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ROCK-MECHANICS STABILITY AND SAFETY OF FERENC-HEGY CAVE, BUDAPEST, HUNGARY

KŐZETÁLLÉKONYSÁGI VIZSGÁLATOK A FERENC-HEGYI BARLANGBAN (BUDAPEST, MAGYARORSZÁG)

GÁBOR SZUNYOGH

Donát Bánki Faculty of Mechanical and Safety Engineering, Óbuda University,
H1081 Budapest, Népszínház str. 8., Hungary,
szunyogh.gabor@bgk.uni-obuda.hu

Abstract: Jelen cikk azzal a kérdéssel foglalkozik, hogy Budapest beépített területei alatt található barlangok befoglaló kőzetének mozgásai, illetve a barlangokban megfigyelhető omlások folyamatai jelenleg is zajlanak-e (veszélyeztetve a felszíni létesítményeket), vagy már nyugvópontra jutottak. Vizsgálatra a Budapest „elit negyedét" képező Rózsadomb alatti mintegy 50 km összhosszúságot kitevő barlangok közül a csaknem hét kilométer hosszúságú Ferenc-hegyi-barlangot választottuk, mert az arra vonatkozó következtetések adaptálhatók a többi barlangra is, sőt, mint módszer, más városok alatti barlangok biztonsági értékelésére is alkalmas. E kutatás során mintegy ezer repedés adatait vettük fel, melyek öt, jól elkülöníthető csoportba voltak sorolhatók. Az egyes csoportokba tartozó repedések keletkezésében egy olyan hierarchikus sorrendet sikerült feltárni, ami alapvetően meghatározza az általuk kiváltott omlásveszély mértékét. A cikk ismereteti az egyes repedéscsoportok jellegezetességeit és szerepét az omlásveszély kialakulásában, valamint bemutatja azt a módszert, amellyel megítélhető a lakott területek alatti barlangok állékonysága.

Keywords: urbanized terrain, cave, collapse hazard, stability, safety, rock displacement

Introduction

Rózsadomb (Rose Hill) is an exquisite historic and residential area on the Buda side of Budapest, the capital of Hungary. This relatively small, 5 to 6 km^2 area, is home to many expensive villas. Yet, from the perspective of geological engineering Rózsadomb is particularly sensitive. More than 100 caves are known under its surface, with the total length exceeding 45 km (*LEÉL-ŐSSY* & & *SZANYI* 2011). The upper-storey passages of this underground labyrinth, running close to the surface, at times cause damage to public roads, buildings, water supply lines, sewage systems and other structures. Since the bedrock of the Rózsadomb caves (Pál-völgy, Mátyás-hegy, Ferenc-hegy, József-hegy, Szemlő-hegy, Molnár János, etc.) contains an extremely large number of cracks, and many collapses can be found in their passages, this leads to a question: what rock mechanics processes cause this cracking, and are they still in progress (endangering structures on the surface and visitors and researchers in the caves) or have they come to a standstill?

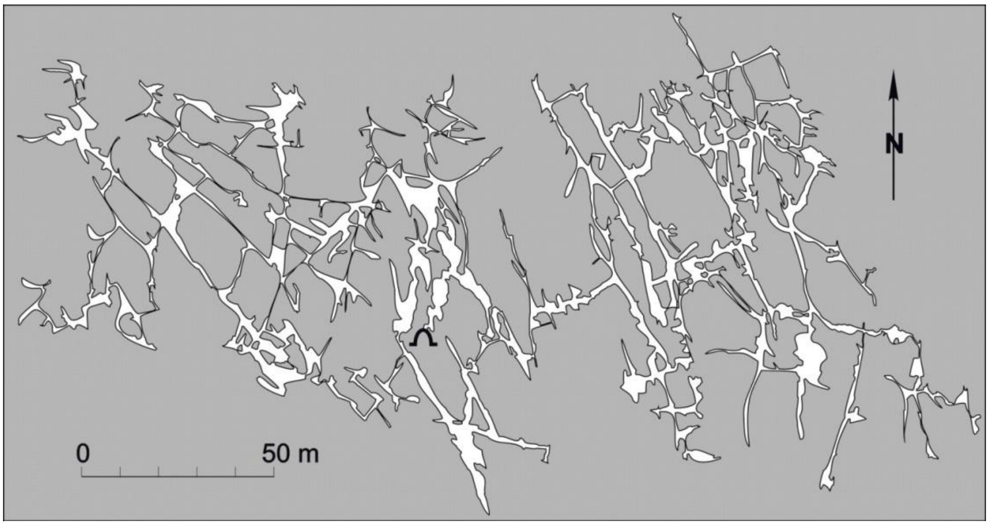

Fig. 1. Map of the examined sections of Ferenc-hegy cave

Important question arises: are the tectonic movements responsible for the cave development still active?

Ferenc-hegy (Francis Mountain) cave (*Fig. 1*) appears to be a perfect test-site for addressing this problem. Its overall structure and morphology are identical to those of other Rózsadomb caves. It is partly located under urbanized and partly under undeveloped terrain, which provides an opportunity to explore the possible effects of civil engineering on caves. Nearly 7 km of Ferenc-hegy passages are located within a 150×300 m^2 area. Such high density of passages is typical of the caves of thermal hypogene origin in Buda Hills.

Stability and support of natural underground cavities represent a special chapter in mining engineering. Special conditions associated with natural cavities make the traditional approaches of rock mechanics inapplicable. On one hand, the strength of rocks in cave walls is typically high and the natural break-down is not expected. On another hand, the rocks sometimes become unstable due to tectonic fault, natural fissures, weakened zones and old collapses. The walls are commonly coated with flowstones which may be prone to breakage. The initial re-configuration of strains following the formation of cavity is typically accomplished long ago, but ongoing tectonic movements may induce new changes into the strain field and may locally result in hazardous concentrations of strain. Assessment of stability and safety of caves, require special methods.

Our study in Ferenc-hegy cave addressed the following questions:

- Can the cracks be classified by basic rock mechanics aspects?
- What morphological features characterize each group, and what roles do they have in the risk of collapse?
- Are there any recent movements along the tectonic faults, which determine the structure of the passage system, which may be hazardous to the surface facilities?
- To what extent are the different types of cracks observed in the cave walls hazardous?
- Are the collapse zones observed in the cave active or quiescent?

Brief history of cave stability analysis

The scientific study of cave collapses was pioneered by *DAVIES* (1951). Assuming that limestone generally has a bedded structure, the roof of the cave can be approximated by a simply-supported or a cantilever beam. Consequently, the risk of collapse can be assessed by classical strength analysis. However, *WHITE* & *WHITE* (1969) pointed out that the natural rocks are commonly fractured; sometimes exceed the elastic deformation, and that over time their stability may be reduced. Studying collapse in the Mammoth cave (Kentucky, USA) they found that the process during which cantilever beam suffered a slow but significant deflection took almost a year. Since such large deformations can be explained only by micro-cracks in the rock and by taking into account its toughness, the laws of crack spreading must be taken into account when modelling the collapse mechanism. *THARP* (1995) found that this process is very slow: propagation of cracks through limestone beds may require 10^3 to 10^6 years. He also noted that because the direction of spread of the majority of cracks is parallel to bedding planes, they do not significantly affect the stability of rock cantilever beam. This, supported by a number of practical examples, suggests that the classic rock mechanical calculation methods can be applied with quite a good approximation to caves (*WHITE* and *WHITE* 1997).

The issue of stability of caves also played a role at the geological engineering assessment of karstified territories. *BALWIERZ* & *DZUŁINSKI* (1976) carried out model experiments to simulate cave roof collapses. *JIANYI* & *JIAN* (1987) numerically evaluated propagation of rock mass movement between an underground void and Earth's surface during cave-in process. *KUTEPOV* & *KOZSEVNYIKOVA* (1989) provided rock mechanics analysis of several case studies of surface collapses.

In Hungary mainly classic civil engineering, rock mechanics and mining security methods were used to assess and mitigate the cave collapse hazards. The effectiveness of this approach was not always clear. In some cases, primarily when the assessor was also a speleologist, the proposed mitigation measures were adjusted to the specific properties of the caves; in many other cases the hazards were overestimated. For example, for the show part of the Aggtelek-Baradla Cave was recommended not only securing its really hazardous sections, but also requested supporting or removing a number of hanging stones, natural arches and stone balconies. Our subsequent tests have shown that the latter were in fact perfectly stable (*SZUNYOGH*, 1993).

Application of cave stability examination methods that represent slightly modified versions of "normal" civil engineering, rock mechanics and mining security methods appear to be suitable for addressing specific safety issues in caves. The overall safety assessment of several kilometer-long cave systems, however, required a special method, which was developed by *SZUNYOGH* (2010a, 2010b). The method was successfully tested in the course of evaluation of 15 Hungarian caves, and was approved as a standard for cave stability examinations by the Hungarian Nature Conservation Authority (*HUNGARIAN STANDARDS* 2007, 2008).

Methods

In the course of this study we have collected the primary information, particularly: carefully examined the passages of Ferenc-hegy cave and surveyed and mapped all cracks, zones of collapses, and areas potentially important from the rock mechanics point of view. For various forms of rock destructions we determined the origin of these destructions and assessed whether the causative processes are quiescent or still active. On the basis of survey the main moments of bedrock fragmentation, the direction, and the impact area of loads imposed on the rock were determined.

In the course of our stability studies we examined about thousands of cracks. Their positions were documented by recording their strike, dip direction and angle, and width.

The collected information served as a basis for the diagnosis of the future potential destruction of the cave. Each passage segment was categorized in terms of its potential hazard; places where cave-in could propagate upwards and reach the Earth's surface were identified and, based on the type of the passage ending (blind solution wall or collapse), the hypothetical stability of the adjacent (not yet discovered) cave parts was assessed.

General characteristics of cracks in Ferenc-hegy cave

Cracks were classified into five groups with well-defined characteristics.

Primary cracks About 250 primary cracks were observed on the ceiling of Ferenc-hegy cave. They form a grid system corresponding to the overall maze layout of the cave (*Fig. 2*). (Although the stability tests were performed for the entire cave, and complete cave map showing results of these studies is available, only the western half of the cave map is presented in this paper.) Primary cracks are located within 5-10 metres from each other and can be followed through several passages. They are best recognized where the original solution surface of the cave is pristine and is not obscured by collapse or concealed by calcite coatings or clay deposits. Primary cracks are mostly located at the centreline of passages, suggesting that there is a close relationship between the position of these cracks and the structure of the cave: the dissolution of passages started along these cracks. This implies that primary cracks pre-date the hypogene dissolution process.

Primary cracks are used to be viewed as potentially significant hazard:

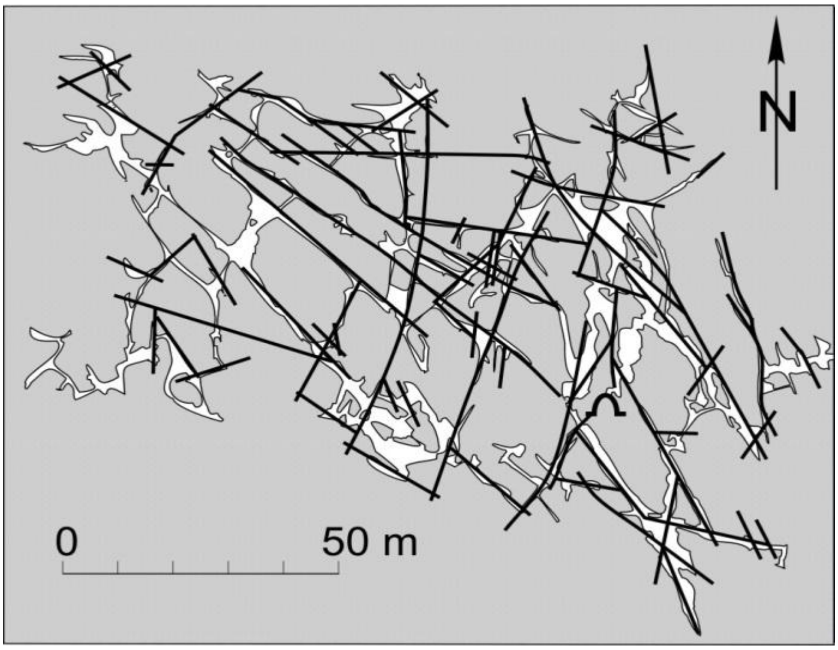

Fig. 2. Primary cracks documented in the western part of the Ferenc-hegy cave

civil engineers who designed buildings above the cave feared that blocks of bedrock separated by these cracks may move independently, slide along the cracks, and induce destruction of the buildings. Mitigation of this hazard is possible through employing special foundation techniques, but it would make the construction prohibitively expensive. In order to assess this hazard the cracks were thoroughly investigated.

Most of primary cracks have width of 1 to 5 mm, although sometimes, partly because of subsequent dissolution and partly because of rock movements, they widen to 2-3 cm (*Fig. 3*). Very often their surfaces are coated with scalenohedral calcite crystals (dogtooth spar), which in places fuse together and seal the crack completely. In most cases the presence of primary cracks does not distort the smooth rounded surface of passage ceiling (*Fig. 3a*). In some cases, however, the bedrock appears to be more refractory around the primary cracks, resulting in more complex solution surfaces (*Fig. 3b*). In rare cases the crack and the solution ceiling form a continuous, curved transition (*Fig. 3c*). Most of primary cracks are near-vertical. In some cases they dip at ca. 60° (*Fig. 3d*). Without exception, passages follow the planes of primary cracks.

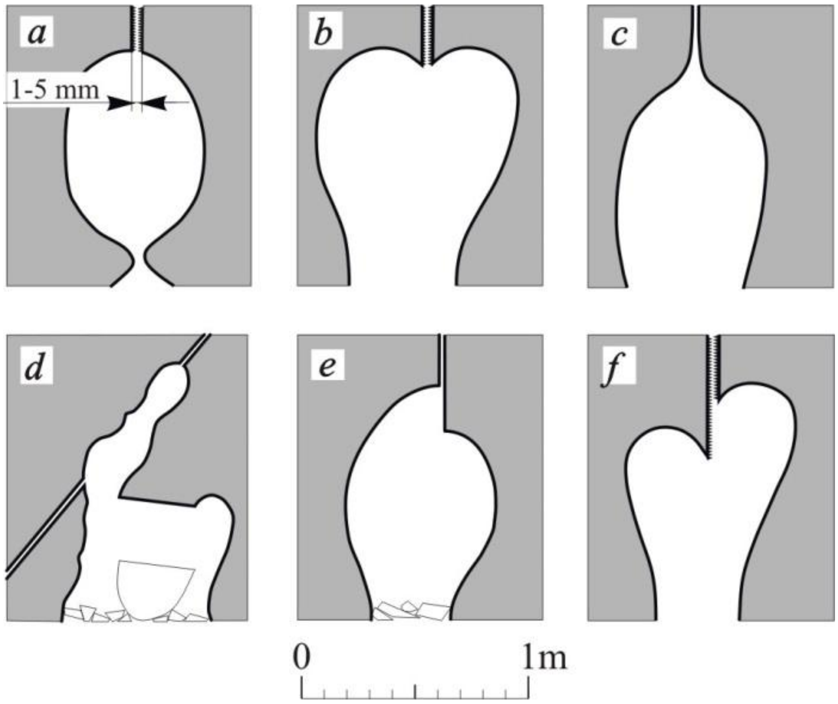

Fig. 3. Schematic cross-section showing typical relationships of primary cracks and cave solution morphology

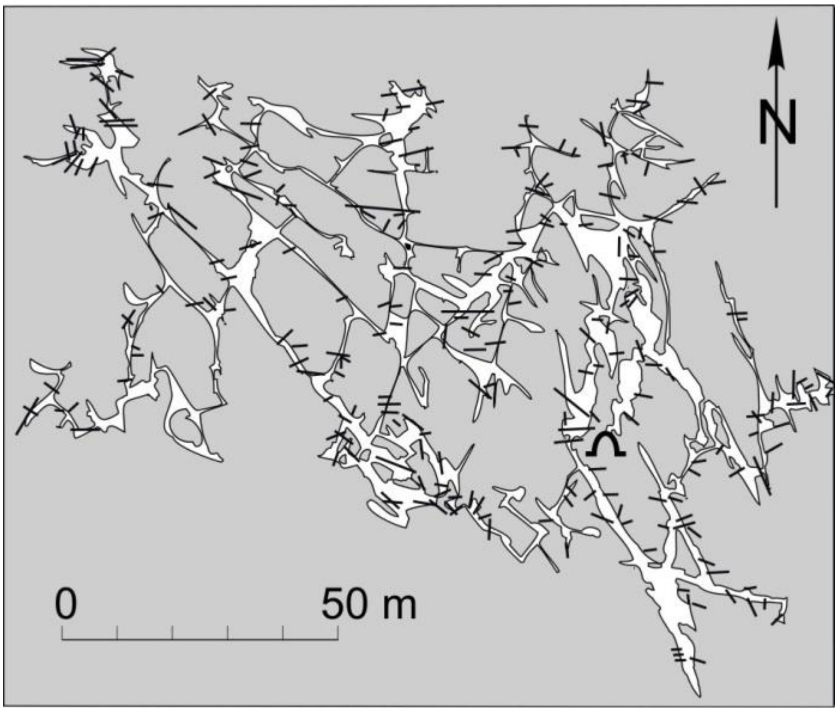

Fig. 4. Secondary cracks in the western part of the Ferenc-hegy cave

It is also commonly observed that the rounded ceiling of passages or smaller-scale spherical cavities is higher on one side of the crack (*Figs. 3e* and *f*). Because in a few meters away the height of the roof is the same on both sides of the crack, and no transverse crack can be observed, we conclude that the height difference is not a consequence of mechanical displacement of bedrock but it is solutional feature.

After a thorough investigation of rocks surrounding primary cracks we have found no indications bedrock displacements associated them post-dating the cave formation. (Several special cases will be discussed below). We conclude that probability of such movements in the future is vanishingly small; in other words, primary cracks controlling the pattern of cave passages do not pose any hazard.

Secondary cracks Rock blocks located between cave passages are penetrated by several large and apparently old cracks (*Fig. 4*). Since they extend from one passage to another (i.e. connect two primary cracks) they are considered secondary with respect to the primary cracks. As will be shown below, these cracks play a fundamental role in the destruction of caves and surface rock movements.

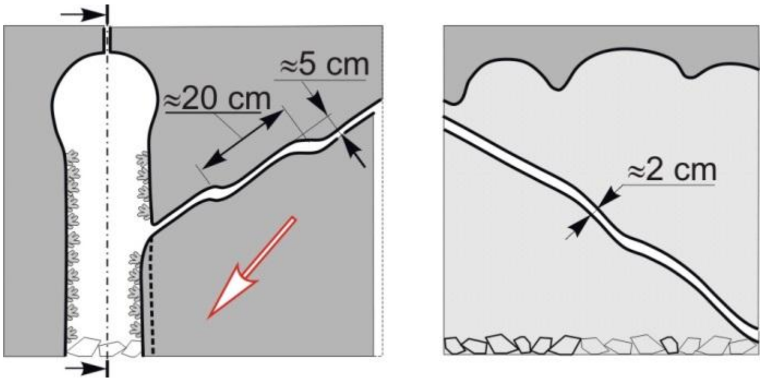

Fig. 5. Secondary cracks. (Large arrow indicates the direction of rock movement)

On average the secondary cracks are 2 cm-wide, but can be wider in case of rock movements, wider. Their surface is wavy (*Fig. 5*) with wavelength of 20-30 cm, and the amplitude of about 5 cm. The wave shapes are usually asymmetric, one side being steeper and the other gently sloping. The surface of these cracks does not look fresh; it is covered by dust and clay. There are no sharp fractures on their surface. Their intersections with the passage walls are rounded, indicating that the cave-forming process was still active after their formation. There is a wide diversity in their strike and dip although the latter is mostly 20 to 40°. While displacements do not typically occur along primary cracks (such mobilization was observed in only 6 cases) secondary cracks could generate displacements of 1-10 cm.

The origin of secondary cracks is not entirely clear. The asymmetric wavy surfaces are suggestive of shear failure (*JAKOBI*, 1976). An initially intact rock between two adjacent passages subjected to shearing load by tectonic forces (indicated as ***F*** in *Fig. 6a*) will develop an oblique fracture with slightly stepped surface, along which the adjacent blocks will move

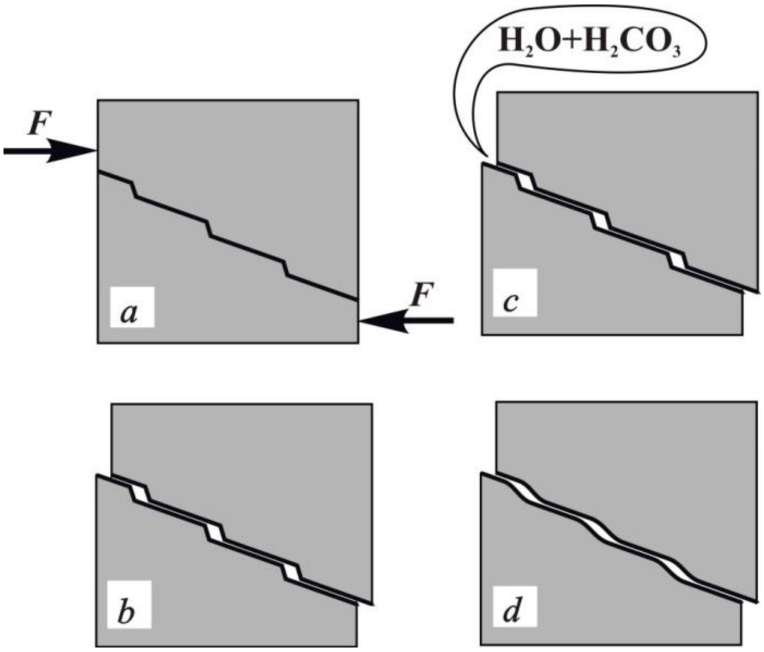

Fig. 6. Development of secondary cracks

(*Fig. 6b*). The morphology of secondary cracks indicates that they were accessed by aggressive water (*Fig. 6c*) which resulted in solutional smoothing of the stepped surfaces of cracks (*Fig. 6d*).

The asymmetric wavy surfaces of secondary cracks can be observed on almost every ceiling of halls with flat roof, since all of these halls are the results of collapses occurring along secondary cracks (Szakadék-Hall, Bocskai-Hall, Lapos-Hall, etc.). The role of secondary cracks in the cave damage process is that they weakened the self-supporting qualities of the rock and made it prone to cave-ins.

Tertiary cracks Movement of rock blocks confined by secondary cracks (1-10 cm) locally leads to high concentrations of mechanical stress, particularly where independently moving blocks are in contact. This results in cracking and fracturing of the limestone along the boundaries of these blocks. The resulting tertiary cracks are relatively young (in fact they are currently being generated), which is indicated by their fresh surfaces, clear grey colour, and absence of dust or clay on their surfaces. Their track is zigzagging and their penetration into the cave passage walls is sharp-edged, not corroded (*Fig. 7*). Almost two hundred such cracks were observed, although, the number would have been much greater, if all cracks of each collapse zone were counted. The surface of tertiary cracks consists of flat

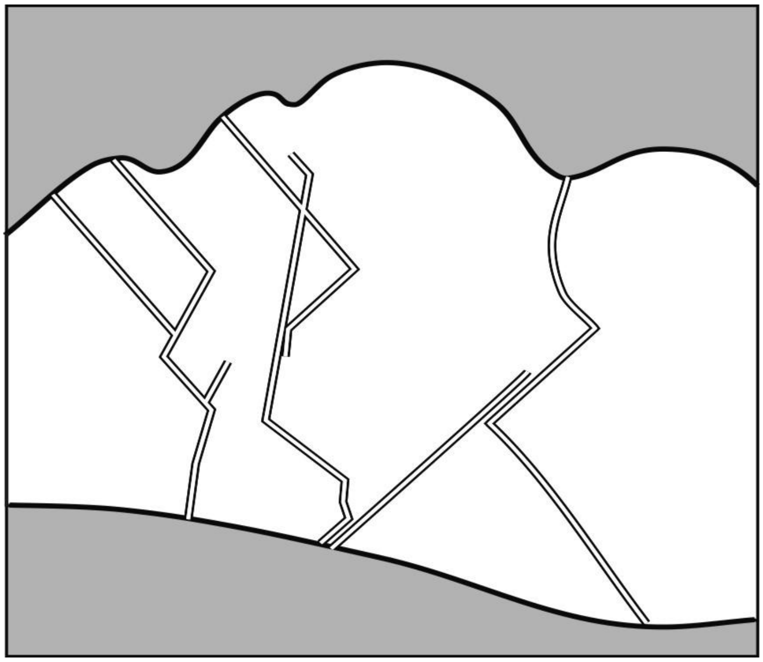

Fig. 7. Typical configuration of tertiary cracks on a passage wall

elements, that is, the waviness is not typical of them. Their width is generally 0.1-0.5 cm, and very rarely reaches 1 cm. Tertiary cracks frequently develop nearly parallel or at acute angle to the passage walls. This leads to cleaving out or collapse of the walls. In terms of cave stability, tertiary cracks are therefore a source of local collapse hazards.

Faults Faults are large-scale disruptions, exceeding the dimensions of the cave and commonly associated with significant differential displacement of bedrock. Identification of faults is important because in case of re-activation they can induce damaging shear stresses on surface facilities and buildings. The potential hazard of faults for cave itself, therefore, would not be great, but could be very significant for the surface structures.

Identification of faults in Ferenc-hegy cave is difficult. Rocks in which the cave is developed have rather uniform colour and texture; it is therefore difficult to recognize displacement of adjacent rock blocks which would indicate faulting. To identify faults we can only rely on their morphological characteristics, specifically: perfectly flat surfaces and very large dimensions along strike. Based on these criteria 26 cracks were qualified as faults.

Bedding planes with argillaceous intercalations Two bedding planes hosting 2 to 3 cm-thick clay layers, with east-west strike and dip of 35-40° to the south, spaced about 1 m from each other were observed in ca. 50 different sections of the cave. In many places these clay-bearing partings control the location of collapses (separations, cave-ins). Significance of these partings is that they reduce the tensile strength of the bedrock in vertical direction. If such clay-bearing partings occur in the rock above large cave halls, the self-supporting capacity of the ceiling may not be sufficient and the rock plates between the clay layers may collapse.

The main types and causes of destruction in Ferenc-hegy cave

The destruction processes were examined from two perspectives. On the one hand, we explored the reasons of destruction since the cave formation (because it characterizes the global processes in the hydrothermal karst area of Rózsadomb). On the other hand, we identified the currently active fracture zones. The purpose was twofold: such areas indicate potential hazard for surface buildings and cave passages affected by active fracture process can be dangerous for cavers and visitors.

The causes and processes of destruction of the bedrock vary depending on which type of cracks they are associated with.

Vertical displacements along primary fractures It was earlier assumed that the main passages of NW-SE direction in Ferenc-hegy cave are associated with tectonic crevices, along which movements occurred after cave formation, resulting in displacements of adjacent rock blocks. Our examination of ceilings of passages does not support this hypothesis. Apart from few sections of the cave (discussed below) the ceilings proved to be intact everywhere. It is obvious that primary cracks (with, initially, microscopic crevice width) were formed by tectonic fragmentation of the bedrock. Although their role in formation of the cave was most significant (aggressive thermal waters moved along them and created the cave) no rock movements occurred along these cracks after the formation of cave.

As an exception to this rule, four passage segments were found where the rock was also fractured along the primary cracks. In these segments the primary cracks can only be recognized on short segments. This is because due to the collapse the passage sides have had an abrasive effect on each other, removing the botryoidal calcite (popcorn) coating. On the floor of these passages rock fragments and chips with fresh fracture surfaces were observed. Where such active crevices intersect cross passages, a large number of tertiary destructions occur, causing immediate danger of collapse.

Cave-ins along secondary cracks This type of collapse causes the

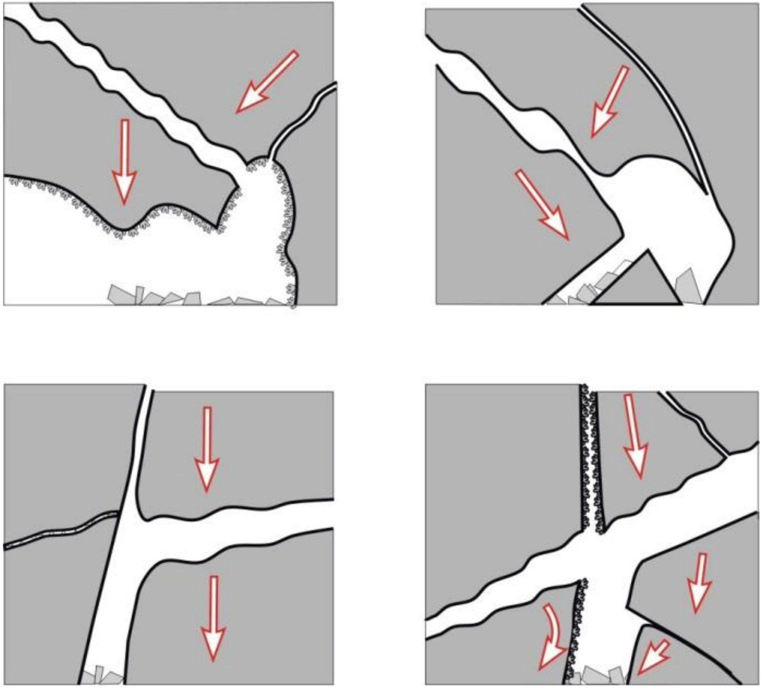

Fig. 8. Weber cavities in Ferenc-hagy cave. (Arrows indicate the directions of rock movement)

greatest destruction of the cave. Due to the highly cavernous character of rocks in the Rózsadomb, blocks bounded by the secondary cracks continuously subside. Thereby, the cracks on the tops of the subsided blocks dilate, making room for subsidence of higher blocks. The movements are probably initiated by collapses of unknown cave chambers located at deeper levels. This process is well known and commonly observed in mining; cavities that open during cave-ins are known as Weber cavities (*JAKOBI*, 1976). In Ferenc-hegy cave Weber cavities can be observed in several places (*Fig. 8*). These cave-ins are particularly hazardous in terms of the collapse risk (see below). The secondary cracks, which caused those cave-ins that are outside the cave routes (i.e. people do not have to move through the Weber cavities), do not pose a threat to the cave visitors, but they can cause surface subsidence.

Collapses caused by tertiary fractures The tertiary fractures result in the fragmentation of rocks in a relatively small area, so these are the main threat of collapse. While the size of blocks bounded by the secondary cracks is usually greater than the passage size, so they cannot fall down, the tertiary cracks in most cases create smaller rock blocks, which can move and slide into the passages, potentially causing accidents. The unstable rock conditions which lead to such collapses can be observed in several places in Ferenc-hegy cave (*Fig. 9*). The fallen rubble sometimes creates false floors dividing the passages into levels.

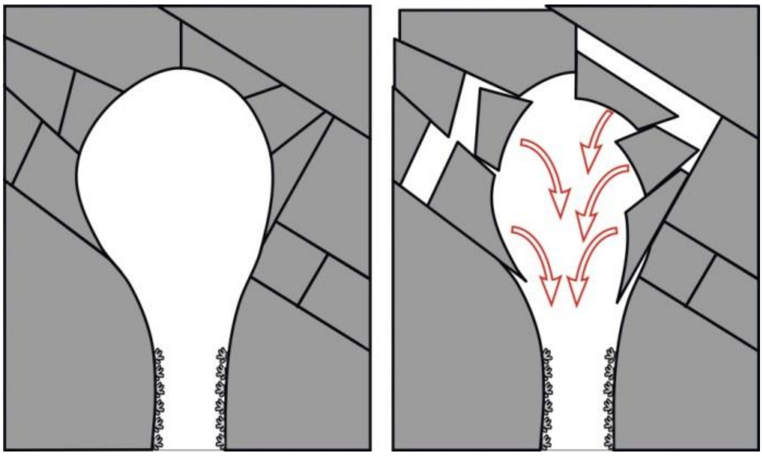

Fig. 9. Loosening of the bedrock caused by tertiary fractures and the resulting collapse

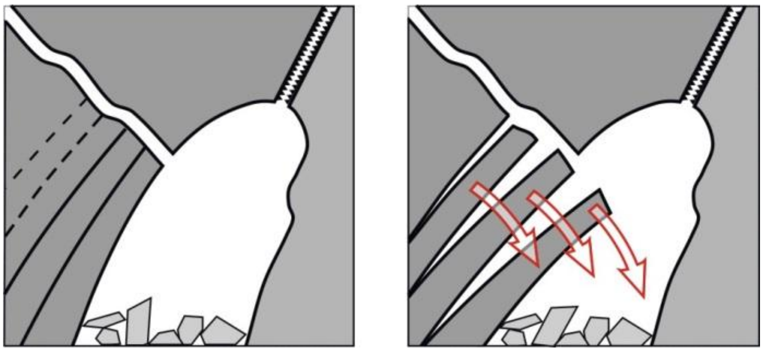

Fig. 10. Loosening of the rock along tertiary cracks (Arrows indicate the directions of rock movement)

Due to tertiary cracks the passages may get closed not only as a result of collapses, but also as a result of slow loosening: rock slabs gradually become detached from the passage walls (*Fig. 10*). Because of the general loosening the surface of passage walls becomes deformed. Since the calcite coatings are relatively rigid and are bound relatively weakly to the surface of the bedrock, they cannot withstand such deformations and finally spall off. The spalled tiles of botryoid calcite (popcorn) crusts, 0.1-0.5 m^2 in size and 5-10 cm-thick abundantly cover floors of passages (*Fig. 11*).

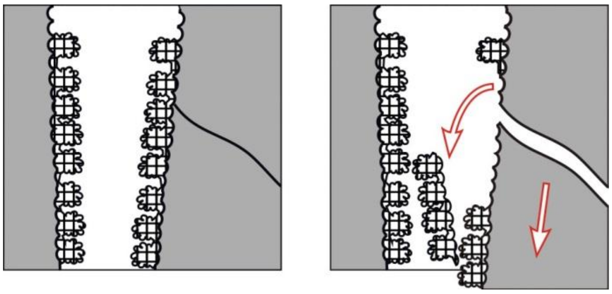

Fig. 11. Destruction of calcite coatings caused by rock loosening.
(Arrows indicate the directions of rock movement.)

The spatial distribution of different types of destruction in the cave is shown in *Fig. 12*.

Direction of rock displacements and stresses-causing displacements The secondary and tertiary cracks causing the critical destructions in Ferenc-hegy cave have a chaotic layout, which means that they do not have a preferred direction. However, secondary cracks, which basically determine the rock mechanical "image" of a cave, cause a vertical movement: the blocks of rock move downwards and the Weber cavities move up. Because of the general loosening of the bedrock, the movements also have a transverse (perpendicular to the walls of passages) component. Along the

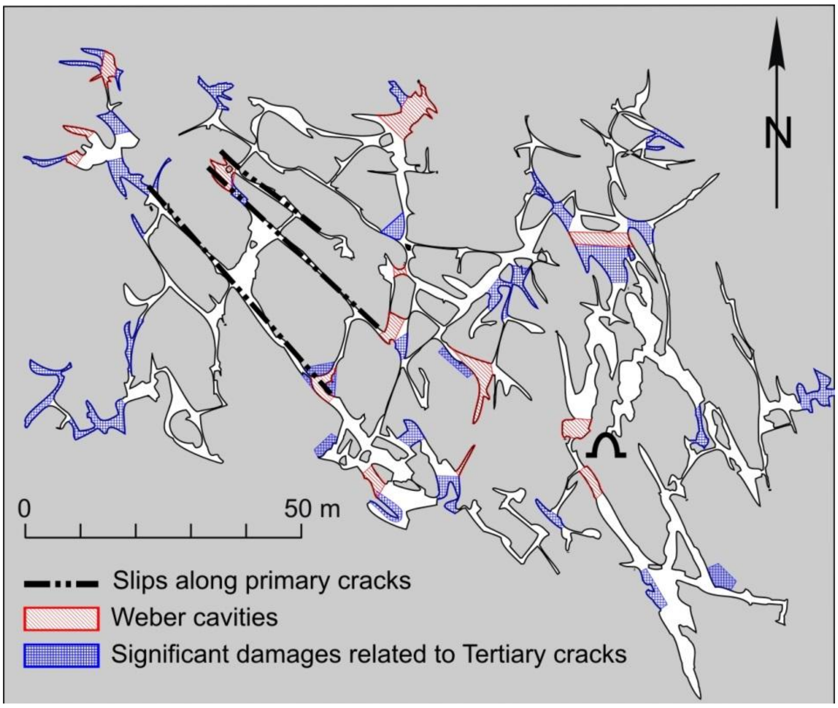

Fig. 12. Occurrences of different types of damage in western part of the Ferenc-hegy cave

primary cracks the direction of rock movements is also vertical, although such displacements have occurred only in a few passages, and can therefore be considered subordinate. It can be concluded that the destruction of Ferenc-hegy cave was caused, primarily, by the reduction of the bedrock strength, which is due to the high density of passages.

The range of rock displacements Displacements along primary cracks are limited to only a few passage segments. The secondary cracks practically extend throughout the entire area of the cave, so the movements associated with them encompass the entire cave area. Tertiary cracks do not have direct effect on the Earth's surface and only cause changes in the vicinity of certain cave passages. The active, on-going movements are limited to several small areas of the cave. The rest of the area is currently stable.

The active (hazardous) zones of Ferenc-hegy cave Whether or not the area of destruction is currently active can be inferred from observations. The surfaces of the passive cracks are dusty, coated with loam and commonly corroded. This indicates that their state did not change for a long time. In contrast, the surfaces of cracks in the active zones look fresh. Rock fragments with rough surfaces and sharp edges can be found lying on the

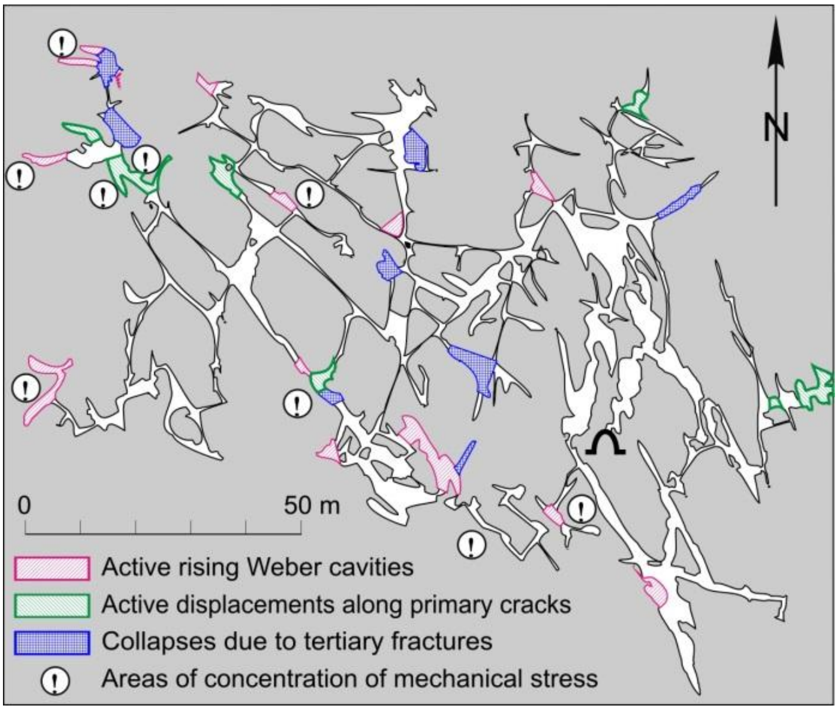

Fig. 13. Occurrence of active rock mechanics zones in Ferenc-hegy cave

floors of passages or precariously hanging in the cracks. The damages to botryoid coatings are fresh and free of dust and clay.

The active zones can be classed into four groups according to their origin: cave-ins in progress (active rising Weber cavities); active displacements along primary cracks; collapses due to tertiary fractures; and areas of concentration of mechanical stress (where the surface of the rock spalls off and splits up). Their distribution in the cave is shown in *Fig. 13*.

Surface manifestations of movement processes in Ferenc-hegy cave

The interaction of the cave and its environment was examined on the basis of three criteria:

Probable connections between cave and surface Small-diameter but high-reaching shafts plugged in their upper parts by sharp-edged rock debris were identified in several parts of the cave. These shafts pose the risk of cave-ins reaching up to the surface. Hearing outside noises in the cave can also indicate the dangerous nearness of surface. Finally the sites of conspicuous air draft may indicate as yet unknown passages leading to the surface, which may threaten the foundations of surface facilities.

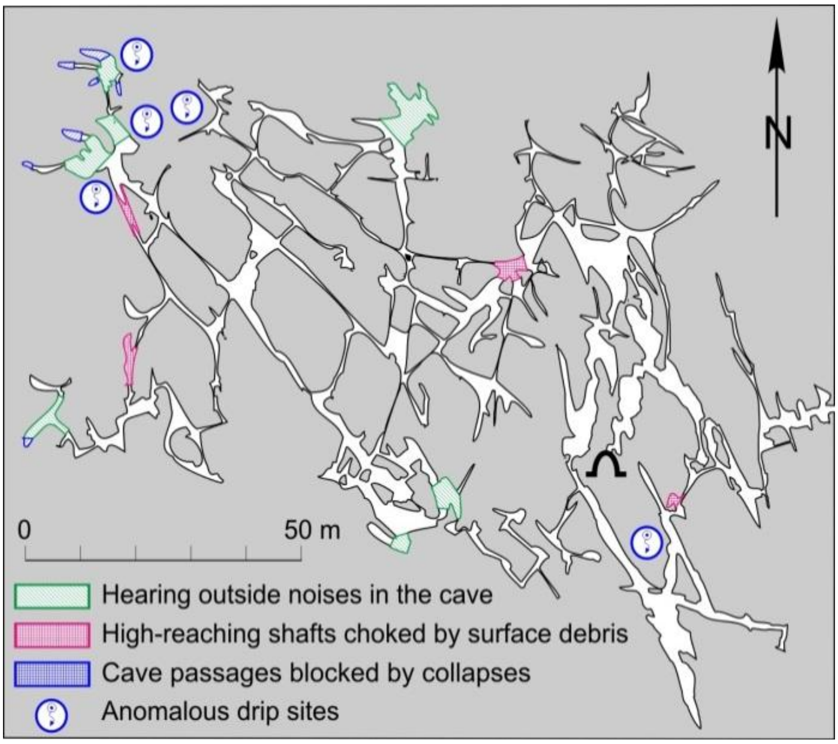

Fig. 14. Zones, showing high connection to the surface in Ferenc-hegy cave

Cave passages blocked by collapses The passages leading out of the main area occupied by the cave, impassable due to rock collapse suggest that the cavity network may be more extensive than it is presently known, and so, lead underneath the built-in areas (which may dangerous for stability of buildings). The collapsed corridors located north of the Pillér (Pillar) Hall are particularly interesting. In this area the passages are intersected by a vertical fracture line; the presence of large collapsed chambers beyond this line can be inferred from the large amounts of debris.

Anomalous drip sites During our observations the cave was completely dry. Several occurrences of dripping water were associated with the near-surface ground disruption and pipe damages. Near the place of water dripping south of Iszaptó (Sludge-lake) Hall, sewage smell was perceptible. In the Pillér Hall and to the north of it the abundant water inflow caused dissolutions and clay wash-out in the clastic rock. The water inflow resulted in the reduction of roof stability at both places.

Locations of these points connecting the cave to the surface are shown in *Fig. 14*.

Measures to mitigate the rock mechanics hazard in Ferenc-hegy cave

We have established that the rock-damage processes associated with secondary cracks are omnipresent in the entire cave. It would not be feasible to try and prevent movements associated with these fractures; neither it is necessary. Employing support in currently active areas (with some exceptions) also seems unnecessary, as they represent inherent parts of the long-lived and largely unstoppable cave destruction process; not a results of human activities. Of course, visitors to the cave, and particularly tour guides should be alerted to these active hazards, and the tour routes should be designed so that such areas are avoided.

Collapse hazard related to anthropogenic activities was identified only in the southwest trending passages of the cave, located under Törökvész Street. The collapse zone located south of Két-szikla (Two-Cliff) Hall is considered life threatening. This area must be excluded from any touristic activities. Another highly problematic area is the entrance to Pillér Hall and its exit to the Ágyúcsövek (gun-barrels). This area is frequented by visitors and cavers. Engineering measures to support and secure these local zones would be highly desirable, because inexperienced cave visitors can easily cause the collapse of the roof.

Conclusions

In the course of the stability examinations data of about a thousand cracks were recorded, which were subdivided into five distinct categories (primary, secondary and tertiary cracks, faults and argillaceous intercalations). It was found that cracks in different groups were formed in different ways, and there is a definite order in their formation process. This sequencing basically determines the extent of the danger of collapse generated by them.

We posit that the conclusions of this study can be applied to other caves, and the applied method is suitable for the safety assessment of caves in other cities as well.

On the basis of underground surveys and the conclusions drawn from them, the question if the increased infiltration due to surface constructions worsened the conditions of cave stability can be answered; proposals can be submitted for measures to increase the cave stability; further research directions can be designated under areas disturbed by constructions in order to detect rock movements and rock deteriorations; the history of the fracture system of Rózsadomb caves with thermal water sources can be hypothetically constructed, and also, further processes can be predicted.

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