

Stability Assessment of Caves and its Results

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***Abstract:** Commissioned by the Department of Speleology Ministry of the Environment and Regional Development author has carried out numerous investigations on cave stability and prepared cave security plans over the past twenty years. Since cave security measures differ in many respects from the usual reinforcement of subterranean cavities, a summary of the methods follows of investigations on cave stability elaborated and applied successfully by author on several occasions.*

***Keywords:** cave; stability; protection; collapse risk*

1 The Objective of Cave Security Projects and the Main Phases of Security Measures

Investigations on cave stability serve three distinct purposes. Firstly, areas with risks to life and accidents are identified and thus necessary security measures can be taken. Secondly, in the interest of environmental protection (cave conservation) they highlight sources of possible cave (or cave formations) decay or destruction and indicate ways of prevention [1]. Their third task is to lay down the foundations of legal protection for cave supervision authorities.

The demand for *protection of life and prevention of accidents* is evident without further explanation. *Protection of caves* has to be underlined as it may conflict with the primary aim since the elimination of the risk of cave collapse may often cause the annihilation of the object to be protected. Consequently, traditional security measures (common in civil engineering and mining) have to be reconsidered with special regard to the aspects of cave preservation [2].

The need for *Legal Protection* is motivated by the fact that caves (as also rock walls, chasms, etc.) form natural environments where unpredictable accidents such as land slides, rock fall, avalanches, etc. may occur [3]. Absolute security can be aimed at only in the case of human constructions. Under such circumstances the persons in charge of cave management have to take proper care and do

everything reasonable in order to prevent accidents [4]. Consequently, measures for legal protection should include provisions by which the person in charge of a cave may be able to prove that an accident was indeed an unforeseen natural disaster rather than the consequence of human negligence. Unfortunately, in Hungary legal aspects are not paid proper attention: No adequate double system of control has been worked out (one for the cave manager and another for an independent supervisory body) nor are daily records made to prove that due care has been taken. (In all other underground activities daily records are strictly prescribed by the Mining Authority.)

The first step in prevention begins with a survey of stability, searching for apparently dangerous areas, evidence for the existence (or absence) of risk and a forecast of probable collapses [5]. Safety measures found necessary by the survey of stability are then to be planned and carried out accordingly [6]. Finally, parallel with planning the efficiency of the safety measures is to be checked at fixed intervals.

2 Main Causes of Collapsing in Caves

Risk of caving in may be induced by some intervention resulting in an upset equilibrium (e.g. excavation). Certain blocks of rock may become unstable, lose support and topple.

The roof of a cavity may also lose its stability if the supporting arch is impaired.

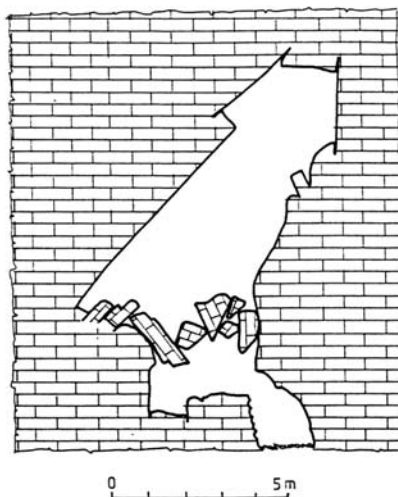


Figure 1

Risk of caving-in due to possibly impaired arch-function (*Béke-cave*)

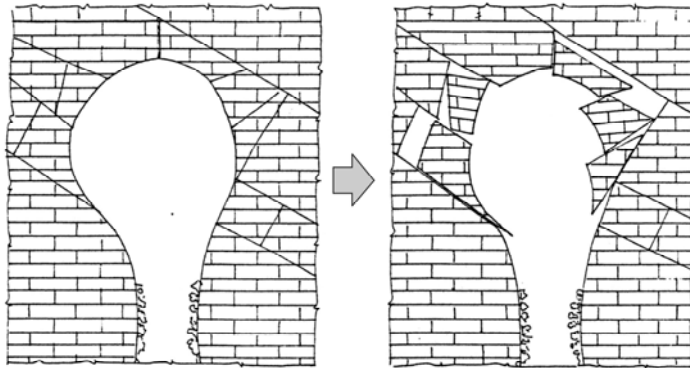


Figure 2

Risk of caving-in due to loosening of rock holding the cave (*Ferenc-hegyi cave*)

This may have several causes: Material falls out or is washed out from between vault units or the key stone securing the arch is displaced or the pillars supporting the arch may have subsided, e.g. as a consequence of tectonic movements (Fig. 1).

Underground passages may also cave in if the supporting rock loosens and crumbles [7]. An especially good example is the shrinking cavities of Ferenc-hegy cave (Fig. 2).

Finally, the most dangerous causes of collapses are present-day rock movements (Fig. 3). These may occur as tectonic slips along faults or macrofissures (as for instance in the Ferenc-hegy cave), induced by mechanical stress on the host rock (e.g. in the Anna cave of Lillafüred) or by seismic events (e.g. in the crystal-cave in the yard of the active quarry at Beremend, and in the Siklós-cave) [8].

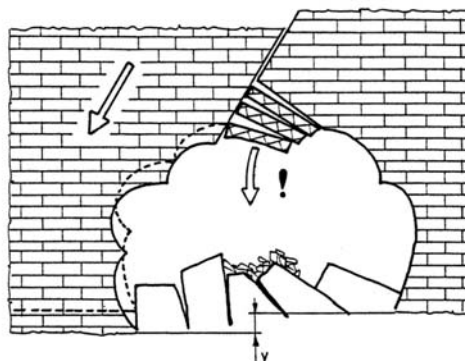


Figure 3

Risk of caving-in due to rock deterioration resulting from drag along fissures (*Siklós cave*).

⇓ Direction of present day rock movement; y— extent of rock movement

3 Identifying Areas with Possible Caving-in Risk

As a first step, a general picture of the joint pattern has to be formed [9]. A survey of all joints in the cave has to be made, noting their strike, angle of dip, width as well as other (geological, rock mechanical, speleological) features. Concurrently with the survey a map of joint angles with the cave axis (indicating strike and dip) has to be drawn. Thereby a so-called *joint element map is prepared*. As a result *the joint pattern is mapped regionally* (already above ground desk work). A general view of the mechanical conditions of the whole cave may then be obtained by a minute analysis of this map (Fig. 4).

With the help of the regional joint map the areas of a possible caving-in may be ascertained, and thereby sections of passages may be classified according to their degree of risk. The necessary security measures will have to be designed accordingly [10].

An analysis of the regional joint map may reveal a *hierarchical system*.

Primary, first-order joints fundamentally control cave destruction, cutting through the rock support of the cave and crossing quite a few passages. They often coincide with the main tectonic lines of the passages (as in the Ferenc-hegy cave) or are in conformity with the orientation of rock stress characteristic of the region (e.g. in the Anna cave).

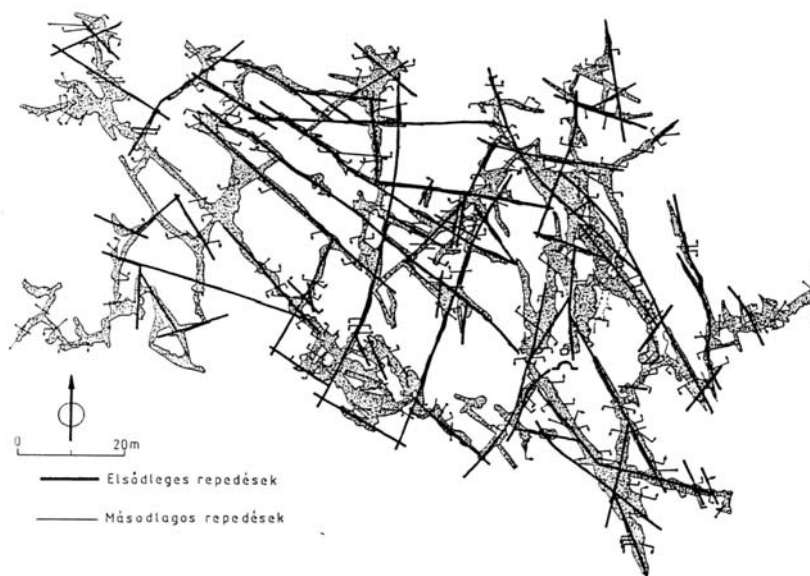


Figure 4
Regional map of joint pattern (Ferenc-hegy cave)

Secondary joints extend to the areas enclosed by primary joints, i.e. they affect only rock masses between pairs of primary joints and only cross a couple of passages.

Tertiary joints extend to even more restricted areas than the secondary ones, mostly observed in a single passage. They are usually related to secondary joints.

Finally, *isolated joints* or groups of joints on the regional map are explained by local stress concentrations and to be evaluated accordingly.

A survey of the hierarchical joint system is fundamental in order to evaluate the risk of collapse and in planning the necessary measures.

The *next major step* in revealing areas of caving-in risks is a thorough investigation of the cave surface. This work comprises a close inspection of sections of rock surface which appear to be dangerous, their representation in views and cross sections, the evaluation of the stability of rock blocks already surrounded by cracks as well as dating joints from the thickness of dust, clay or dripstone coating, or by the eventual presence of fresh rock splinters.

Sections of surfaces with tertiary joint deserve particular attention, as – in author's experience – they are sources of major risk.

In certain cases other criteria (e.g. regularly repeated rock fall, drizzle of small rock, appearance of capillary cracks, etc.) may also help in classifying risk.

Using appropriate symbols, all these factors are to be represented on *the regional risk map of the cave*. An analysis of all the information from the joint pattern map, the regional risk map and from the results of the detailed survey will decide if and where a cave-in may presently be expected or excluded.

4 Evidence for the Presence (or Absence) of Collapse Risk

First of all, it has to be determined whether the process leading to the deterioration of the cave is still active [11]. It is to be studied if the supporting rock is still overstrained (e.g. as a result of relatively rapid tectonic movements, slow sliding of the support, or of explosions in nearby mines). Relying upon various accompanying phenomena we can establish whether the slip along joints is still active. Recent damage to dripstone coating, accumulation of clean (not dusty, or clayey) rock fragments under the cracks, reappearance of clast falling from the fractured area and regularly cleaned away are all signs of activity along joints.

A study rock fragments wedged between the flanks of cracks highly assists the assessment of crack activity (and at the same time the identification of the direc-

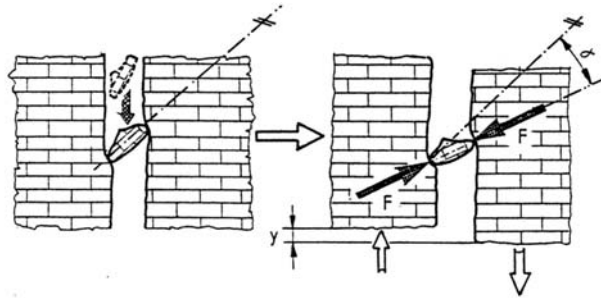


Figure 5

Explanation of wedging in of debris, \uparrow , \downarrow — Direction of present-day rock movement; y — extent of rock subsidence; α — forced turn of debris under stress; F — stress force resulting from wedge-in

tion of rock movement). If falling stones have got firmly wedged in cracks, it may be rightly assumed that the bodies of rock forming the flanks of the crack are sliding away on each other, since the rock fragments are "rolled" between them (Fig. 5).

Knowledge on the direction of rock movement along a joint will help to decide whether a piece of rock separated by a crack is likely to fall loose or not. No new break is to be expected if only dilatation occurs. However, if internal stress increases induced by rock movement, rock fall is to be expected.

Frequent sources of risk are *hanging stones*. Their stability may be judged by finding the forces which keep them in balance, (i.e. why they have not collapsed so far), and the possibility will also have to be considered whether these forces will reduce in the future (with regard to rock movement along cracks) to a dangerous extent (Fig. 6). The "weakest link" in the support (the critical point) has to be found and — if necessary — artificially reinforced.

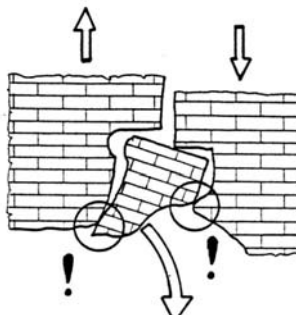


Figure 6

"Hanging Stones", Critical points of equilibrium (*Anna-cave, Lillafüred*). \uparrow , \downarrow — directions of present day rock movements

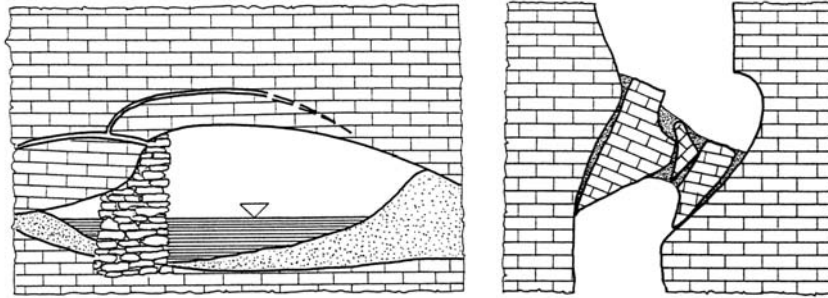


Figure 7

a) Cracked roof secured by built up stone wall (*Béke cave*). b) Project of yielding arch structure with load bearing plastic fill in the gaps of the arch (*Pál-völgyi cave*)

If the cracked rock mass is held stable like an arch or vault, the keystone is to be found and the risk of its dislocation assessed. If it is found probable, the keystone is to be secured. It is advisable to make a sketch (schematic representation of the statics) of the vault, indicating active force directions. Subsequent mechanical calculations serve to decide whether the arch is stable or unstable.

Movements still in progress may – if needed – be measured by instruments. For this purpose micrometers with continuous precision readings (self-recording instruments) to one thousands of a millimetre are recommended as it is the only way to find out what dislocation is caused by occasional slips or thrusts. In knowledge of the stability reserve (calculated by earlier statics schemes) the time of a collapse may be forecast and the frequency of the necessary inspections planned.

Having revealed the character and the mechanism of the expected collapse we may design the appropriate measures to ensure security.

5 Aspects for Planning Reinforcement Measures

Author's experience shows that special reinforcement projects should be designed for a particular cave and, if possible, "in situ" that is in the cave itself.

Knocking off loose stones should be avoided. Removing any block may often impair the overall equilibrium and alter the original face of the cave. This method of risk mitigation is only admissible if there is no other solution available. Instead, an attempt should be made to fix rocks liable to fall in their position.

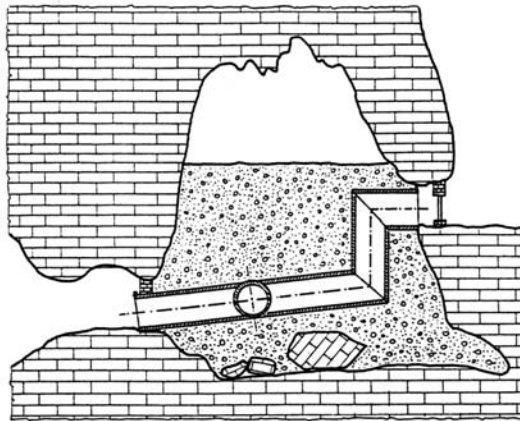


Figure 8

Plan of communications through a room which cannot be secured against caving in by means of a load bearing steel tube bedded in safety fill

Reinforcement work should correspond to the stress causing deterioration. If, for instance, a slight loosening of the cracked rock (i. e. a joint dilatation) is to be expected, a security device capable to yield is to be used. If movement along a crack is not likely in the future (but the rock is in a state of instability) equilibrium is to be restored by abutment or gluing (Fig. 7.a.) or the use of minor roof bolts.

The application of some mechanical device in order to prevent a dislocation of the keystone will prevent a vault from caving in. If present-day rock movements along primary or secondary cracks may cause the deterioration of a vault, a yielding arch is to be created by filling the gaps between the elements of the arch with some synthetic resin capable to bear load yet sufficiently elastic to yield to deformation. (Fig. 7b)

If rendering a chamber safe should involve expenses in excess of its speleological value, it is advisable to stow the cavity lest a cave-in should trigger harmful effects along other, valuable sections of the cave. Communication through such a stowing may be ensured by means of a load bearing steel tube bedded in the fill (Fig. 8).

Conclusions

Stability analysis of caves reveal, firstly, areas of risk, secondly, they indicate the necessary preventive measures and finally, in the event of accidents which cannot be foreseen, they provide for drafting legal protection to authorities exercising supervision over caves. Risk mitigation begins with a survey of stability, comprising the identification and mapping of areas of apparent risk, providing evidence of the existence of actual danger and a forecast of caving in to be

expected. Concurrently, special reinforcement projects should be designed for a particular cave in proportion to the stress causing deterioration. If rock movements are still in progress, yielding safety structures are to be used; however, if rock movements have already ceased, rigid security methods (gluing, abutment or bolting) may also be considered. A vault caving-in may be prevented by stabilising the key elements and/or by filling the gaps between the elements of the arch. If the roof cannot be reasonably secured the cavity has to be stowed and means of safe communication have to be built.

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