB borehole.

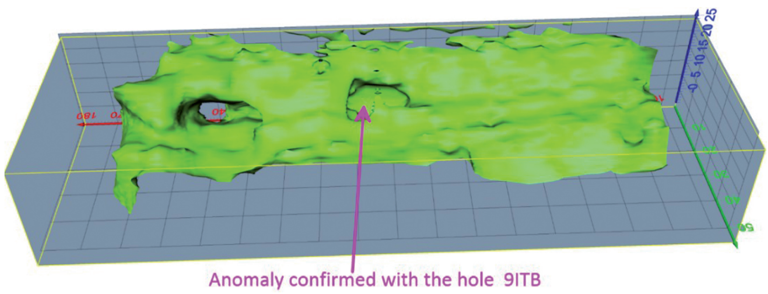


Fig. 7. An example of a 3D visualization of geophysical test results (spatial representation of resistance for a value of 140 Ωm), a visible profile along the northern slope, which describes anomalies indicating the course of tunnels and one of the exits from the shelter (on the east side of the slope)

Geophysical measurements made by three different methods (ERT, SRT and MASW [16]) along the terrace of the Castle of the Pomeranian Dukes, from the side of the escarpment, made it possible to draw some conclusions regarding the effectiveness of selected geophysical methods in difficult urban conditions. The compiled geophysical resulting profiles are presented in Fig. 8. Profiles of boreholes were used to interpret the results of geophysical surveys. The ERT cross-section is difficult to interpret, due to significant disturbances in the distribution of electrical resistance from the existing technical infrastructure [17].

Nevertheless, in the tunnel zone, a clear contrast of electrical resistance is observed – passage from about a few dozen Ωm to over 1000 Ωm. This place is indicated by an arrow (Fig. 8a). The SRT cross-section (Fig. 8b) shows the velocity distribution of the longitudinal wave. The conditions of measurements using this method, in urban conditions (numerous disturbances from urban traffic and the operation of various devices), do not give certainty for the accuracy of timing the first ascensions of waves, and thus the modeling of the cross-section of the velocity of longitudinal waves [18, 19]. The tunnel is marked indistinctly, as a zone of increase in the speed of seismic waves, which are reflected from the reinforced concrete casing. In addition, the correlation of hole profiles with the obtained distribution of the velocity of longitudinal waves allows for the separation of three layers (embankments, clays, sands), while the location of the velocity limits between them does not coincide exactly.

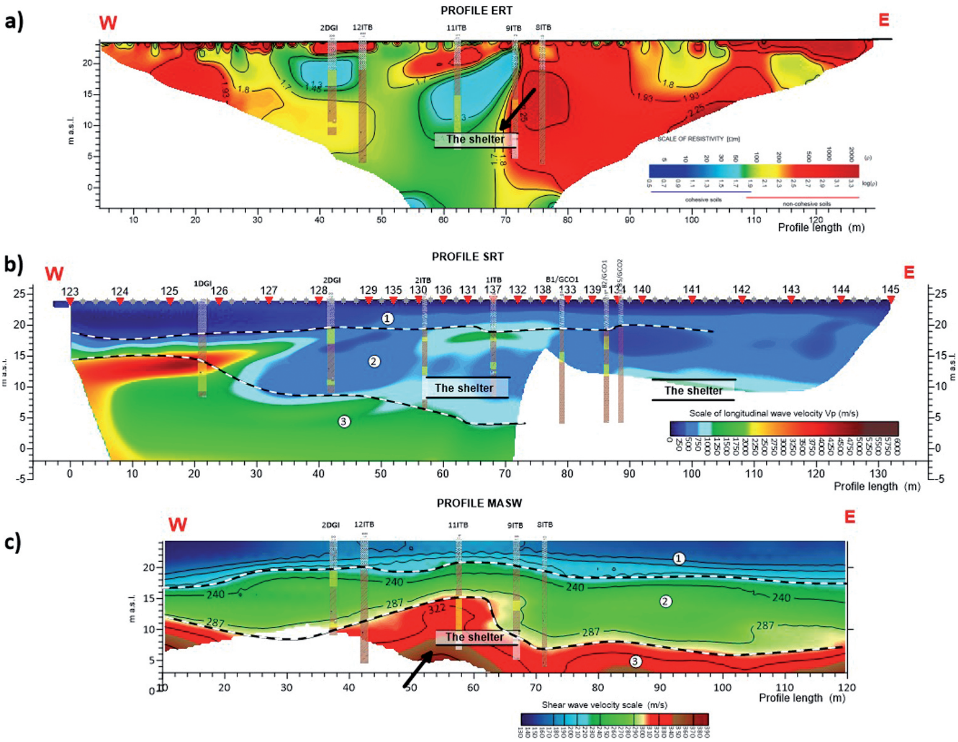


Fig. 8. List of geophysical profiles (described in text), interpreted layers: 1 – embankments, 2 – clays, 3 – sands

The MASW cross-section (Fig. 8c) shows the distribution of the velocity of the transverse wave. It is a seismic method, giving the best results in seismic noise conditions [16]. The determination of the velocity of transverse waves is generally based on the diagram of the dispersion curve (graph of the dependence of the phase velocity of the Rayleigh wave, frequency increase) [20–22]. In the analyzed cross-section near the tunnel found, an increase in the speed of transverse waves can be noticed, which are probably generated by the reinforced concrete casing of shelters (this place is indicated by a black arrow in Fig. 8c). In addition, the positions of seismic boundaries correlate quite accurately with the profiles of boreholes.

3.2. Tunnels inspection

A detailed description of these discoveries along with the documentation of the identified tunnels is included in the investigation reports [8, 9]. Most of the underground corridors were made using the mining method using prefabricated reinforced concrete slabs and beams, approx. 1.9 m high and approx. 1.5 m wide (there are local widening and narrowing of the tunnels). Analyzing the type of structure – by analogy with the known objects of this type in Szczecin [23], they were considered to be German tunnels from World War II, serving as shelters (Fig. 9, 10).

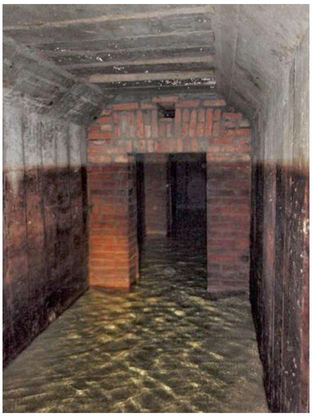
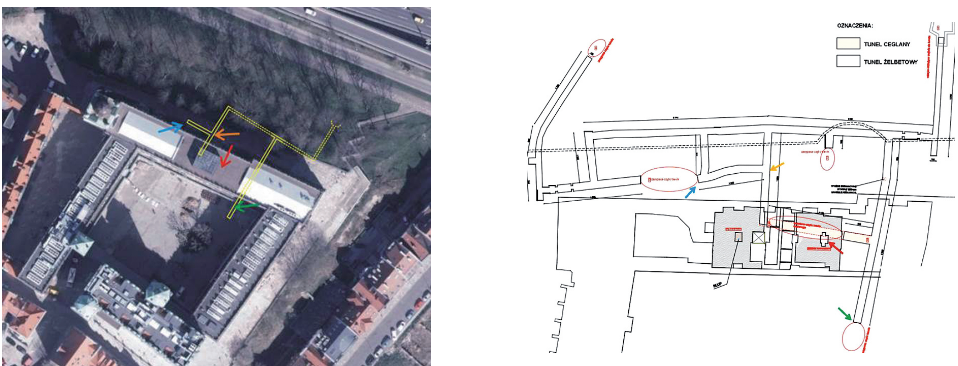


Fig. 9. View of the lock under the western part of the northern slope – visible water at the bottom of the tunnel and traces of historical or periodic levels of its occurrence (Photo: T. Godlewski, 2021)

Fig. 10. View of the tunnel running along the northern slope – visible level of maximum flooding of the tunnel (Photo: T. Godlewski, 2022)

At the site where the existence of the tunnel network was first confirmed (borehole 9 ITB – orange arrow in Fig. 11), a detailed camera inspection revealed the existence of an intersection from which three corridors depart in mutually perpendicular directions (north, west, south). Thus, it has been shown that the previously discovered cavern in the area of the



(a)

(b)

Fig. 11. View from above (a) of the Pomeranian Princes Castle – indicated (in yellow) an outline of the confirmed and probable presence of underground tunnels in the area of the terrace and the slope, based on the 2020 studies carried out [8, 9]; b) the established inventory of tunnels on the basis of direct exploration [24] – the red arrow indicates the site of the disaster and the collapse within the brick tunnel. The others are explained in the text

location of the sinkhole from the 1970s (blue arrow in Fig. 11) is closely related to the course in the vicinity of these tunnels. These objects, in the base of the Castle hill, due to the nature of the structure (the use of a temporary casing made of bricks, prior to the execution of the reinforced concrete structure – with the disturbed ground zone around) and the conditions related to their implementation (numerous leaks, especially at the unfinished stages, voids at the face) constitute drainage points and privileged groundwater flow directions. These conditions led to the formation of local voids and erosive cavities along the tunnel structure, which was confirmed by numerous inspections.

The investigation carried out within the courtyard [9] was aimed at confirming or excluding the existence of the structure according to historical plans (underground shelter for nearly 1500 people). Analysis of the results of the seismic wave velocities distribution, at a depth of approx. 16 m b.g.l. (the approximate depth of the tunnel location, which was detected by earlier drillings), made it possible to distinguish two linear zones of reduced velocities, similar to the hypothetical tunnels drawn in the archival German plans. The verification of these zones by drilling and dynamic probing (DP) showed that these anomalies result from the lithological heterogeneity of the native soil (the presence of highly waterbearing sandy layers of lower density). Thus, apart from the fragment in the area of the 16ITB borehole (green arrow in Fig. 11), the existence of other underground structures in the ground under the courtyards has not been confirmed. Additional studies in the courtyard also confirmed earlier findings indicating the complex nature of the first groundwater level within the Castle Hill (sandy lenses at different depths, with confined water), which may affect the analysis of the causes of the disaster.

4. Discussion

4.1. Geological and historical conditions

The performed tests did not confirm the construction of the entire tunnel system, as planned according to archival German plans. It can be assumed that the plans, for some reasons (including unfavorable ground conditions or the advancing war front), have not been fully implemented. The findings disclosed during the investigation indicate the possibility that the tunnel builders were "surprised" and could significantly contribute to the development of the analyzed failure. Within the scope of the previously described findings, it is necessary to indicate the geological conditions (soil and water) related to the genesis and the current situation of the building at the Castle Hill. Under a layer of centuries-old fill grounds (6÷8 m thick), this substrate is made up of Pleistocene glacial till deposits (Fig. 12).

Described historical embankments and moraine sediments (formed as clay sands and sandy clays with gravel and silt interbeddings) create a complicated system of layers and thus complicated geotechnical conditions. Moraine formations usually occur as stiff to hard. Within the described complex of glacial formations (clay) there are numerous interfaces and sand-gravel lenses, with a structure indicating strong distortions of a glacitectonic nature

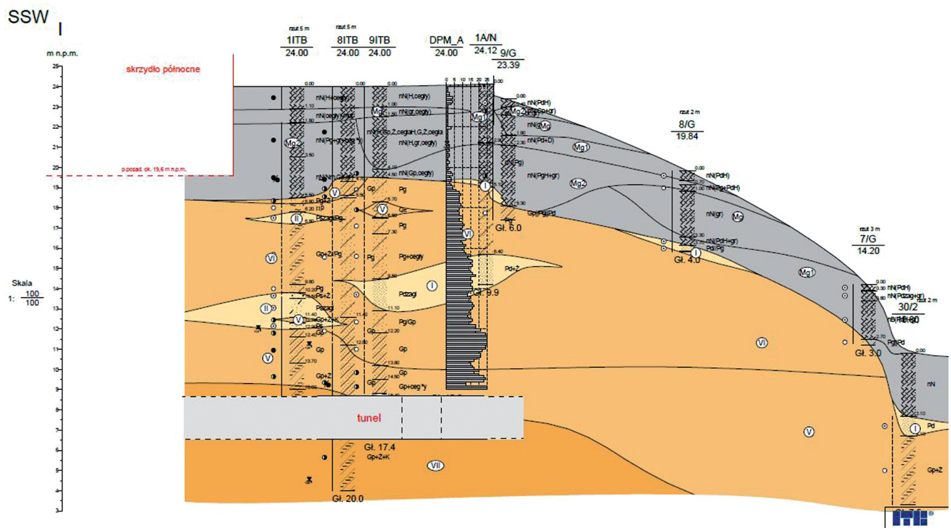


Fig. 12. Part of the geological cross section from the castle to the north slope, with a visible location of the tunnel under the embankment layer (gray) within the moraine formations (brown) [9]

at the micro and macro scale. These conditions (in terms of the observed soil structure) make these layers more predisposed to the described [2] probable mechanism of failure.

The sediments that build the Castle Hill also have numerous layers of silty sands and silts, sensitive to liquefaction in the event of changing water conditions. The described situation took place during the construction of tunnels. In a situation, when during the work, a stratum (lens) of saturated sands was found on the tunnel route under the courtyard. The visible, unfinished face (Fig. 13a), is the result of "pouring" sand with water into the tunnel, and despite an attempt to build a temporary support, the phenomenon was not stopped.

The carried out investigation of the tunnels (Fig. 11), apart from an attempt to "avoid" the problem in the courtyard – as evidenced by numerous revealed side corridors, revealed the presence of older structures located under the northern wing of the Castle (Fig. 13b). Directly at the failure location (red arrow in Fig. 11), an oval tunnel with traditional lining (made of bricks) was found, with a visible sinkhole, which was the result of the catastrophe. The tunnel is partially flooded, there are visible traces of fresh and long-lasting infiltrations. The bricks are falling apart in some places, and the walls of the tunnel show bulges and deformations.

This discovery directly indicates the nature of the catastrophe (sinkhole), revealing the place where the ground shifted from under the column. The presence of a brick tunnel and its sensitivity to changes in environmental conditions (in terms of humidity) indicate the course of the phenomenon, i.e. the formation of a sinkhole as a result of loss of the tunnel linings's load-bearing capacity. In the course of further analyzes, the factor that triggers the visible effects should be determined.

(a) (b)

Fig. 13. a) The view of the face of the unfinished tunnel under the courtyard (behind the green arrow according to Fig. 11) – you can see the inflows, the phenomenon was of a sudden nature as evidenced by the extent of the ceiling of the already constructed lagging in relation to the position of the provisional protection, b) view of the oval brick tunnel along the north wing – a visible collapse directly located below the failure site (red arrow according to Fig. 11), (Photo: T. Godlewski)

5. Conclusions

The historical past of a building has a key influence on the variability of geotechnical conditions [26, 27]. These conditions change with a modification of the structural system, a change in function or only architectural elements (fashionable in a given period). These grounds change the flow of rainwater (new directions of runoff), often causing uneven subsidence [28]. The monuments also suffer numerous damages resulting from history events (fires, war devastation, bombing). The above-mentioned reasons (reconstruction, modernization and destruction) lead to the characteristic effects in terms of the current condition of the structure and the possibility of the further use. In the facility in question, military operations, including the implementation of projects, i.e. underground shelters, also had a negative impact on the structure, resulting in a structural failure. This, however, contributed to the verification of the legends and assumptions regarding the existence of underground structures, which could be confirmed using well-planned geophysical and geotechnical surveys.

The advantage of geophysical surveys is the relatively quick recognition of significant areas, which, with all the problems regarding the correct interpretation of the results, allows you to indicate places that require accurate (quantitative) checking by classical methods. The effectiveness and usefulness of the results of imaging tests, qualitatively the properties of the examined center depends on the selection of the appropriate research method and measurement technique, which will allow the recording of expected anomalies (contrasts of physical features) in the substrate. For this purpose, the most effective solution is to use complementary different methods and confirm the obtained results with point penetration methods (drilling, sounding). One should remember about the need to conduct extended investigations and analyzes (geotechnical and constructional) in relation to the often turbulent history of the structure (and the circulating legends).

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Od legendy do odkrycia – historyczne i geotechniczne uwarunkowania odkrycia tuneli pod Wzgórzem Zamkowym w Szczecinie

Słowa kluczowe: badania geotechniczne, metody geofizyczne, tunele, obiekt zabytkowy

Streszczenie:

Historyczna przeszłość budynku ma kluczowy wpływ na zmienność warunków geotechnicznych. Warunki te zmieniają się wraz z modyfikacją układu konstrukcyjnego, zmianą funkcji lub tylko elementów architektonicznych (modnymi w danym okresie). W artykule opisano różne badania geotechniczne i geofizyczne, które doprowadziły do odkrycia potencjalnych przyczyn katastrofy historycznego skrzydła Zamku Książąt Pomorskich w Szczecinie. Przeprowadzone badania doprowadziły do odkrycia podziemnego systemu tuneli zbudowanych pod Zamkiem, których istnienie tylko podejrzewano. Tunele zostały zbudowane głównie w czasie II wojny światowej, ale także przed tym okresem. W artykule podsumowano aktualne fakty odkryte w wyniku badań oraz uwarunkowania historyczne i geotechniczne związane z wykonaniem tuneli żelbetowych i murowanych.

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