IMPLICATION OF SPELEOLOGICAL STUDIES FOR KARST SUBSIDENCE HAZARD ASSESSMENT

Edited by Alexander Klimchouk and David Lowe
Preface:

Viewing karst from the inside out

Hazards related to collapse and subsidence due to dissolution are the “classical” and probably the most acute practical problem in karst regions (see Milanovic’s review in this volume for typical examples in some civil construction practices). The global cost of the related subsidence damage, and of preventative and remedial measures in karst terrains, is tremendous. Karst subsidence and the hazards that they pose present one of the main subject areas of applied karstology, and of geological engineering in karst regions. A vast literature exists dedicated to karst subsidence phenomena and processes, and to the development of assessment and predictive approaches and remedial measures (see, for instance, the proceedings of the series of Multidisciplinary Conferences on Sinkholes and the Engineering and Environmental Impacts of Karst, held in the United States since 1984).

However, geological engineering practices in karst regions are still quite far from having well established and efficient approaches to the assessment and prediction of subsidence hazards on different scales. One of the reasons is the extreme variability of karst structures and settings, which do not lend themselves to unambiguous formalization and categorization. Another reason, and probably the main deficiency of the karst subsidence literature, is the somewhat schematic and speculative nature of the views about the structure and morphology of underground karstification, which lies at the core of the subsidence problem. When drawing inferences about the cavities that cause subsidence, and interpreting geophysical surveys and drilling data, geological engineers commonly operate with rather inadequate concepts of caves, taken from general geology textbooks that were published some decades ago. Moreover, the possibility of gaining deeper and more adequate understanding of breakdown processes from speleological observations remains virtually unexploited. This is where cave scientists can, and should, contribute to resolving applied problems in karst. However, their works to date have mainly been concerned with the relationship of breakdown to cave sediments and morphology.

Special attention to cave breakdown started with the works of Davies (1949, 1951), which were concerned mainly with the mechanics of breakdown. White and White addressed the issue in more detail in 1969 (and restated their findings in 2000), adding an outline of a number of geological processes that could activate breakdown in caves. During the last two decades some studies, particularly in Eastern Europe, focused on the types of cave breakdown that are potent enough to propagate through the overburden and generate surface deformation.

An important conclusion of White and White, that breakdowns in caves are not random events but are a result of specific geological processes triggered by specific geological forces, was not properly appreciated by geological engineers working in karst. Moreover, it is not commonly appreciated that caves themselves are not isolated spaces randomly distributed within soluble rocks but are systems forming regular patterns in response to certain hydrodynamic and structural conditions. Accessible cave systems give a unique opportunity to study many details of breakdown structures at the level of their origin, to study their distribution with respect to morphological elements of the cave itself and with respect to structural and lithological elements of the rocks. Moreover, thorough investigation of breakdown structures in caves allows inferences to be drawn about processes that activate and participate
in breakdown and about the stages of breakdown development and upward stoping. As rightly noted by Osborne in this volume, "...studies by specialists with experience in working inside karst and an understanding of how breakdown processes work within karst are essential, both to provide background information and for solving site-specific problems".

The purpose of this volume is to bring together papers presenting such experience within a single cover. Most of the papers place special emphasis on cave characteristics and studies of breakdown structures within them when addressing subsidence problems. To illustrate that this approach really promises to bring new insights to karst subsidence studies, we would refer to just one conclusion that emerges from several papers within this volume, and obviously contradicts common views: size of cavities has little relevance to subsidence hazard. Observations in caves (see the review in Waltham’s paper) and numerical modeling (see Kortnik’s paper) suggest that some very large caves can be quite stable, even at relatively shallow depth. In contrast, a breakdown structure triggered by failure of a cave roof at a depth of more than 400m can quickly propagate upwards to cause a catastrophic collapse at the surface, if its development is guided by a vertically-oriented tectonically weakened zone and involves hydrodynamic processes (see Andrejchuk’s paper on the Bereznikovsky Collapse). Further contrast is provided in papers by Klimchouk and Andrejchuk (Western Ukraine) and by Andrejchuk and Klimchouk (fore-Ural). They demonstrate that most breakdowns potent enough to propagate through the overburden relate not to the biggest main trunk passages, but to specific morphological features of cave systems. These are linked genetically to vertical zones of weakness and paths of cross-formational flow, and they expose or breach the host rock/overburden contact. Šušteršič describes several specific speleogenetic/structural situations favorable to the formation of collapse dolines. Here again the size of the underlying caves is of subsidiary importance. The size of caves appears to be more relevant in terms of receptacle capacity to accommodate breakdown material, rather then being the principal factor in triggering failure and initiating the breakdown structures that present potential geohazards.

The papers presented in this volume report many other interesting findings concerning actual breakdown mechanisms and the regularities of breakdown distribution. Some of the emerging ideas have clear potential for implementation within general, regional and local hazard assessment schemes. Two papers (by Klimchouk and by Waltham) attempt to categorize and classify karst subsidence settings. Although their schemes are based on quite different principles, both papers place special emphasis upon caves.

It is not claimed that this volume gives a comprehensive coverage of the full spectrum of experience that speleological studies could offer to help resolve the problems of collapse and subsidence in karst regions. However, we hope that it contains details of studies that are both interesting and valuable, and which will draw more attention both from cave scientists and from geological engineers towards the promising approach outlined in the title of this special issue.

Alexander Klimchouk and David Lowe
the Editors
LIST OF AUTHORS

Vjacheslav Andrejchuk:
Department of Earth Science, University of Silesia, ul. Bedzinska 60, 41-200 Sosnowiec, Poland.
E-mail: geo@wnoz.us.edu.pl

Alexander Klimchouk:
Institute of Geological Sciences, Natl. Academy of Sciences of Ukraine, P.O.Box 136, Kiev-30, 01030 Ukraine.
E-mail: klim@speleogenesis.info

Martin Knez:
Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia.
E-mail: knez@zrc-sazu.si

Jože Kortnik:
University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Geotechnology and Mining, Aškerčeva 12, SI-1000, Ljubljana, Slovenia
E-mail: joze.kortnik@ntfgam.uni-lj.si

David Lowe:
British Geological Survey, Kingsley Durham Centre, Keyworth Nottingham NG12 5GG, UK.
E-mail: djlo@bgs.ac.uk

Petar Milanovic:
Belgrade, Yugoslavia
E-mail: petar.mi@Eunet.yu

Mario Parise:
CNR-IRPI, c/o Istituto di Geologia Applicata e Geotecnica, Politecnico di Bari, Via Orabona 4, 70125 – Bari, Italy.
E-mail: cerimp06@area.ba.cnr.it

Marco Delle Rose:
CNR-IRPI, c/o Istituto di Geologia Applicata e Geotecnica, Politecnico di Bari, Via Orabona 4, 70125 – Bari, Italy.
E-mail: cerimp06@area.ba.cnr.it

Tadej Slabe:
Karst Research Institute ZRC SAZU, Titov trg 2, 6230 Postojna, Slovenia.
E-mail: Slabe@zrc-sazu.si

France Šusteršič:
University of Ljubljana, Dept. of Geology, A_{ker_eva} 12, SI-1000, Ljubljana, Slovenia.
E-mail: france.sustersic@ntfgeo.uni-lj.si

R.A.L. Osborne:
School of Development and Learning, Faculty of Education, A35, University of Sydney, N.S.W. 2006, Australia.
E-mail: a.osborne@edfac.usyd.edu.au

Tony Waltham:
Nottingham Trent University, Nottingham NG1 4BU, UK.
E-mail: tony.waltham@ntu.ac.uk
SUBSIDENCE HAZARDS IN DIFFERENT TYPES OF KARST: EVOLUTIONARY AND SPELEOGENETIC APPROACH

Alexander KLIMCHOUK

ABSTRACT
The typology of karst, based on distinguishing the successive stages of general hydrogeological evolution, between which major boundary conditions and the overall circulation pattern change considerably, gives a natural clue, properly to classify and tie together karst breakdown settings, speleogenetic styles and breakdown development mechanisms. Subsidence hazards vary substantially between the different karst types, so that classifying individual karst according to typology can provide an integrated general assessment. This provides a useful basis for selection and realization of region- and site-specific assessment schemes and management strategies.

Intrastratal karst types, subjacent karst in particular, are most potent in generating subsidence problems. Exposed karst types, especially open karst, are the least likely to pose subsidence hazard problems, despite them being recognized more obviously as karstic areas.

KEYWORDS: karst types, karst subsidence hazard assessment, karst breakdown mechanisms

1. Introduction

The term "karst subsidence" refers to the surface features resulting from more or less long acting destructive processes, hidden in the subsurface, which precede the appearance of surface landforms. When addressing subsidence origin, mechanisms and (eventually) prediction, it is common to refer, explicitly or implicitly, to this preceding hidden development. It is therefore convenient to use the more general concept of "karst breakdown" to denote the totality of processes and phenomena of gravitational and/or hydrodynamic destruction of the ceiling of a karst cavity and of the overlying sediments.

There can be many different approaches to karst subsidence hazard assessment, depending on scale (from regional to site-specific), natural settings and practical purposes. However, for general regional assessment it is desirable to develop a more unified integrated approach that would result in a basis for selection of region- or site-specific assessment schemes and management strategies. This paper is an attempt to outline such an approach, based on the evolutionary typology of karst. Though this approach seems to be quite promising for karst subsidence hazard assessment in both carbonates and sulphates, this paper places special emphasis upon
gypsum karst.

Karst typology, based on distinguishing successive stages of general hydrogeological evolution, between which major boundary conditions and the overall circulation pattern change considerably, seems to give a natural clue to classify and tie together karst subsidence settings, speleogenetic styles and breakdown development mechanisms.

2. The evolutionary typology of karst

An evolutionary approach to the typology of karst has been elaborated by Klimchouk (1996) and Klimchouk and Ford (2000). It incorporates some earlier ideas on differentiation between karst types suggested by Ivanov (1956), Quinlan (1978) and others. Types of karst are viewed as successive stages of hydrogeological evolution, between which the major boundary conditions, the overall circulation pattern and extrinsic factors and intrinsic mechanisms of karst development appear to change considerably (Fig.1). The different types of karst are marked by characteristic styles of karst system development, which result from certain regular combinations of:

a) structural prerequisites for groundwater flow and speleogenesis;
b) flow regimes;
c) recharge modes and recharge/discharge configurations;
d) groundwater chemistry;
e) degree of speleogenetic inheritance from earlier conditions.

The evolutionary sequence of karst types is also linked to the relationships with insoluble cover beds, the very important factor of the breakdown development. Consequently, it makes a convenient basis to view breakdown mechanisms and assess subsidence hazards on a regional scale.

Fig.1 outlines the entire sequence of karst settings (stages) that a given formation could experience during its history. In actuality no known individual karst displays all of the possible sequence, but many have experienced several of the stages. The karst may be destroyed completely, along with its host formation, within the same stage that its development commenced. This is more common for karst in sulphates than in carbonates and is the fate of most salt karsts. On the opposite extreme, carbonate karst can survive through several burial-exposure cycles, being repeatedly fossilised and rejuvenated.

Syngenetic karst in evaporites, if it develops at all, is embryonic, limited in extension and does not present appreciable engineering problems. More commonly, freshly deposited sediments are buried without suffering significant earlier dissolution. Karstification may be initiated at any of the stages of intrastratal development or delayed until stripping of the cover exposes the rock.

Intrastratal karst is considered to develop within rocks already buried by younger strata, where karstification is later than deposition of the cover rocks. Hydraulic and hydrochemical conditions are shown to be quite potent for the development of deep-
Sedimentological stages

**SYNGENETIC KARST**
(early diageneetic processes)

**DEHUDED KARST**
EXPOSED KARST

**MANTLED KARST**
MANTLED KARST

**BURIED KARST**
BURIED KARST

**ENTRANCED KARST**
ENTRANCED KARST

**OPEN KARST**
OPEN KARST

**DENUDED KARST**
DENUDED KARST

**DEEP-SEATED KARST**
DEEP-SEATED KARST

**SUBJACENT KARST**
SUBJACENT KARST

**BURIAL WITH NO APPRECIABLE SPELEOGENESIS**
BURIAL WITH NO APPRECIABLE SPELEOGENESIS

**LIMITED OR NO INHERITANCE**
LIMITED OR NO INHERITANCE

Key to stratigraphy on icons:
- cover is older than karst
- cover is contemporaneous with karst
- cover is younger than karst
- karstifiable unit
- formation underlying a karstifiable unit

Fig.1. - Evolutionary types of karst (from Klimchouk and Ford, 2000).

*Deep-seated karst* in many situations, particularly when soluble beds are sandwiched between insoluble but pervious formations and where vertical cross-formational hydraulic communication is favoured (Klimchouk, 1997a, 2000a). As a consequence of standard denudation and uplift on the continents, the deep-seated rocks are shifted with time into progressively shallower positions. At some stage *en route* to the surface, erosional incision into the cover rocks locally breaches the hydrogeological confinement and the aquifer is brought into direct hydraulic connection with the surface (*subjacent karst*). Further incision causes inversion of the circulation system, drastic changes in recharge–discharge configuration and establishment of vadose zone and water table conditions within the karstic strata (*entranced karst*). At this point some insoluble beds still commonly cap the unit over most of its area. Progressive denudation may eventually expose the rock entirely (*denuded karst*, which also falls into the category of *exposed karst* types).

The boundaries between the above types are transitional in reality but can be drawn in the following way. *Deep-seated karst* is not evident at the surface and the soluble
rock is not exposed. **Subjacent karst** occurs where the soluble rock is locally breached by erosion over a minor part of its thickness, and karst features may already be expressed at the surface as springs and/or collapse and subsidence features. **Entrenched karst** is where the entire thickness of the soluble rock is entrenched along valleys, but the insoluble cap remains over most of the interfluves. **Denuded karst** is where the caprocks are removed. Where there is continuous karst development from the deep-seated stage to the denuded stage the role of inheritance can be quite important.

The different intrastratal karst stages are marked by characteristic changes in the geological controls of speleogenesis, in the dynamics of the flow system, recharge mode and recharge/discharge configurations and in the groundwater chemistry. Confined circulation systems, inherent in deep-seated karst, remain dominant although progressively diminishing through the subjacent stage. Confined systems then give way to unconfined phreatic flow when passing to the entrenched and exposed stages, with consequent development of water-table and vadose zones. The mode of recharge to a given karst unit (which to a great extent determines the style of speleogenesis) tends to switch from predominantly diffuse and steady flow from the adjacent formations in deep-seated karst, to highly focused and variable flow from the surface in subjacent and entrenched karsts where caprocks are poorly permeable. However, the occurrence of diffusely permeable caprocks may still maintain diffuse recharge in these settings. Recharge becomes less focused and variable in denuded karst, but underground flow patterns are largely inherited from the earlier stages.

**Open and denuded karst** types (soluble rocks exposed at the surface) are characterized by similarly exposed geomorphic settings, but differ in their previous karstification history. Whereas denuded karst is former intrastratal karst, **open karst** represents the “pure line” of exposed development. That is, karst evolved solely when the soluble rock has been exposed to the surface, with either limited or no inheritance.

**Mantled karst** is karst covered by significant thicknesses of unconsolidated sediments, which accumulate as the karst develops. Most common are soils formed from the insoluble residuum of impure limestones and dolostones (locally-derived or “autochthonous” deposits). Mantled karst should be distinguished from **buried karst**, which is a complete infilling and burial by later materials such as transgressive marine sediments, reducing or (usually) terminating the karstification. Buried karst should not be confused with intrastratal karst, where the karstic rocks were buried before any karstification occurred. “Buried karst” has the simple direct meaning that a karst was exposed and then buried. When karst is buried, it is generally fossilized, and so represents the most unambiguous case of true palaeokarst.

### 3. Genetic types of caves in gypsum, their relevance to the karst types and potency to generate karst breakdowns

Cavities play the most fundamental role in karst breakdown processes as they give rise to the development of additional (absent before the onset of speleogenesis) strain in ceiling and overburden materials, thus stimulating ceiling destruction when certain
critical values are exceeded. In other words, speleogenesis and the presence of dissolutional cavities are the ultimate cause of karst subsidence. Therefore, knowledge of the distribution and characteristics of cavities in a given karst is one of the most important components of subsidence hazard assessment.

In most cases karst breakdown processes develop where the soluble rocks are already karstified to some degree. The importance of contemporary speleogenesis (i.e. in a time-scale that corresponds to the assessment goals) on karst breakdown potential is negligibly low in carbonate karst but in the case of evaporites it should be taken into account because of the much higher dissolution rates of sulphates and haloids in many natural or anthropogenically modified situations. In any case, the existence of cavities, whether inherited from past settings or formed under contemporary settings, is the most important consideration for the assessment of karst breakdown potential.

Caves of different kinds can have different potential to generate breakdowns. It depends not only on their size and the depth of occurrence, but also on their origin, which determines the characteristics of cave patterns and presence of morphogenetic components related to transverse structural or lithological discontinuities in the overburden. Such components, for instance, are shown to be the main breakdown-generating features in the gypsum karst of the Western Ukraine (see Klimchouk and Andrejchuk, this volume); a rule that probably holds true for any intrastratal karst. Moreover, knowledge of cave origin allows inferences to be drawn about the relation of cave patterns to specific past or modern geological or geomorphological features. Hence it gives an important clue to subsidence prediction. An example is the characteristic relationship between artesian transverse caves and valleys (palaeo-valleys) partially incised into the confining overburden.

Although comprehensive judgement on cave genesis can be based only on special speleogenetic studies, some preliminary ideas on what kind of caves can be expected in a given karst can be inferred from identifying its type. There is a distinct relationship between genetic types of gypsum caves, speleogenetic settings and the types of karst (Klimchouk, 2000b; see Table). Complications arise from the fact that the sub-types of intrastratal karst, as well as denuded karst (former intrastratal karst) may inherit cave patterns formed during the preceding stages. This makes speleogenetic studies indicative of a karst type and of the evolution of a given karst.

During the deep-seated stage caves are likely to form where gypsum is sandwiched between aquifers or at least underlain by an aquifer. In the former case, depending on the structural pre-requisites present (uniform fissuring or discrete prominent discontinuities), either maze caves (type 1 in the Table) or large discrete voids (type 2) can be formed by transverse flow across the gypsum bed. In the latter case, and also where a thick gypsum sequence, sandwiched between aquifers, is of negligible vertical permeability, large discrete voids can form along the base of the gypsum due to natural convection and removal of dissolved load via the underlying aquifer. Caves of both types can be inherited, though become relict, in the subsequent stages (subjacent, entrenched and denuded), with superimposed development of contemporary caves of types 3 and 4.
Table. Genetic classification of caves in gypsum, with relation to karst types and speleogenetic settings

<table>
<thead>
<tr>
<th>TYPE OF KARST</th>
<th>SPELEOGENETIC SETTINGS</th>
<th>CHARACTERISTICS OF SOLUTION CAVES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro-geological</td>
<td>Initial</td>
<td></td>
</tr>
<tr>
<td>conditions</td>
<td>permeability</td>
<td></td>
</tr>
<tr>
<td>Principal</td>
<td>(before speleogenesis)</td>
<td></td>
</tr>
<tr>
<td>Complementary</td>
<td>Flow pattern through</td>
<td></td>
</tr>
<tr>
<td></td>
<td>gypsum and type of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>recharge</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrastratal</td>
<td>Confined (artesian)</td>
<td>1. Rectilinear 2-D or 3-D (multi-storey) mazes</td>
</tr>
<tr>
<td>deep-seated</td>
<td>Fairly homogeneous</td>
<td></td>
</tr>
<tr>
<td></td>
<td>generally low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Very heterogeneous</td>
<td></td>
</tr>
<tr>
<td></td>
<td>generally low to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>negligible, locally high</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ascending transverse</td>
<td></td>
</tr>
<tr>
<td></td>
<td>flow across gypsum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>unit sandwiched between</td>
<td></td>
</tr>
<tr>
<td></td>
<td>aquiferous beds, with</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible lateral</td>
<td></td>
</tr>
<tr>
<td></td>
<td>component; dispersed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>basal recharge</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ascending transverse</td>
<td></td>
</tr>
<tr>
<td></td>
<td>flow; localized basal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>recharge</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lateral flow in the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>underlying aquifer,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>natural convection &quot;cells&quot;</td>
<td>in gypsum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrastratal</td>
<td>confined, phreatic,</td>
<td>2. Discrete voids, commonly large and isometric</td>
</tr>
<tr>
<td>subjacent</td>
<td>water table, vadose</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heterogeneous: low to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ascending flow with</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible considerable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lateral component;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>localized or dispersed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>basal recharge</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Descending flow with</td>
<td></td>
</tr>
<tr>
<td></td>
<td>considerable lateral</td>
<td></td>
</tr>
<tr>
<td></td>
<td>component; localized</td>
<td></td>
</tr>
<tr>
<td></td>
<td>recharge from coverbeds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and via superficial</td>
<td></td>
</tr>
<tr>
<td></td>
<td>sink points;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible backflooding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>from nearby rivers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Continuing development</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of types 1 and 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrastratal</td>
<td>phreatic, water table,</td>
<td>3. &quot;Through caves&quot;: linear or crudely dendritic in plan, horizontal,</td>
</tr>
<tr>
<td>entrenched</td>
<td>vadose</td>
<td>included or step-like in profile</td>
</tr>
<tr>
<td></td>
<td>Heterogeneous: low to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Descending flow with</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible considerable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lateral component;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>localized recharge from</td>
<td></td>
</tr>
<tr>
<td></td>
<td>coverbeds and via</td>
<td></td>
</tr>
<tr>
<td></td>
<td>superficial sink points;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible backflooding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>from nearby rivers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Continuing or newly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>started development of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>type 3 caves</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exposed</td>
<td>phreatic, water table</td>
<td>4. Vertical pipes developing downwards from the top of the gypsum</td>
</tr>
<tr>
<td>denuded</td>
<td>vadose</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heterogeneous: generally</td>
<td></td>
</tr>
<tr>
<td></td>
<td>high</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Descending flow with</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible considerable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lateral component;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>localized recharge via</td>
<td></td>
</tr>
<tr>
<td></td>
<td>superficial sink points;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible backflooding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>from nearby rivers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Continuing or newly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>started development of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>type 3 caves</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exposed</td>
<td>phreatic, water table</td>
<td>Vertical pits at sink points</td>
</tr>
<tr>
<td>open</td>
<td>vadose</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heterogeneous: generally</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Descending flow with</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible considerable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lateral component;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>localized recharge via</td>
<td></td>
</tr>
<tr>
<td></td>
<td>superficial sink points;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible backflooding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>from nearby rivers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Development of type 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>caves</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exposed</td>
<td>phreatic, water table</td>
<td>Vertical pits at sink points</td>
</tr>
<tr>
<td>open</td>
<td>vadose</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heterogeneous: generally</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Descending flow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>with possible</td>
<td></td>
</tr>
<tr>
<td></td>
<td>considerable lateral</td>
<td></td>
</tr>
<tr>
<td></td>
<td>component; localized</td>
<td></td>
</tr>
<tr>
<td></td>
<td>recharge via superficial</td>
<td></td>
</tr>
<tr>
<td></td>
<td>sink points;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>possible backflooding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>from nearby rivers</td>
<td></td>
</tr>
</tbody>
</table>
The most unambiguous case in terms of karst type/cave type relationship, is where a sulphate sequence rests on, or is sandwiched between, impervious formations. This situation excludes the possibility of the formation of artesian caves, both maze and discrete void types. Karstification is unlikely to evolve in the deep-seated stage and speleogenesis during any subsequent stage is limited to types 3 (linear or crudely dendritic “through caves”) and 4 (vertical pipes or pits). If karstification commences only during the exposed stage, it results in open karst, where only contemporary caves form in accordance with the present settings.

The potency of caves to generate breakdowns varies between types. In maze cave systems of type 1 the bulk of cave passages present little or no potential for breakdown until shifted to a shallow subsurface position. However, breakdowns can readily initiate from outlet cupolas/dome pits, which represent places where water discharged from a cave system to the upper aquifer during the period of transverse artesian speleogenesis (Klimchouk and Andrejchuk, this volume). Caves of type 2 associated with prominent structural discontinuities can generate breakdown structures active enough to propagate through large thicknesses of overburden (Klimchouk and Andrejchuk, 1996). Voids similar in morphology and size but formed solely by “upward” dissolution due to natural convection (not related to cross-formation discontinuities and flow) can remain stable until moved to the shallow subsurface. Linear or crudely dendritic caves of type 3, genetically associated with unconfined settings, present little potential for breakdown. Vertical “descending” dissolution pipes (type 4) commonly initiate breakdown in the overburden in intrastratal entrenched karsts but genetically similar vertical pits formed in exposed karst settings do not generate any breakdown hazard.

In unconfined gypsum karst, dissolution at the water table is not considered as a separate speleogenetic situation, but it can give rise to considerable modification of caves of any genetic type. Conditions where the water table is positioned within the karstified gypsum can establish in all the karst types except deep-seated karst. In gypsum aquifers that receive constant or periodic aggressive recharge low in TDS, chemical stratification develops due to the density difference between the “fresh” water still low in sulphates and the bulk water enriched in sulphates (Klimchouk, 1997b). Consequently, the water in the uppermost layer (5 to 15 cm) of cave lakes (“aquifer windows”) generates much higher dissolution rates than water in deeper parts (Klimchouk and Aksem, 2002). This has a pronounced morphological effect, causing the development of horizontal notching and inwardly inclined wall facets in caves of any type that appear to be within the water table fluctuation range. Such lateral enlargement of caves may increase the cross-sectional spans of passages and chambers three to four times, hence drastically decreasing the ceiling stability and increasing the potential for breakdown and subsidence to occur. The most pronounced development at the water table occurs where recharge comes from an underlying aquifer, or from non-karstic surfaces, or as backflooding from a nearby river, i.e. without having much contact with gypsum. Hence, it is most common within subjacent and entrenched karsts. In exposed karsts the above effect is less important.
4. Settings of karst breakdown and their relevance to karst types

Karst breakdown development and subsidence occurrence depend on many conditions and factors, the totality of which can be viewed as a setting for the karst breakdown process in a given karst. For the purposes of general subsidence hazard assessment it is necessary to distinguish typical settings within a tangible classification scheme. In Fig.2 such an attempt is presented, based on the most common combinations of the three categories of conditions and factors that strongly influence the karst breakdown process, namely:

1) Presence and structure of the overburden;
2) Lithological (geotechnical) properties of individual units in the cover;
3) Hydrogeologic conditions (especially piezometric levels and hydraulic gradients).

These categories correlate to the criteria used to distinguish the evolutionary types of karst. It can be seen from Fig.2 that settings evolve from left to right according to hydrogeological conditions, from confined to unconfined, and from below upward, according to the cover structure, from deep-seated karst with multiple-layer cover, to exposed karst with no cover. Therefore, the evolutionary typology of karst, suggested above as the basis for integrated regional subsidence hazard assessment, contains a useful indication of karst breakdown settings.

The suggested classification also gives room for consideration of breakdown processes and mechanisms.

In the open karst setting (0-U1) and in cases of single-layer cover represented by solid rocks or soft but impervious sediments (I-C1 and I-U1), mainly gravitational processes take part in karst breakdown development.

In settings where loose pervious sediments occur in the cover, a variety of gravitational and hydrodynamic processes can take part in breakdown development, and this overall process commonly consists of a number of stages. The composition of the component processes and stages of breakdown development (i.e. the breakdown mechanism) are determined by the layered structure of the overburden, the permeability and coherence of particular beds, and by hydrogeological conditions. As the proposed classification of breakdown settings includes all these factors, the mechanisms, when adequately revealed, formalised and classified, can be put into a relationship with the specified settings.

In general, beds of permeable loose sediments (i.e. sands) provide a setting wherein processes of hydrodynamic destruction (such as suffosion, liquefaction, erosion, etc.) predominate, whereas low-permeability or fully-drained beds of more coherent sediments or solid rocks promote arching, which supports void stoping and serves as an arena for mainly gravitational destruction. During the course of breakdown propagation through the stratified overburden, some non-equilibrium stages can be followed by quasi-equilibrium stages. The ability of some beds within the overburden to bridge a void is the main pre-requisite for the collapse style of eventual surface deformation (as against gradual subsidence).
<table>
<thead>
<tr>
<th>COVER STRUCTURE</th>
<th>HYdrogeological CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C - confined</td>
</tr>
<tr>
<td>0 - no cover</td>
<td></td>
</tr>
<tr>
<td>I - single layer</td>
<td>I-C1</td>
</tr>
<tr>
<td>IIa - multiple layers: pervious layer at the base</td>
<td>IIa-C1</td>
</tr>
<tr>
<td>IIb - multiple layers: impervious layer at the base</td>
<td>IIb-C1</td>
</tr>
</tbody>
</table>

Legend:
- loose pervious sediments
- karstified soluble rocks
- piezometric levels and heads
- cross-formational flow

Fig. 2. - Classification of karst breakdown settings
5. Subsidence hazard in different types of gypsum karst: regional examples

As shown above, the evolutionary types of karst differ quite naturally in styles of speleogenesis, karst breakdown settings and characteristic breakdown mechanisms. Thus it is natural that subsidence hazards differ substantially between karst types, and that it can be assessed in general by classifying a given individual karst according this typology. A brief appraisal of the each conceptual karst type is given below, with particular regard to their potency to pose subsidence hazards. Representative regional examples are referred to from the extensive review of gypsum karst of the world presented in Klimchouk, Lowe, Cooper and Sauro (1996) and references therein.

If developed at all, syngenetic karsts in evaporites are incipient, limited in extent (as for instance in some modern evaporate basins in the Qinghai-Xizang Plateau, China and in the Caspian region, Turkmenistan) and they do not present any engineering problems. More commonly, freshly deposited sediments are buried without suffering significant earlier dissolution. Where buried, karstification may commence during any of the stages of intrastratal development, or be delayed until stripping of the cover exposes the rock.

Exposed karst areas in evaporitic rocks are commonly rather limited in extent, and despite the fact that they are more obviously recognised as “karst” than is intrastratal karst, they too present only limited or no engineering problems. In open karst, solution dolines that form gradually are overwhelmingly predominant, whereas collapse and subsidence features are rare. This is for two reasons:

Gravitational breakdown mechanism (cave ceiling collapse) dominate in open karst. In general, this mechanism is of much less importance in generating collapse/subsidence features than those involving hydrodynamic destruction and void stoping through the overburden.

Contemporary cave development in open settings favours the formation of linear or crudely dendritic caves of rather small cross-section, which rarely give rise to massive ceiling destruction.

However, collapse and subsidence features may occur more readily in denuded karst, mainly reflecting the large degree of inheritance in underground karstification (much higher overall cave porosity) and the presence of patches of loose material at the top of karstic rocks.

Examples of open karst include Zorbas in South Spain, the Erbo basin in East Spain, the Central Apennines and Sicily in Italy, and some areas in the North Caucasus in Russia. The Gypsum Plain in West Texas and New Mexico, USA, probably falls into the denuded karst category.

Deep-seated intrastratal karst is now considered to be much more widespread than traditionally supposed, although it is, by definition, not evident at the surface. This is either due to the considerable thickness of overburden (which prevents breakdown structures reaching the surface) or because breakdowns have not yet been triggered. However, human impacts may change conditions rapidly (for instance, by
changing hydrodynamic gradients, flow rates and the circulation pattern by ground-
water abstraction) so that breakdown processes are triggered and intensified to cause
subsidence at the surface. This makes deep-seated karst settings particularly haz-
ardous, because related areas previously not recognised as karst may present engi-
neering problems that are not expected. The above situation signifies an induced
transition from deep-seated to subjacent karst type. Remarkable examples are asso-
ciated with the open-pit mining of sulphur and clays in the deep-seated karst belt of
the Western Ukraine.

Depending on structural pre-requisites, caves forming in deep-seated gypsum
karst are either artesian maze systems or large discrete voids. Modern (presently at
the artesian stage) maze caves are identified by indirect means in the deep-seated
karst belt in the Western Ukraine; relict cave systems are known in (the entrenched
carst of) the Western Ukraine, Ural (Russia), the Madrid basin (Spain) and the
Paris basin (France). The most instructive examples of the large discrete cavities are caves
of the “schlotten” type in the Zechstein gypsum of the South Harz, Germany
(Kempe, 1996). In this region, more than 100 cavities of this type have been inter-
sected by mines, at depths of up to 400m. They can be very big, up to 40 to 60m in
cross-section and height.

Subjacent karst is by far the most relevant to the subsidence problem, because it
represents a transitional stage during which progressive erosional entrenchment dras-
tically changes the hydrodynamics, from confined through semi-confined to vadose
and water-table conditions. These changes are usually accompanied by reduction of
the overburden thickness caused by denudation, thus permitting propagation of
breakdown features from a soluble unit to the surface. Most karst areas, whether car-
bonate or evaporite, which demonstrate distinct engineering problems due to subsi-
dence belong to this type. Changes occurring during the subjacent karst stage include
well-recognized breakdown-triggering effects (Newton, 1984; White and White,
2000). These effects include decrease of hydraulic heads and removal of buoyant
support, increase of hydraulic gradients and flow velocities, base level back-flood-
ing, etc. Most of these accelerate dissolitional enlargement of cavities due to the
increase of flow rates, action of back-flooding and vadose water and dissolution at
the water table. They also enhance piping and erosion, migration of unconsolidated
deposits into karst cavities and washing-out of cavities, thus further enhancing the
potential for subsidence.

When passing from deep-seated to the subjacent karst stage, artesian caves, both
maze-like and large discrete voids, readily give rise to breakdown development. In
the artesian maze systems of the Western Ukraine, breakdown structures are scattered
throughout the passages. They were initiated predominantly at points where outlet
cupolas/domes (the features through which upward discharge from the systems took
place during the artesian stage) have revealed and exploited local zones of the low-
est integrity within the immediately overlying bed and the entire overburden
(Klimchouk and Andrejchuk, this volume). Because of the small size and gauging
effect of such outlet features, and the multi-layer structure of the overburden, break-
down columns propagate to the surface through many stages during extended time periods.

Large discrete voids can generate large and deep single-event collapses. This is exemplified by the collapse sinkholes common in the Zechstein gypsum of the South Harz gypsum karst, and by historically recent collapses generated by cavities in the gypsum bed within the Muschelkalk succession in the Stuttgart region, Germany (i.e. Eisinger Loch collapse formed in 1966). It is likely that smaller cavities of this type cause some of the subsidence hazards in the Ripon and Darlington areas of the UK.

In general, cavities of this type are probably the main trigger for the development of “vertical through structures” (VTS). This is a generic term suggested for typical phenomena of many deep-seated and subjacent gypsum karst regions of the world, commonly referred to as breccia pipes, collapse columns and “geological organs” (Klimchouk and Andrejchouk, 1996). They may reach a remarkable vertical extent, up to several hundred metres, by upward stoping across a multi-storey artesian system that includes soluble beds. VTS are not merely breakdown structures, but complex hydrogeologic structures whose development depends on focused cross-formational groundwater circulation and continuing dissolution of intercepted soluble beds and infallen clasts.

Entrenched karst is generally less prone to generate subsidence and related engineering problems than subjacent karst. This is because most of inherited cavities are stabilized with respect to the new conditions, the water table is commonly lowered below the bottom of a karst unit and contemporary dissolution is localized along a limited number of lateral flow paths or along the water table where it remains within gypsum. The entrenched karst zone in the Western Ukraine exemplifies this situation (see Klimchouk and Andrejchuk, this volume). The main speleogenetic triggers for breakdown development in entrenched karst are vertical solution pipes. They develop downward from a suitably protective bed at the top of gypsum (commonly limestone or dolomite), due to focused dissolution by groundwater that percolates through the overburden, or leaks from perched aquifers above the gypsum along prominent vertical discontinuities. Pipes 1 to 5m wide cut across the whole gypsum stratum or down to the water table, commonly intersecting relict lateral passages. The density of vertical solution pipes can be high, for instance, up to 300 pipes per km² at the Kungursky Cave area in the fore-Ural, Russia (see Andrejchuk and Klimchouk, this volume). Breakdown structures that initiate after the pipes are ready to propagate through the large thicknesses of the overburden because of involvement of hydrodynamic mechanisms in the breakdown processes and the presence of the discontinuity in the overlying stratum, which was instrumental in the development of the dissolution pipe in the first place.

Among other types, exhumed karst, and mantled karst may cause pronounced subsidence problems, particularly where the water table is positioned within a karst unit. Areas within the major river valleys in the Ebro Basin in Zaragoza region, Spain, exemplify the subsidence hazard associated with the alluviated subtype of mantled karst.
Buried karst does not normally generate subsidence, as it commonly results from marine transgression. Thus it loses its hydrological function and becomes fossilized.

6. Conclusion

The evolutionary typology of karst can be used as the basis, or as an important initial step, for general regional assessment of subsidence hazards. The types of karst differ quite naturally in their styles of speleogenesis, karst breakdown settings and characteristic mechanisms of the breakdown formation. Therefore, subsidence hazards also differ substantially between the karst types, so that one can obtain a kind of integrated general assessment by classifying a given individual karst according to this typology. This provides a useful basis for the selection and realisation of region- and site-specific assessment schemes and management strategies.

Intrastratal karst types, subjacent karst in particular, are the most potent in generating subsidence problems. Exposed karst types, especially open karst, are the least likely to pose subsidence hazard despite the fact that they are more obviously recognised as karstic areas.

Acknowledgement

This study was partially supported by the ROSES (Risk of Subsidence due to Evaporite Solution) Project ENV4-CT97-0603 funded by the EC Framework IV Programme. Thanks to Dr. David J. Lowe for smoothing the English text,


THE ENGINEERING CLASSIFICATION OF KARST WITH RESPECT TO THE ROLE AND INFLUENCE OF CAVES

Tony WALTHAM

ABSTRACT
The engineering classification of karst defines various complexities of ground conditions, in terms of the hazards that they provide to potential construction. Karst is divided into five classes (from immature to extreme). The three key parameters within the classification are caves (size and extent), sinkholes (abundance and collapse frequency) and rockhead (profile and relief). As one component of karst, caves are a hazard to foundation integrity, though natural surface collapses over caves are extremely rare. A cave roof is normally stable under engineering loading where the roof thickness is greater than 70% of the cave width. Construction can proceed over or around caves that are known. The main difficulty is finding unseen voids; ground investigation in mature karst may require extensive borehole probing, and microgravity is the most useful geophysical technique.

KEYWORDS: engineering classification of karst, subsidence hazard

1. Engineering and ground conditions
A classification of ground conditions - that is usable and useful for the civil engineer - identifies the degree to which any feature or group of features is present. Designation of a class for a particular site can present a useful concept of the scale and complexity of difficult ground conditions or geohazards that may be anticipated. It can also provide a first-pass guideline to design parameters that may be appropriate to a site; and it semi-quantifies any site description that may otherwise be very subjective in communications between engineers. The divisions within a classification should be recognisable, even though their differences relate to the geological and geomorphological history of the site that may be outside the understanding or background data of the non-specialist engineer.

With these premises in mind, an engineering classification of karst was prepared as part of a review of ground conditions on carbonate rocks by a Technical Committee of the International Society of Soil Mechanics and Geotechnical Engineering.
2. The engineering classification of karst

Karst ground conditions are divided into a progressive series of five classes. These are represented in Fig. 1 by typical morphological assemblages, and are further

---

**Fig. 1** - Typical morphological features of karstic ground conditions within the five classes of the engineering classification of karst. These examples show horizontal bedding of the limestone; dipping bedding planes and inclined fractures add complexity to most of the features, and also create planar failures behind steep cliff faces. The dotted ornament represents any type of clastic soil or surface sediment.
defined in Table 1 by their major identifiable parameters. These five classes provide the basis of an engineering classification of karst, that characterises karst environments in terms of the complexity and difficulty that the ground presents to the foundation engineer. The number of classes is limited to five in order to make the classification accessible and useable. Further subdivision would render the system complicated and cumbersome, and progressively less applicable due to the spectacular variations that can occur within karst. A full engineering description of the ground conditions on a site does demand more detail, and the karst class may then be qualified by defining specific parameters, as described below.

The engineering classification of karst is based largely on the three features that are most relevant to engineers concerned with the integrity of structural foundations in karst terrains - sinkholes, rockhead and caves. Any other parameters of karst morphology are generally less significant, though it should be possible to relate them to the established karst classes.

Sinkholes as labelled by most engineers are the same features as dolines labelled by most geomorphologists. They constitute a major karst geohazard with respect to their nature, size, spatial frequency and rate of new occurrences. The karst classification recognises the six main types of sinkholes/dolines (as defined in Lowe and

Table 1. The engineering classification of karst. This table provides outline descriptions of the three key parameters; these are not mutually exclusive, and give only broad indications of likely ground conditions that can show enormous variation in local detail. The table should be viewed in conjunction with Fig. 1, which shows some of the typical morphological features. NSH = rate of formation of new sinkholes per km² per year

<table>
<thead>
<tr>
<th>Karst class</th>
<th>locations</th>
<th>sinkholes</th>
<th>rockhead</th>
<th>caves</th>
</tr>
</thead>
<tbody>
<tr>
<td>kI Undeveloped</td>
<td>Only likely in deserts and periglacial zones, or on impure carbonates</td>
<td>Rare NSH* &lt;0.001</td>
<td>Almost uniform; minor fissures</td>
<td>Rare and small; some isolated relict features</td>
</tr>
<tr>
<td>kII Normal</td>
<td>The minimum in temperate regions</td>
<td>Small suffusion sinkholes or dropout sinkholes; open stream sinks NSH 0.001 - 0.05</td>
<td>Many small fissures, notably in the top few metres; significant depressions</td>
<td>Many small caves; most &lt;3m across</td>
</tr>
<tr>
<td>kIII Mature</td>
<td>Common in temperate regions; the minimum in the wet tropics</td>
<td>Many suffusion sinkholes and dropout sinkholes; large dissolution sinkholes NSH 0.05 - 1.0</td>
<td>Extensive fissuring, with secondary opening; relief of &lt;5m; some loose blocks in cover soil</td>
<td>Many caves &lt;5m across, at multiple levels</td>
</tr>
<tr>
<td>kIV Complex</td>
<td>Localised in temperate regions; normal in tropical regions</td>
<td>Many large dissolution; many subsidence sinkholes NSH 0.5 - 2.0</td>
<td>Pinnacled relief of 5-20m; loose pillars, extensive fissures</td>
<td>Many caves &gt;5m across, at multiple levels; isolated larger chambers</td>
</tr>
<tr>
<td>kV Extreme</td>
<td>Only in the wet tropics</td>
<td>Very large sinkholes of all types; remnant arches; NSH &gt;&gt;1</td>
<td>Tall pinnacles, relief of &gt;20m; loose pillars undercut between deep soil fissures complex dissolution cavities</td>
<td>Complex 3-D cave systems, with passages &gt;10m wide and chambers &gt;20m across</td>
</tr>
</tbody>
</table>
Waltham, 2002), though the most important are the subsidence sinkholes (both suffo­sion and dropout types) that form in cover soils over a fissured limestone (Table 1).

Rockhead relief is critical to engineering design where foundations have to trans­mit structural loads to solid rock beneath an unstable soil cover. The scale of rock­head relief increases to the pinnacled rockheads of the more mature karst in the higher classes.

Caves represent ground where engineering strength and bearing capacity are sig­nificantly reduced. The critical dimensions are the width of the void and the thick­ness of the rock cover, and these factors are further considered below.

Intact rock strength is not a part of the classification. Most carbonates that are eroded into cavernous karst are strong rocks (with unconfined compressive strengths greater than 50 MPa). Most of the weaker carbonates tend to have fewer and/or smaller caves, so minimising the impact of lithological variations. Chalk is a special case that warrants specific attention and has its own classification (Ward et al, 1968). Gypsum karst must be classified independently in order to acknowledge both the material weakness of bedded gypsum and also its potential for cavity development within engineering time-scales.

The classes of karst are defined and recognised by typical assemblages of mor­phological features (Fig. 1, Table 1). These cannot be absolute, as karst is too variable to lend itself to complete quantification, but they are guidelines to the ground condi­tions. The classes can be recognised in a climatic context. A geomorphologist may equate the immature classes kI and kII with glaciokarst or desert conditions, and the very mature classes kIV and kV with karst of the wet tropics, but these concepts would not be familiar to an engineer. Most of the dissolitional features of the lower classes of karstic ground conditions also appear as components within the more mature karsts. The parameters in Table 1 are not exclusive; a desert karst may have almost no active dissolitional development, and therefore appear to be of class kI, whereas it may contain unseen caves remaining from phases with wetter palaeo-cli­mates.

The extreme local variability of karst ground means that there are limits to how successfully karst can be classified. Whereas the scale of rockhead relief may lend itself to quantifiable classification, the distribution of individual sinkholes and under­ground cavities is so diverse, chaotic and unpredictable that a classification provides only broad concepts of their likely abundance. The class parameters (Table 1) cannot be more than guidelines to the typical state. A further problem is caused by the lack of interdependence between the components of the karst (Fig. 2). Within a region whose overall topography is best classified as a mature karst of class kIII, a single small construction site may reveal a minimally fissured rockhead that is best ascribed to class kII, and an isolated large cave chamber at shallow depth that is more typical of class kIV. The original classification of the karst region into class kIII is valid, but the local variations that typify karst mean that any small site sample may fall into a higher or lower class.
Fig. 2 - A rare example of a large collapsed cavern in karst in Nepal. Though the collapse is indicative of karst class kIV or kV, it is one of only three collapse features in a small limestone outcrop whose otherwise minimal karst landforms indicate a lower class of karst. This anomaly is largely due to very rapid landform development in limestone that is less than 500 years old.

3. The full description of karst ground conditions

A single class label may be helpful in creating concepts of the scale of anticipated foundation difficulties at a particular site, but it is not a full description of the karst ground conditions. The variations that are typical of karst may demand a more specific and more detailed definition. In such cases, a description of karst ground conditions should embrace four parameters, so that it becomes “Karst class + sinkhole density + cave size + rockhead relief”.

Karst class is an overview figure in the range I to V, as defined in the classification and recognisable within Fig.1 and Table 1.

Mean sinkhole density may be a simple number per unit area, based on field mapping, available maps or air photographs. Ideally, it should be a rate at which new sinkholes failures (NSH) are occurring, expressed in events per km² per year. In practice, the data could only be derived from local records, which are rarely going to be adequate for anything better than a broad generalisation. An NSH rate >0.1/km²/y would normally be expected in a karst of class kIII or higher. The NSH rate may be temporarily enhanced by engineering activities, in which case this variation should be noted.
Typical cave size should be a dimension in metres, based on available local data, which represents the largest cave width that is likely to be encountered. It would be larger than any local figure for mean cave width, but may reasonably exclude dimensions of the largest cave chambers that are statistically very rare (though mention of both those in an appended note would be appropriate if the data were available).

Rockhead relief should be a measure in metres of the local relief in the karst rockhead. This figure should include depths encountered within buried sinkholes. A distinction between pinnacled rockheads and those that are buried pavements (with a more tabular and perhaps fissured morphology) would be a helpful qualifier, if the data are available.

Though the four-parameter description may appear to be rather cumbersome, it can be reasonably argued that any lesser qualification is incapable of representing the vagaries of karstic ground conditions.

Every engineer must recognise that karst ground conditions are immensely variable, and always demand thorough site-specific investigation. Because of the local variability of karst ground conditions, every site on karst should be regarded as unique. The classification of karst provides only a broad indication of the engineering difficulties of a site, and therefore offers guidance on suitable approaches to elucidating and overcoming the ground difficulties; but it can be no more than an approximation when applied to a medium as variable as cavernous limestone.

4. Caves within the karst classification

Cave dimensions vary from those of impenetrable fissures upwards to vast caverns. In temperate regions, cave passages are generally less than 10m in diameter, but caves 30m in diameter are more common in the wet tropics. This distribution of typical cave sizes does correlate with the five classes of karst (Table I). Both surface landforms and cave passages are larger and more mature in wet tropical regions, where dissolution rates have been high for long periods without interruptions or temporary reductions in cold stages of the Pleistocene. Karst of classes kI and kII is therefore typified by cave passages normally only a few metres across, though scattered larger chambers can occur. Karst of class kV typically has trunk passages more than 10m in diameter, with even larger chambers, though many tributary passages may be much smaller.

Some of the most widespread difficulties with any engineering classification of karst are created by an immature modern karst that contains ancient large cave passages. A modern desert or polar environment may inhibit current dissolution processes. A mature karst may have evolved during wetter and/or warmer stages of the Pleistocene (or Tertiary). The old surface landforms may progressively be destroyed by the modern weathering, but the caves may survive. Observation of the surface may indicate a karst of class kI, but caves commensurate with classes kIV or kV may be present. Karsts in northern Greenland and in the Australian Nullarbor demonstrate the case where a simple karst classification is inadequate, and a fuller description (as above) is required.
Cave systems can also be of spectacular complexity. Surface lowering and valley entrenchment over long periods of time mean that most limestone masses have evolved through an earlier phase when they were saturated beneath a water table and a subsequent phase when they were largely free-draining into adjacent valleys. Most cave systems are therefore multi-phase, with an early network of tubular phreatic caves modified and entrenched by later phases of vadose canyon caves. The older passages are generally modified by roof breakdown debris and partly or completely filled by allogetic clastic sediments or the deposition of stalagmites and flowstones. Such variety further complicates any engineering classification of the karst that has to relate to the size and extent of the voids. Most caves are however stable in their natural state; conventional engineering would require little or no roof support in excavated tunnels or caverns of comparable sizes (Fig. 3).

---

**Fig. 3** - Cave stability related to cave width and rock mass quality (*Q* value after Barton et al, 1974). The envelope of the limestone caves field is derived from observations of caves around the world. The labelled fields of stable, support and unstable are those applied in guidelines for the Norwegian Tunnelling Method; they refer to engineered structures with public access, and are therefore conservative when related to natural caves. The top apex of the envelope is defined by the parameters for Sarawak Chamber, in the Mulu caves of Borneo; the roof span of this chamber is stable on engineering timescales, but isolated blockfall from the ceiling would render it unsatisfactory were it to be used as a public space.
On both small and large scales, the patterns, shapes and profiles of cave passages are determined by the structural and lithological features of the host limestone; the overall patterns are also influenced by the past and present hydrology. Though the guiding features can be recognised in all mapped caves, the locations of unknown caves cannot be predicted, except in the broadest of terms. Limestones have too many structural elements to consider, and fissures may develop on any or all of them, so that there are too many choices for subsequent cave development from only some of the fissures. The distributions of inception horizons, shale beds, past water tables and mixing zones are generally only understood after a detailed geomorphological study of the karst, underpinned by a large database of cave surveys. These are not available to most engineering investigations, and unknown cave locations remain a major problem on construction projects.

5. Natural cave collapse

The roof of a limestone cave may collapse either in its natural state or under an imposed load from engineering activity. Natural collapse is by progressive failures of roof rock units (Fig.4), which may eventually reach the ground surface. Wall or pillar failures (which are alternative collapse mechanisms in mines) rarely occur in natural caves that are isolated voids within large rock masses. Imposed

*Fig.4 - Evolution of a cave roof by large block-fall in massive limestone, in Yordas Cave, England. Flowstone high on the cave walls indicates that the roof profile has remained almost unchanged for >100,000 years.*
loading may either accelerate or precipitate the natural processes of cave roof failure. Whether natural or induced, cave failure is a rare event in strong limestones, but the geohazard is created because the distribution of natural caves is notoriously unpredictable. A single cave was found, purely by chance during routine maintenance, just a few metres beneath the main runway of Palermo airport, on Sicily. It was 25m wide, and though there were no signs of breakdown, the consequence of even partial failure was so severe that it was filled with concrete (Jappelli and Liguori, 1979). The site is on a coastal platform of young limestone, where wide cavities are notably prone to development by dissolution at the interface between salt and fresh water at either current or past sea levels.

Cave roof breakdown is normally a progressive failure of individual beds or blocks, that develops upwards as a process known as roof stoping or cavity migration (Fig.5). It is rapid (on a geological time-scale) in thinly-bedded limestones. It may stop where a single bed is thick enough to resist failure by acting as a stable beam or cantilever over the cave void. A stable compression zone develops as an arch within a roof mass, and its arch profile rises typically to about one third of the cave width. Within this compression zone fractured rock may become very stable. Rock can fall away from the tensile zone beneath it, while the arch retains its integrity. Most large cave chambers have roofs that are compression arches with very low pro-

Fig.5 - Progressive bed failure in the roof of a passage in Agen Allwedd, Wales. The breakdown process causes upward void migration of the void over an increasing pile of rock debris; in this case, the original dissolution cave was 12m below the present roof, but this migration has probably taken more than 100,000 years
files in fractured rock (Fig.6). The process can be seen in the entrance chamber, 150m wide, in Tham En, Laos (Waltham and Middleton, 2000), and the giant Sarawak Chamber in the Mulu caves is similar.

Arch development relies on lateral compressive stress to maintain integrity, and such stress is normally present in deeply buried limestone. Lateral stress may be inadequately low near to the ground surface, and particularly in caves that lie parallel to an open cliff face or valley side. In these situations, the rock mass may relax towards the unconfined surface and a stable compression arch cannot develop within it. Progressive stoping failure of a cave roof may then continue unhindered. The end result is a breccia pipe (Fig.7) and/or a surface collapse (Fig.8). Open karstic fissures also permit greater deformation of an arch and accelerated failure of a cavern roof.

Cave roof collapse is also a natural consequence of ground surface lowering until a rock roof is so thin that it fails under its own load. A Slovenian cave, Brezno pri Medvedovi Konti, has an almost circular chamber, 130m across, beneath a gently domed roof that is 45m thick. This was modelled numerically, with a roof progressively thinned as if by surface lowering (Kortnik and Sustersic, 2000; see also paper by Kortnik in this volume). Massive failure (with no imposed load) started only when the roof at its thinnest part was down to just 15m thick. Reducing the strength of the modelled roof rock did not affect this thickness, though re-failure deformation was greater. Though difficulties were recognised in modelling the limestone fractures, the

Fig.6 - A stable roof with a roughly arched profile has developed in structurally complex limestone to span 40m in the entrance chamber of Tham Nathan, Laos.
Fig. 7 - A breccia pipe in thinly bedded limestone, created by upward stoping within a small cave. It is now exposed in a sea cliff in Halong Bay, Vietnam. The open cave is less than 5m below the ground surface in the cliff section, and nearly 20m of breccia pipe is exposed above sea level.

Fig. 8 - A zone of collapsed blocks of limestone in Penyghent Gill, England. The original cave (that still continues behind the collapse) was over 15m wide, but the rock roof had been thinned by erosion to less than 2m, and may have been loaded by a Pleistocene glacier.
data confirm that a very thin rock arch can be stable. Cave collapse still can and does occur, but the statistical chance of a natural cave roof collapse at any one point, within an engineering time-scale of a few hundred years, is extremely low. The geohazard exists but is essentially irrelevant, unless or until a failure is induced by imposed structural loading.

6. Cave collapse under imposed load

Loadings imposed on a cave roof by engineering works have the potential to precipitate natural failures that may have taken thousands of years to develop in the unloaded state. Total structural loads are mostly small in comparison to the loads imposed by rock and soil overburden, but they are commonly concentrated to stresses of >1 MPa (equal to a rock column 40m high) on small foundation pads, column bases or pile tips.

An informal guideline to the stability of the natural rock roof over a cave is that the ground is stable (for normal engineering activity) if the thickness of rock is equal to or greater than its span; this excludes any thickness of soil cover or heavily fissured limestone at rockhead. This guideline appears to be conservative in most situations. For typical limestone karst where the rock mass is of fair quality, in rock mass class III, with a Q value of 4-10 (Barton et al, 1974), a cover thickness of intact rock that is 70% of the cave width ensures integrity (Fig.9). This applies under foundation loading that does not exceed 2 MPa, which is half the SBP appropriate for sound limestone. The concept covers limestone with a normal density of fractures and bedding planes; local zones of heavy fissuring may reduce cave roof integrity. It covers normal limestone with a degree of dissolutional widening of fissures, and is therefore independent of the engineering classification of karst (except with respect to the anticipated cave width).

This guideline is based on a scatter of documented experience at individual sites and correlation with data on failures of mined cavities. There is almost no reliable data on the loads required to cause the failure of a limestone cave roof. Physical and numerical modelling of artificial caves in sandstone under Nottingham, UK, (Waltham and Swift, in prep) has confirmed the critical parameters:

- failure loads increase over thicker roof rock;
- failure loads decrease over wider caves;
- failure loads increase sharply where only a small part of the loading footprint extends over intact rock beyond the cave walls;
- minimum failure load is not over the centre of a cave but is over the edge of the cave where stress concentration develops.

The modelling results for the sandstone were calibrated to a full-scale test of a cave roof loaded to failure, but that type of data is rarely available. Caves 5m wide in the sandstone are routinely built over, with heavy structures on 5m of rock roof and lighter structures on 3m of rock. Many older structures (that pre-date modern building codes) stand on very much less rock thickness and over wider caves. The
Nottingham sandstone has a Safe Bearing Pressure of 1 MPa.

Quantification of modelled or theoretical failure loads over limestone caves fails through lack of data on the in situ rock mass properties (notably with respect to fracture patterns and fissure development). Physical modelling was extended from the Nottingham sandstone to karst limestone that is much stronger as intact material. This showed the relative strengths of cave roofs of different bed thicknesses and with inherent fractures (Fig.9). Numerical modelling did not adequately represent the greater fracture densities in the strong limestone, and calibration of the physical models is only possible by a tenuous link to the one real test on sandstone. The available data concur with the guideline that the limestone roof thickness should exceed 70% of the cave width. Any but the softest of recent limestones would be stronger than the sandstone, and the test data imply that a guideline demanding roof thickness greater than cave width is conservative in karst. At any site, inspection of an individual cave roof may indicate variance from the guideline ratio to ensure stable ground.

Most karstic caves lie at depths within the limestone rock mass, where they constitute no hazard to civil engineering works with conventional foundations on the
surface (Fig. 10). The potential hazard in civil engineering works is the large cave that lies at shallow depth, where it may threaten foundation integrity. Caves may commonly reach widths of 10m in karst of class kIV, where borehole proving to 7m would therefore be appropriate. Caves of even larger sizes are common in class kV karst, and can occur in karst of less mature classes.

Fig. 10 - A stable cave passage 100m below the ground surface in Mammoth Cave, Kentucky, USA. Stability of the cave is also enhanced by the flat arch profile of the ceiling carved by dissolution in a singularly unbroken bed of limestone

7. Construction over caves

Where caves are found at critical locations under planned foundations, the normal remedy is to fill them with mass concrete. Grout injection through boreholes may incur considerable losses by flowage into karstic cavities that extend far off site, and perimeter grout curtains may therefore reduce total costs. Alternatively, creating access to a cave may allow installation of shuttering and removal of any weak floor sediment before filling, as a concrete fill would lose its load-bearing capacity where placed over a soft fill. A lean-mix fill is however satisfactory on top of soft sediment where its only purpose is to prevent blockfall from the roof. Relocation of footings is usually an expensive option, but can prove essential over complex caves (Waltham et al, 1986). Bored piles can be placed through a cave to sound footing in the rock below; geotextile sleeves can be used to cast the concrete through the cave (Heath, 1995), but total cave filling is often preferred for its simplicity, at costs that may be little different.

It is impossible to predict both the number and the size of caves beneath any given karstic site. Each site has to be assessed individually within the context of its geomorphology, and engineering works must respond to the local conditions. Local records and observations may indicate the typical and maximum cave sizes previ-
ously encountered. The cave size determines the engineering philosophy whereby a defined minimum of sound rock should be proven by drilling beneath every foundation pad and pile tip (see below). Experience in Slovenia (Sebela et al., 1999) indicates the major variations that may be represented within a mature cavernous karst; cave discoveries and collapses have both been common during road construction, but subsequent cave collapses directly under operational roads have not occurred.

8. Engineering exploration of cavernous karst

The greatest single difficulty in ground investigations on karst is the detection of underground cavities. Local data are the only guide to local cave passage widths, and also to the extent of caves with respect to the statistical chance of one lying under a given point. Ultimately, there is little alternative to closely spaced probing (non-cored drilling) of the rock; however, it needs 2500 boreholes per hectare to have a 90% chance of finding one cave 2.5m in diameter. On any site, an appropriate number of exploratory probes can only be defined in terms of the known local conditions (including the geomorphological history), the sensitivity of the structure to be built, and the results achieved as the investigation proceeds in stages. Belgium’s Remouchamps Viaduct provided a classic example of the unpredictable nature of karst (Waltham et al., 1986). On the initial ground investigation 31 boreholes found no caves. Subsequent excavation of the pier footings found two unknown caves. A second phase of investigation was therefore instigated, but 308 new boreholes found no more caves.

Probes beneath every pile foot and column base are frequently the sensible option, and are essential at many sites on mature, cavernous karst. Site-specific risk assessment can indicate whether a typical or a maximum cave width is used to determine drill hole probing depths beneath foundation sites. If the concept of a cave being stable where its rock cover exceeds its width (see above), the depth to be probed is the likely cavity size, but this is very conservative, and probing to lesser depths is satisfactory except for the most heavily loaded structures. In karst of classes kI - kIII, caves more than 5m wide are unusual, and drilling 3.5m should therefore confirm integrity for most purposes. Engineering practice varies considerably, by proving 5m beneath pile tips in Florida (Garlanger, 1991), 4m under foundations in South Africa (Wagner and Day, 1986), 2m under caissons in Pennsylvannia (Foose and Humphreville, 1979), and only 1.5m under bridge caissons in North Carolina (Erwin and Brown, 1988). It is significant that the Florida proving was for small-diameter piles in a karst where large caves are known to exist, whereas the caissons in North Carolina were lightly loaded on a weak limestone.

Large caves at shallow depths constitute the major geohazard, and they commonly have open entrances nearby, so that they are best assessed by direct exploration. Small shallow cavities may be collapsed by dynamic compaction (with drop weights), and this may be appropriate on karst of classes kIII or kIV, particularly in weak limestones.
Geophysical identification of ground voids has not produced consistently reliable interpretations, and there are many reports of it producing no useful data for engineering purposes. However, technology is advancing rapidly, and there are new geophysical techniques that can produce useful results in certain situations (Cooper and Ballard, 1988).

Some of the best data come from microgravity surveys, which continue to improve in value with increasing sophistication of their data analysis. Gravity survey data provide a direct measure of the extent of voids within a rock mass. Individual caves can be identified by negative anomalies, whose amplitude relates to the cave size and whose wavelength is a function of the cave depth. Fourier analysis of data from a grid with spacing of 2m can identify caves only 1m across at various depths; this is directly applicable to engineering investigation (Butler, 1984; Crawford et al, 1999; McDonald et al, 1999; Styles and Thomas, 2001). There is the prospect that bands of gravity values and anomaly relief could be applied to the classification of karst, but this awaits the accumulation of gravity data from a range of sites as the technique becomes more widely employed.

In a single rock type, seismic velocities decrease in a rock mass that is more fissured and cavernous; seismic data have already been correlated broadly with engineering classifications of the rock mass, and this could offer a second geophysical tool with which to characterise the karst classes. Three-dimensional cross-hole seismic tomography (3dT) is newly developed with the improved computer analysis of massive banks of data (Simpson, 2001). Though invaluable for tunnel projects and sites with available deep boreholes, it is limited in application to surface investigations of greenfield sites.

All types of electro-magnetic geophysical surveys have serious limitations in cavity searches. A cave full of clay produces a positive conductivity anomaly, whereas an empty cave produces a negative anomaly, while both are potential engineering hazards. A mixture of both filled and empty caves provides spectacularly confusing data. Ground-probing radar suffers similar difficulties, and is limited to shallow depths. Three-dimensional resistivity tomography is time-consuming and expensive, but can be combined with microgravity to identify rockhead and so distinguish caves from any buried sinkholes that create similar gravity anomalies.

Cavernous karst can constitute seriously difficult ground for engineering works. The chances of a cave lying undetected beneath a foundation and causing a structural failure (except by sinkhole development within a cover soil) are statistically very small. But the impact of a total ground collapse can be very high. Proving that there is no cave within a given block of limestone can be difficult and/or expensive. A better option is commonly to design foundations that can survive total roof collapse of a predictable but unknown cave.

REFERENCES


CAVE BREAKDOWN BY VADOSE WEATHERING

R.A.L. Osborne

ABSTRACT

Vadose weathering is a significant mechanism for initiating breakdown in caves. Vadose weathering of ore bodies, mineral veins, palaeokarst deposits, non-carbonate keystones and impure, altered or fractured bedrock, which is intersected by caves, will frequently result in breakdown. Breakdown is an active, ongoing process. Breakdown occurs throughout the vadose zone, and is not restricted to large diameter passages, or to cave ceilings. The surfaces of disarticulated blocks are commonly coated, rather than having fresh broken faces, and blocks continue to disintegrate after separating from the bedrock. Not only gypsum, but also hydromagnesite and aragonite are responsible for crystal wedging. It is impossible to study or identify potential breakdown foci by surface surveys alone, in-cave observation and mapping are essential.

1. Introduction

Breakdown is a significant process in both karst and non-karst caves, and it can have implications for the stability of both cave voids themselves and for structures founded on rocks above caves. A range of professionals, including engineering geologists, mining engineers, geotechnical engineers and structural engineers, may be asked to advise on issues relating to cave breakdown, including foundation conditions on cavernous karst, collapse structures in the karst surface and the safety and stability of show caves. Frequently an outside-in approach is taken to the processes of breakdown and collapse and to ways of ameliorating their effects on humans and their technology.

When viewing karst from the inside-out, breakdown is found to be a common and largely natural process within caves. In many cases breakdown has no surface expression or effect. Frequently ground failure and subsidence in karst is not caused by breakdown and the resultant failure of massive bedrock, but the failure of unconsolidated material filling dolines and cave entrances, due to the removal of fines by infiltrating water.

Increasingly, caves are being seen as inherently stable features with life spans, as open voids, extending over hundreds of millions of years, not ephemeral underground landscapes that rapidly disintegrate.

Studies by specialists with experience in working inside karst and an understand-
ing of how breakdown processes work within karst are essential, both to provide background information and for solving site-specific problems.

1.2. Breakdown

Breakdown has been variously defined as a process, as a material, or as both. Davies (1951) defined breakdown as a process:

\textit{The failure en masse of the roof or walls of caverns},

whereas White and White (2000) proposed a narrower definition, which restricted breakdown to the materials:

\textit{disarticulated fragments of bedrock that have broken free and fallen into a cave passage}.

A broader definition is used here sees breakdown as both the process by which the materials surrounding cave voids become disarticulated and the materials (fragments, blocks) that have become disarticulated.

Whether breakdown (sometimes called collapse) is a cave forming (speleogenetic) or cave destroying process is a matter of contention. Waltham (1974) stated that:

\textit{Collapse is frequently cited as the cause of large cave chambers. This is incorrect - in fact the real cause is quite the contrary... collapse does not form caves, it fills them in.}

Most commentators, however (e.g. Bögli, 1980), recognised, and recent discoveries in Mallorca (Gines, 2000) have indicated that breakdown is involved in the development of many large chambers.

Where cave breakdown intersects the ground surface the result is a collapse doline. There is an extensive literature on the origin of collapse dolines, and Sustersic (2000) provides a good review. It is not intended to discuss the interaction between cave breakdown and surface failure here, but rather to concentrate on what observations in caves indicate about the behaviour of breakdown as both a process and a material.

1.3. Mechanisms causing breakdown

Davies (1951) applied beam failure models derived from mining engineering to the problem of cave breakdown.

In their classic work on cave breakdown, White and White (1969) identified eight processes activating cavern breakdown:

1- loss of buoyant support by draining of galleries;
2- undercutting of banks by floodwater stoping at the base level;
3- removal of support by free surface stream action;
4- crystal wedging and attack by sulfate mineralization;
5- frost wedging;
6- undercutting by later cavern development;
7- undercutting and removal of material by vertical shafts and shaft drains;
8- weakening of ceiling beds through attack by acid surface water.
All but three (# 4, 5 and 8) of these mechanisms involve the removal of some type of support.

Recently, Slovenian workers have made significant contributions to the study of breakdown. Stanka Šebela and Jose Čar (Šebela and Čar, 1991; Šebela, 1996, 1998, Šebela and Čar, 2000) have shown the importance of geological structures such as faults, fault zones and fold axes in the development of breakdown chambers and related collapse dolines at Postojna Cave. Mihevc (1995) recognised that large chambers in vertical caves can form by the breakdown of the rock mass (walls) between two adjacent shafts. Šušteršič (1998, Fig.3B), in describing the development of an unroofed cave, indicated that breakdown is a near-surface weathering phenomenon.

The sediment-filled channel is intersected by the surface weathering zone. Breakdown of the channel ceiling takes place and the fill supports large blocks of the parent rock.

Whereas Davies (1951) dismissed the contribution of earthquakes to cave breakdown, recent work in Croatia (Buzjak, 2000) has emphasised the role of neotectonics in the final failure of cave voids, leading to the development of collapse dolines.  

1.4. Implications of failure mechanisms involving removal of support

Breakdown in caves is commonly attributed to loss of buoyant support, as phreatic caves are initially drained - the first of the mechanisms proposed by White and White (1969). If breakdown is primarily a product of failure brought about by removal of support, one might expect that:

- Active breakdown would be a common feature of the lower vadose zone (where hydrostatic support has been most recently lost) and a rare feature of the upper vadose zone where a significant time interval has followed loss of hydrostatic support.

- Breakdown would be very common in large passages and quite rare in passages of relatively small dimensions.

- Breakdown should be essentially a process affecting the ceiling and upper walls of cave passages; lower wall and floor breakdown would be unexpected.

- The surfaces of recently fallen blocks should be fresh, as they result from recent breakdown

Fig. 1 - Eastern Australia showing locations of sites described. Black dots and zones represent major cavernous karsts developed in Palaeozoic limestones. Based on map by K. Grimes (2000).
cracks in fresh rock, initiated after the removal of hydrostatic or other support.

- Breakdown should quickly become self-limiting as an arch of equilibrium dimensions is produced.
- Observations in caves in the Palaeozoic limestones of eastern Australia (Fig. 1) during the last twenty years and more recently in Europe (Fig. 2) have shown that these five expectations are commonly not met. The observations do suggest that vadose weathering of:
  - Ore bodies and mineral veins,
  - Palaeokarst deposits,
  - Non-carbonate keystones,
  - Impure, altered or fractured bedrock
is a significant mechanism for triggering breakdown.

Fig. 2 - Europe, showing locations of sites described:
A = Mammut hole, Dachstein, Austria,
B = Manita Pec, Starigrad Paklenica, Croatia,
C = Kozja jama v Pogorelem hribu, Slovenia,
D = Treak Cliff Cavern Cavern, Castleton, England,
E = Wet Sink Cave, Forest of Dean, England,
F = GB Cave, Mendip Hills, England..
2. General observations of breakdown in caves

Whereas there is no doubt that removal of support plays an important role in breakdown, the author’s observations indicate that vadose weathering plays a significant role in many, if not most, occurrences of breakdown in high strength (strongly indurated) limestones. Breakdown in poorly indurated limestones, such as aeolian calcarenites, has not been investigated.

The following general observations have been made of breakdown in caves.

2.1. Breakdown is an active, ongoing process

The most striking impression gained from examining active breakdown sites in caves is that zones in the rock are literally (and rapidly) in the process of “blowing apart” or disintegrating.

Since the environment in caves tends to protect breakdown features from the elements, the apparent “freshness” and “rapidity” of the process is more often than not an illusion. What is clear, however, is that breakdown is a process active today, not one that occurred mostly in the past (i.e. just after the caves entered the vadose zone).

2.2. The position of breakdown relative to the water table

In all of the areas where observations have been made, breakdown, particularly that resulting in the development of large breakdown chambers, was commonly found to be occurring high in the vadose zone. That is, in areas quite removed from where the limestone has recently lost hydraulic support from phreatic water.

High-level breakdown chambers are quite common. European examples include Grosse Dom in Mammuthole, Austria (Fig.2A) and Manita Pec in Croatia (Fig.2B). A good example is Kozja jama v Pogorelem hribu, (Fig.2C) in the high karst of Slovenia near Mt Nanos. It is an isolated breakdown chamber (Fig.3) in which breakdown processes are currently active. The entrance elevation of Kozja jama v Pogorelem hribu is 1090m, some 1,000m above the regional karst water table.

2.3. Breakdown in small-section passages and chambers

Whereas breakdown does play a major role in the development of some large chambers, breakdown is by no means restricted to large-section cave passages. In the limestone caves examined by the author this is only a qualitative observation. However, Klimchouk and Andrejchuk (this volume) have shown quantitatively that, in large gypsum caves, there is no direct correlation between large passage diameter and the occurrence of breakdown.

2.4. Breakdown occurs in cave walls and floors

Davies (1949) noted that collapse of cave walls accounts for a large amount of rock debris in caves. The author’s observation have shown that breakdown is not restricted to the cave ceiling and the area just below the ceiling-wall junction, as might be expected from failure due to loss of support, but also occurs at a variety of levels in cave walls and at the wall-floor junction.

In Treak Cliff Cavern, Castleton, England (Fig.2D), heaving of bedrock can be observed at the wall-floor junction. At Jenolan Caves, N.S.W. Australia (Fig.1), gyp-
sum wedging is resulting in active failure by exfoliation of thin scales of limestone around the walls and ceiling surfaces of a circular-section passage with a diameter of about 1.5m.

2.5. Surfaces of breakdown blocks

Fallen breakdown blocks, in general, do not have the clean, fresh bedrock surfaces that might be expected if they were the result of failure along recently propagated cracks. On the contrary, recently fallen blocks are commonly coated with thin layers of clay, limonite and other minerals, giving them a weathered appearance. On being broken open, however, the centres of such blocks are found to be composed of fresh, unaltered limestone.

The walls of the Grand Dome, Glory Hole Cave, Yarrangobilly Caves, N.S.W. Australia (Fig.1), have a distinct yellow colour, as do fallen blocks from the break-
down pile lying on the chamber floor. The interior of these blocks, however, is dense (sound) white limestone, transected by sparry veins containing small crystals of pyrite (Osborne, 1996). In this, and many other instances, breakdown blocks are found to bounded by pre-existing discontinuities in the limestone (veins, joints, micro-faults etc.) that have been opened/mobilised by weathering, rather than by recent fractures of sound rock.

2.6. Continued fragmentation of fallen blocks

At many of the localities examined (e.g. Kozja jama v Pogorelem hribu), fallen blocks in breakdown piles were found to be in the process of disintegration. This disintegration was clearly taking place after the rocks had fallen (Fig.4). This continuation of fragmentation, principally due to crystal wedging, plays an important role in the removal of breakdown material from cave voids.

Post-parting disintegration, dissolution of breakdown by strong acid released from the weathering of pyrite, and dissolution of breakdown piles below the water table provides the answer to Waltham’s dilemma (see above). Whereas breakdown may in some cases fill caves, commonly the breakdown pile is removed, resulting in continued expansion of the cave void.

2.7. Movement of breakdown piles may be independent of fresh breakdown

Breakdown piles in caves, like talus slopes and cones in the surface environment, may move without any new material being added to them. Also, like their surface equivalents, breakdown piles should be considered to be in a constant state of slow motion. As a consequence, movement of a breakdown pile may considerably alter the

Fig. 4 - Limestone blocks in breakdown pile, Kozja jama v Pogorelem hribu. Note “weathered” surface of blocks. Blocks show continuing post-fall disintegration. Lens cap 55mm.
internal geography of a cave, without any change occurring in the shape or stability of the enclosing bedrock void.

When movement of breakdown blocks in caves is investigated it is essential to establish if there is significant new breakdown of the cave wall or ceiling, or if the movement is restricted to the pile (or sections of the pile) itself.

2.8. Minerals involved in crystal wedging

Whereas gypsum, generally derived from the weathering of pyrite, is the most commonly observed mineral involved in crystal wedging, it is not the only species involved. Hydromagnesite has been implicated in breakdown at Wet Sink Cave, Forest of Dean, England (Fig. 2E) and at Jenolan Caves. Secondary aragonite, in the form of spheres, 25mm in diameter, composed of acicular crystals, is actively wedging rock apart at Jenolan Caves. Ferroan dolomite appears to be the precursor of hydromagnesite at Wet Sink Cave and Jenolan Caves and of aragonite at Jenolan Caves.

3. Breakdown initiated by vadose weathering

In the vadose zone, karst materials are exposed to air, undersaturated/oxygenated water and variations in humidity and temperature. Whereas the response of high-purity limestone and gypsum to these conditions will largely be to dissolve, or gain mass through precipitation, other materials (e.g. sulfides, clays, ferromagnesian minerals, etc) will respond by weathering, much as they do elsewhere close to the Earth’s surface.

It is the vadose weathering of Earth materials, other than high-purity bedrock, in the karst rock mass that can be a significant trigger for breakdown.

3.1. Breakdown by weathering of mineralised bodies and veins

A range of ore bodies including Mississippi Valley Type deposits, fluorite and low temperature iron carbonates can be emplaced in limestones. These may be intersected by caves, or may be weathered-out to form caves. Osborne (1993a, 1996, 2000) described how weathering of palaeokarst ore bodies, and veins emplaced in the surrounding bedrock by them, resulted in breakdown.

Though generally stable in the phreatic zone, ore bodies containing sulfides will weather rapidly in vadose conditions, and may be easily removed from the rock mass. In the Underground River at Jenolan Caves large blocks of weathered iron carbonate ore (not bedrock) have fallen from the ceiling, exhuming a previously-filled cavity in the limestone (Osborne, 1993a). The original ore contained calcite, ferroan dolomite and pyrite.

As the ore body is removed, sulfide-bearing veins, extending into the rock mass, will also weather, resulting in the development of breakdown chambers. This process, based on observations at Wyanbene Cave, N.S.W. Australia (Fig.1) is illustrated in Fig. 5.
In Wet Sink Cave, active breakdown is occurring at specific sites in the Chunnel, an elongate cave passage with a rectangular profile and a breakdown floor, developed along a joint in sub-horizontally-bedded Carboniferous limestone containing iron mineralization (Lowe, 1993). The Chunnel is currently the highest level passage known in Wet Sink Cave, located some 30m above the present stream bed. Breakdown is not found in the lower-level stream passages. At active breakdown sites the bedrock is intersected by veins of carbonate iron ore, which are weathering. Breakdown was occurring by the dislodgement of vein-bound blocks from the cave ceiling, partly as a result of crystal wedging by hydromagnesite.

3.2. Breakdown by weathering of palaeokarst deposits

Palaeokarst deposits in limestone (Osborne, 2000) and gypsum (Klimchouk and Andrejchuk, this volume) can be significant foci for breakdown. Palaeokarst deposits are commonly lithologically and chemically different from the bedrock in which they are housed. They are generally scattered (apparently irregularly) through the rock mass. Palaeokarst bodies may not be exposed at the surface. The position of exposed
palaeokarst bodies at the surface gives little indication of their likely disposition within the rock mass as a whole.

This situation is well illustrated at Jenolan Caves. Jenolan Caves are developed in a narrow body of steeply dipping, massive Silurian limestone. Bodies of horizontally bedded, laminated palaeokarst limestone (Caymanite) (Osborne, 1993a, 1999) occur throughout the rock mass. Pyrite is a common, but not particularly abundant, mineral in the palaeokarst deposits.

Breakdown associated with weathering of palaeokarst occurs in The Grand Archway at Jenolan Caves (Figs 6 and 7). Whereas most of the ceiling of the

Fig. 6 - The Grand Archway, Jenolan Caves. A = zone where blocks are separating along horizontal bedding in laminated palaeokarst. B = location of Fig. 7. Map modified after Trickett (1925).

Fig. 7 - Failure of weathering palaeokarst body, adjacent to lens cap, resulting in breakdown of massive limestone. Grand Archway, Jenolan Caves, near location “B” in Fig. 6. Lens Cap 55mm.
Archway is composed of massive, steeply dipping limestone, palaeokarst bodies are exposed in the ceiling adjacent to the southern wall. Here a combination of gypsum wedging due to weathering of pyrite and lack of support is resulting in slab failure of palaeokarst from the cave ceiling along horizontal bedding. This process also brings down adjacent, and/or interspersed, blocks of massive limestone.

It is important to note that a geological survey of the limestone outcrop on the surface above the Grand Archway would give no indication of the presence, or disposition, of the palaeokarst bodies.

3.3. Breakdown by weathering of keystones

Breakdown may be triggered by the weathering of intrusive rock bodies, such as dykes, which have come to act as keystones for cave ceilings.

Non-karst caves, such as some sea caves, frequently develop by the weathering and erosion of dykes in more resistant rocks, and then expand by undermining and breakdown of the surrounding rock and the removal of breakdown debris. Breakdown is triggered by weathering and progressive failure of the dyke, which acts as a central keystone for the cave ceiling.

This process can be seen in St Michael's Cave, a sandstone sea cave at Newport, N.S.W. Australia (Fig.1). The cave is an elongate chamber developed along a pyroclastic dyke that intrudes a sequence of sandstones and mudstones. The dyke now forms the keystone for the cave ceiling (Osborne and Branagan, 1992).

A significant breakdown event in 1980 raised concern about stability of the cave itself, and of houses constructed above it. The event appears to have been triggered by heavy rain and sullage seeping down the dyke, leading to its failure close to the cave ceiling (Fig.8). As a consequence, a significant quantity of sandstone and mudstone slabs detached from the cave ceiling along bedding planes (Fig.9).

Fig. 8 - St Michael's Cave, looking west. The dyke is the vertical dark band in the background just right of centre. The tripod is on top of a fresh breakdown cone produced by major ceiling failure along the dyke in 1980. Blocks in the pile are sandstone, the clastic dyke material weathers to form black silty sand. Note failure along horizontal bedding planes in the upper right of the image.
In karst caves, dykes, and/or vertical sills, intersected by the margins of dissolution cavities can also act as keystones, and their progressive failure may lead to breakdown. Woof’s Cavern in Lannigan’s Cave, Colong Caves, N.S.W. Australia (Fig. 1) is a large chamber developed in vertically-bedded limestone with a vertical sill forming its eastern wall (Osborne, 1985). Breakdown along the eastern side of the chamber occurs when failure of the sill as a keystone results in detachment of slabs from the ceiling along horizontal joints (Fig. 10).

Since weathering of intrusive rock bodies can be a significant trigger for cave breakdown, it is important to know where such bodies intersect karst rocks and the relationship between the intrusive bodies and the cave void.

In-cave surveys are required to determine the relationship between intrusions and caves. This is because the absence of dykes on the karst surface does not indicate their absence in the rock mass, even at quite shallow depths. For example, Osborne (1993b) described three dykes exposed at shallow depth (<10m below the surface) in caves at Bungonia Caves, N.S.W. Australia (Fig. 1). One dyke is exposed in a cave passage within 1m of the surface. However, at the surface directly above it, no trace of the dyke, only massive limestone, is exposed.

3.4. Breakdown by weathering of impure/ altered bedrock

Karst features are most commonly encountered and best expressed in soluble rock of high purity - that is, in limestones, dolostones, gypsum and salt containing more than 95% soluble mineral. Caves can, however, develop in rocks that are considerable less pure, and some cave forming processes (e.g. thermal and hydrothermal speleogenesis) may alter the composition of the wall rock in the cave.

As a consequence, caves may penetrate rocks that undergo a range of vadose...
Fig. 10 - Diagrammatic cross-section looking south, showing breakdown where dyke occurs at the side of cavity, based on Woof's Chamber, Lannigan's Cave, Colong Caves. B = widely spaced steeply dipping beds. J = gently dipping beds. Section after survey by Pryke and T. Moulds, Sydney University Speleological Society, 2002.

weathering processes, not just dissolution. These can result in fragmentation of the rock and, hence, breakdown.

In 1986 a major sinkhole failure occurred in the Snowy Mountains Highway at Yarrangobilly, New South Wales, Australia (Osborne, 1996). This failure was due largely to removal of poorly consolidated sediments filling a natural solution cavity in the limestone. Internal examination revealed that the rock of the cavity wall was composed of weathered, altered limestone, not pure massive limestone like the majority of the Silurian limestone at Yarrangobilly. These cavity walls were fairly weak and beginning to fail as the supporting sediments were removed.

GB Cave, Mendip Hills, England (Fig.2F) one of the largest caves developed in the Mendip Hills of south-western England, consists of a small-section passage that connects to a series of large, breakdown-modified chambers. The small-section passage is developed in thin beds of relatively pure limestone, interbedded with more shaley units. In present vadose conditions the shaley units are breaking down and failing, due to oxidation of iron-bearing phases and hydration of clays, whereas the limestone units (which were more soluble under phreatic conditions) now form resistant beds (Fig.11).

3.5. Breakdown by weathering of fractured bedrock

Sebela (1996, 1998) has demonstrated that a strong relationship exists between breakdown chambers and crush zones related to faults. As well as weakening the fab-
Fig. 11 - Weathering bedrock in cave wall, GB Cave, Mendip Hills, England. Note that dark, impure shaley beds are failing, whereas purer limestone (pale) is more resistant under vadose conditions.

ric of the rock these zones provide easy access for percolation water, and thus both vadose dissolution and precipitation. Whereas vadose dissolution will open spaces between angular clasts in crush zones, and thus promote breakdown, vadose precipitation will cement them together and inhibit breakdown. In studying potential breakdown sites it is not enough simply to know that there are crush zones through which water is infiltrating. It is essential to establish if the water is opening the zones by dissolution, or sealing them by precipitation.

Zupan-Hajna (1997) showed that, in addition to bedrock fragments, crush zones contain fines infiltrating slowly from the surface, loam deposited into fracture zones during floods and tectonic clay produced by pressure solution of the limestone along the faults. While they remain in-situ, these materials may help to stabilise the fractured rock, particularly if they are cemented. Their removal, however, will tend to activate breakdown.

4. Some practical implications

4.1. The need for in-cave investigation

Many of the materials whose weathering is the focus for breakdown will not be recognised by geological or geotechnical surveys of the limestone surface. This is particularly the case with dykes, sills and palaeokarst bodies. Surface investigations,
and conventional approaches such as drilling and geophysical techniques (which are notoriously unreliable in cavernous karst), will not enable either the mechanism driving breakdown or its likely outcome to be determined.

Subsurface investigations by specialists familiar with the cave environment are essential when breakdown is being investigated, or if it is suspected as being a geotechnically significant process.

4.2. Most cave breakdown has no immediate surface effect

Active breakdown zones and inactive breakdown piles are common features of limestone caves, but few are related directly to failure and subsidence of the land surface, and most do not represent a threat to the integrity of natural cave cavities.

It is commonly difficult for those whose principal experience is in dealing with artificial cavities, such as mines and tunnels, to appreciate how stable natural cavities (lacking props, beams and rock bolts) actually are.

4.3. Caves are difficult to destroy

Whereas caves are highly vulnerable environments and their contents are very easily damaged, physically destroying caves (i.e. causing the cave void to fail) is quite another matter. Attempts by limestone miners to destroy caves in limestone quarries in eastern Australia (e.g. at Mt Etna, Queensland, Fig.1) proved to be quite unsuccessful (Osborne, 1994). Similarly fragile mineral deposits are frequently discovered in relatively intact conditions in caves intersected by quarries (see, for example, Leel-Ossy and Vigassy, 2001).

It would appear that the only reliable way to destroy cave voids is to emulate natural processes and remove the enclosing rock from around them. The final natural failure of cave voids, producing “unroofed caves” (Mihevc et al, 1998) may well be due more to surface lowering removing the roof from above the cave (see Kortnik and Šušteršič, 2000, and Kortnik in this volume), than to breakdown stoping removing the ceiling from below.

4.4. Breakdown processes are promoted by infiltrating water

The weathering processes that can trigger breakdown are promoted by contact between metastable Earth materials and fresh oxygenated water. Water acts to lubricate discontinuities between disarticulating blocks, promoting their separation from the rock mass. Infiltrating water will also wash out clay and crushed fines from between blocks in fracture zones. With breakdown, as with many other karst processes, avoiding the concentration of surface drainage is an important management consideration.

4.5. Weathering of pyrite is a powerful agent for promoting breakdown and stoping

Weathering of pyrite has a two-fold effect on carbonate rocks, firstly it releases strong acid to dissolve them and secondly, where the reaction products are not quickly washed away, it results in the growth of gypsum crystals, which wedge the rock apart. It is crucial that beds and rock masses (e.g. palaeokarst deposits) that contain weathering pyrite are identified in any investigation of breakdown.
4.6. Surface failure may result from more than one process
Whereas surface failure in karst is usually the result of unconsolidated materials fail­ing, more than one process (see above and Klimchouk and Andrejchuk in this vol­ume) may be contributing to the outcome. This is another reason why it is essential to investigate karst sites from both inside and out, rather than basing solutions on information derived from the surface and on literature-derived knowledge of internal processes.

REFERENCES

KLIMCHOUK A. and ANDREJCHUK V. (This volume). Karst breakdown mechanisms from observations in the gypsum caves of the Western Ukraine: implications for subsi­dence hazard assessment.


The term karst breakdown is employed in this paper to denote the totality of processes and phenomena of gravitational and/or hydrodynamic destruction of the ceiling of a karst cavity and of the overlying sediments. It refers not only to the existence of a surface subsidence (collapse) feature but, first of all, to the “internal” (hidden in the subsurface) structures that precede development of a surface form.

This study reports and discusses the results of direct mapping and examination of breakdown structures in the gypsum karst of the Western Ukraine, at the level of their origin, i.e. in caves. The accessibility of numerous laterally extensive maze cave systems in the region provided an excellent opportunity for such an approach, which made it possible to examine the relationship between breakdown structures and particular morphogenetic or geological features in caves, and to reveal stages of breakdown development.

It is found that breakdown is initiated mainly at specific speleogenetically or geologically “weakened” localities, which classify into a few distinct types. The most of breakdowns, which are potent to propagate through the overburden, relate with the outlet cupolas/domepits that represent places where water had discharged out of a cave to the upper aquifer during the period of transverse artesian speleogenesis. Distribution of breakdown structures does not correlate particularly well with the size of the master passages. Several distinct mechanisms of breakdown development are revealed, and most of them proceed in several stages. They are guided by speleogenetic, geological and hydrogeological factors.

The study confirms that a speleogenetic approach is indispensable to the understanding of breakdown pre-requisites and mechanisms, as well as for eventual subsidence hazard assessment. Direct observations in caves, aimed both at speleogenetic investigation and breakdown characterization on regional or site-specific levels, should be employed wherever possible.

KEYWORDS: karst subsidence, karst breakdown mechanisms, gypsum caves, speleogenesis, subsidence hazard assessment

1. Introduction

The term karst breakdown is used in this paper to denote the totality of processes and phenomena of gravitational and/or hydrodynamic destruction of the ceiling of a karst cavity and of the overlying sediments. Use of this more general concept avoids potential misconceptions that commonly arise from the ambiguous use of terms “col-
lapse” and “subsidence” in the literature. It has an additional advantage in that it does not refer to the existence of a surface subsidence (collapse) feature and includes “internal” (hidden in the subsurface) processes and phenomena that precede the appearance of a surface form.

Karst breakdown is complex, consisting of a number of processes, with components developing in various combinations, either simultaneously or sequentially. Some components may dominate during certain stages of the breakdown development, whereas others may occur throughout the entire process. The karst breakdown mechanism is understood here as a combination of specific component processes in a regular sequence, and their development in time and space.

An understanding of the karst breakdown mechanisms is crucial to subsidence hazard assessment, prediction and management in karst terrains. A set of component agencies and a shifting of the breakdown process proper (i.e. breakdown mechanism) depends on many factors and conditions, a combination of which is referred to here as “settings”. Analysis of the available literature on the subject suggests that the most important factors that determine settings are: 1) the presence and structure of the overburden, 2) lithological (geotechnical) properties of individual units in the cover, 3) hydrogeological conditions (especially piezometric levels and hydraulic gradients), and 4) degree of karstification and characteristics of the primitive initiating cavities.

Numerous accessible and laterally extensive cave systems in the Western Ukrainian gypsum karst provide excellent opportunities for direct examination and mapping and examination of breakdown structures at the level of their origin, i.e. in caves. Such observations and surveys are indispensable for an adequate understanding of conditions favorable to breakdown initiation and of mechanisms favorable to their development.

2. Geological and hydrogeological background to gypsum karst development

The Miocene gypsum sequence is widespread on the southwestern edge of the eastern European platform, along the Carpathian Foredeep, where it occupies over 20,000km². Gypsum stretches from the northwest to southeast for more than 300km as a belt ranging from several kilometers to 40 to 80km wide (Fig. 1A). It is the main component of the Miocene evaporite formation that girdles the Carpathian folded region to the northeast, from the Nida river basin in Poland across the Western Ukraine and Moldova to the Tazleu river basin in Romania.

Most Miocene rocks along the platform margin rest on the eroded terrigenous and carbonate Cretaceous sediments. The Miocene succession comprises deposits of Badenian (Tortonian) and Sarmatian age. The Lower Badenian unit, beneath the gypsum, includes mainly carbonaceous, argillaceous and sandy beds (30-90 m thick) adjacent to the foredeep, and these grade into rocks of calcareous biohermal and sandy facies (10-30 m thick) towards the platform interior. The overlying gypsum bed is variable in structure and texture. Most commonly it grades from microcrystalline massive gypsum at the lower part through variably grained bedded gypsum in the middle to giantocrystalline rock in the upper horizon. A layer of evaporitic and epigenetic limestone, locally called “Ratynsky”, commonly overlies the gypsum,
Miocene gypsum

I: gypsum entirely denuded
II: entrenched karst
III: subjacent karst
IV: deep-seated karst

Fig. 1 - Location of the gypsum karst of the Western Ukraine (A) and zonation of the region according to evolutionary types of karst (B). Zones of different karst types are labeled by Roman numbers: I = the gypsum is entirely denuded, II = entrenched karst, III = subjacent karst, IV = deep-seated (confined) karst.

ranging from half a meter to more than 25 m in thickness. The gypsum and the Ratynsky limestone comprise the Tyrassky Formation which is overlain by the Upper Badenian unit represented either by argillaceous and marly lithothamnion limestones and sandstone beds or, adjacent to the foredeep, by marls and clays of the Kosovsky formation. The latter grades upward into the Lower Sarmatian clays. The total thickness of the capping marls and clays ranges from 40-60 m in the platform interior to 80-100 m and more in the areas adjacent to the regional faults that separate the platform edge from the foredeep.
There is a distinct trend in the depth of the gypsum occurrence, position of the overall denudation surface within the Miocene succession and the depth of erosional entrenchment in the direction across the gypsum belt, from the platform interior towards the foredeep. The Tyrassky Formation dips 1 to 3° towards the foredeep and is disrupted by block faults in the transition zone. To the south and south-west of the major Dniester Valley, large tectonic blocks drop down as a series of steps, the thickness of clay overburden increases, and the depth of erosional entrenchment decreases. Along the tectonic boundary with the foredeep the Tyrassky Formation drops down to the depth of 1000 m and more. This variation, the result of differential neotectonic movement, played an important role in the hydrogeological evolution of the Miocene aquifer system and resulted in the differentiation of the platform edge into the four zones (Andrejchuk, 1984, 1988; Klimchouk et al, 1985; Klimchouk and Andrejchuk, 1988; Klimchouk, 1996, 2000). The gypsum was entirely removed by denudation within the 1-st zone, but other three zones represent the distinct types of karst: entrenched, subjacent and deep-seated (Fig. 1-B). The gypsum bed is largely drained in the entrenched karst zone, is partly inundated in the subjacent karst zone and remains under artesian confinement in the deep-seated karst zone.

In hydrogeologic terms the region represents the southwestern portion of the Volyno-Podolsky artesian basin (Shestopalov, 1989). The Sarmatian and Kosovsky clays and marls serve as an upper confining sequence. The lower part of the Kosovsky Formation and the limestone bed of the Tyrassky Formation form the original upper aquifer (above the gypsum) and the Lower Badenian sandy carbonate beds, in places along with Cretaceous sediments, form the lower aquifer (below the gypsum), the latter being the major regional one. The hydrogeologic role of the gypsum unit has changed with time, from initially being an aquiclude, intervening between two aquifers, to a karstified aquifer with well-developed conduit permeability (Klimchouk, 2000). Regional flow is from the platform interior, where confining clays and the gypsum are largely denuded, toward the large and deep Dniester Valley and the Carpathian foredeep. In the north-west section of the gypsum belt the confined conditions (zone IV) prevail across its entire width. In its wide south-east section the deeply incised valleys of Dniester and its left tributaries divide the Miocene sequence into a number of isolated deeply drained interfluves capped with the clays (Podol’sky area). This is the entrenched karst zone (zone II) where most of the explored, presently relict maze caves are located. To the south-southeast of the Dniester (Bukovinsky area) the gypsum remains largely intact and is partly inundated (the subjacent karst zone - III). Further in this direction, as the as the depth of the gypsum occurrence below clays increases and entrenchment decreases, the Miocene aquifer system becomes confined (the deep-seated karst zone - IV). In this zone the groundwater flow pattern includes a lateral component in the lower aquifer (and in the upper aquifer but to a lesser extent) and an upward component through the gypsum in areas of potentiometric lows, where extensive cave systems develop as evidenced by numerous data from exploratory drilling.

3. Speleogenesis

Fourteen large caves over 1km in length are known in the region. Most of these caves are presently relict. They are located north of the Dniester, within the 2nd zone
Table 1. Parameters of large caves and cave fields in the Western Ukraine

<table>
<thead>
<tr>
<th>No</th>
<th>Cave name*</th>
<th>Development, m</th>
<th>Specific volume m³/m</th>
<th>Density of passages, km²/km²</th>
<th>Areal coverage, %</th>
<th>Cave porosity, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Optimistychna</td>
<td>214000</td>
<td>2.8</td>
<td>147</td>
<td>17.6</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>Ozerna</td>
<td>111000</td>
<td>6</td>
<td>150</td>
<td>44.6</td>
<td>5.0</td>
</tr>
<tr>
<td>3</td>
<td>Mlynki</td>
<td>25000</td>
<td>3.3</td>
<td>141</td>
<td>37.6</td>
<td>3.4</td>
</tr>
<tr>
<td>4</td>
<td>Kristalna</td>
<td>22000</td>
<td>5.0</td>
<td>169</td>
<td>29.2</td>
<td>6.0</td>
</tr>
<tr>
<td>5</td>
<td>Slavka</td>
<td>9100</td>
<td>3.7</td>
<td>139</td>
<td>27.6</td>
<td>3.4</td>
</tr>
<tr>
<td>6</td>
<td>Verteba</td>
<td>7800</td>
<td>6.0</td>
<td>118</td>
<td>34.7</td>
<td>12.0</td>
</tr>
<tr>
<td>7</td>
<td>Atlantida</td>
<td>2520</td>
<td>4.5</td>
<td>168</td>
<td>30.0</td>
<td>4.0</td>
</tr>
<tr>
<td>8</td>
<td>Ugryn</td>
<td>2120</td>
<td>3.8</td>
<td>177</td>
<td>33.3</td>
<td>5.7</td>
</tr>
<tr>
<td>9</td>
<td>Jubilejna</td>
<td>1500</td>
<td>2.3</td>
<td>278</td>
<td>37.0</td>
<td>4.0</td>
</tr>
<tr>
<td>10</td>
<td>Komsomol'ska</td>
<td>1240</td>
<td>2.1</td>
<td>177</td>
<td>24.3</td>
<td>3.0</td>
</tr>
<tr>
<td>11</td>
<td>Dzhurinska</td>
<td>1130</td>
<td>2.4</td>
<td>126</td>
<td>17.8</td>
<td>2.0</td>
</tr>
<tr>
<td>12</td>
<td>Zoloushka</td>
<td>92000</td>
<td>8.0</td>
<td>142</td>
<td>48.4</td>
<td>3.8</td>
</tr>
<tr>
<td>13</td>
<td>Bukovinka</td>
<td>2400</td>
<td>2.5</td>
<td>120</td>
<td>21.5</td>
<td>4.4</td>
</tr>
<tr>
<td>14</td>
<td>Gostry Govdy</td>
<td>2000</td>
<td>1.7</td>
<td>270</td>
<td>17.5</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td>493820</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Averages</td>
<td>3.9</td>
<td>164</td>
<td></td>
<td>29.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

*The names are given here according to the Ukrainian spelling. In many other publications Russian spelling is common, where most of names ended here with "a", end with "-skaja" or "aja".

(entrained karst). Two other large caves, Zoloushka and Bukovinka, are in the Bukovinsky sub-region, near the Prut River, generally in the area of artesian flow within the Miocene aquifer system (4th zone) but within local, exceptionally uplifted blocks, where entrenchment into the upper part of the gypsum caused unconfined (water table) conditions to be established during the Holocene.

All the large gypsum caves in the region are mazes arranged into laterally extensive multi-storey networks, which have developed along vertical and steeply-inclined fissures. Interconnecting passages form lateral two- to four-storey systems that extend over areas of up to 1.5km². Such areas, termed here cave fields, are defined by drawing an arbitrary boundary closely enclosing the passages on a cave map. Significant morphological parameters of the caves are summarized in Table 1. Figs. 5A, 10, 11 and 12 illustrate some typical cave patterns.

Optimistychna Cave, with more than 214km of surveyed passages, is the longest gypsum cave and the second longest cave of any type known in the world. The
Western Ukraine contains the five longest known gypsum caves in the world, accounting for well over half of the total known length of gypsum caves on the Earth. By area and volume the largest caves are Ozernaja (330,000m² and 665,000m³) and Zoloushka (305,000m² and 712,000m³), followed by Optimisticheskaja Cave (260,000m² and 520,000m³).

The absolute parameters of cave systems change as exploration progresses. Specific parameters are more informative. Specific volume (the cave volume/length ratio, which is in fact the average area of passage cross-section) characterizes an average size of cave passages in a cave system. For the caves of the region this parameter ranges from 1.7 (Gostry Govdy Cave) to 8.0 (Zoloushka Cave) m³/m. The average value for the region is 3.9 m³/m. Passage network density is characterized conveniently by using the ratio of cave length to a unit area of the cave field (km/km²). This parameter varies within the region from 118 (Verteba Cave) to 278 (Jubilejnaja Cave) km/km², with an average value of 164 km/km².

The availability of detailed morphometrical data on caves and host rock bodies allows calculation of areal coverage and cave porosity parameters (fractions of the total area and the volume of the rock within a cave field occupied by passages). The areal coverage varies from 17.5 to 48.4 %, the average value being of 29.5 %. Cave porosity varies from 2 to 12 %, with an average value of 4.5 %.

Maze caves in the region have been developed (and are presently developing in the 4th zone) under confined conditions, due to upward transverse groundwater circulation between the sub-gypsum and supra-gypsum aquifers (Klimchouk, 1990, 1992, 1996, 2000). Such a flow pattern is characteristic of potentiometric low areas, related to topographic lows (valleys), which commonly coincide with zones of enhanced fluid conductivity created within the capping clays by tectonic or stratigraphical discontinuities. Overall discharge from artesian aquifer systems occurs in such areas. Under conditions of transverse circulation in a multi-storey artesian system, all available fissures in the gypsum, which hold similar positions within analogous flow paths, enlarge at comparable rates because of the availability of dispersed aggressive recharge from below and suppressed hydraulic competition due to constrained outflow. This behavior generally favors the development of maze cave structures, but the actual conduit arrangement in any given locality depends upon the initial fissure pattern.

Three major components can be distinguished in the cave systems based on shape, arrangement and hydrologic function of cave mesoforms during the main (artesian) speleogenetic stage (Figs. 2 and 3):

1. **Feeder channels**, the lowermost components in a system: vertical or sub-vertical conduits through which water rose from the sub-gypsum aquifer to the master passage networks. Such conduits are commonly separate but sometimes they form small networks at the lowermost part of the gypsum, along the top of the underlying bed. The feeder channels join master passages located at the next upper level and are scattered rather uniformly through their networks.

2. **Master passages**: horizontal passages that form laterally extensive networks within certain horizons in the middle part of the gypsum bed. They received dispersed recharge from numerous feeder channels and conducted flow laterally to the nearest outlet feature.

3. **Outlet features**: domes, cupolas and vertical channels (domepits) that rise from
Fig. 2 - Main morphogenetic features of maze cave systems in the Western Ukraine shown at their hydrologic functionality. 1 = feeder channels, 2 = master passages, 3 = outlet features

Fig. 3 - Examples of typical morphogenetic features in the caves:
1 = feeder channels, Mlynki and Ozerna caves;
2 = master passage, Dzhurinska cave;
3 = outlet features, Slavka and Optimystycha caves. Photo by A. Klimchouk.
the ceiling of the master passages to the bottom of the overlying bed. They discharged water from cave systems to the overlying aquifer.

Other typical features formed under modern entrenched karst conditions are vertical dissolution pipes, which grow due to a focused descending percolation from the overlying formations. They are 1 to 3m wide, extend downwards through the full thickness of the gypsum from its top, and are commonly superimposed upon relict artesian passages.

The Western Ukrainian maze caves provide the most outstanding and unambiguous evidence for the transverse artesian speleogenetic model. Artesian speleogenesis in the Podol'sky sub-region took place during the Late Pliocene through Early Pleistocene when the overall maze structure of caves became established. Breaching of artesian confinement and further incision of the valleys during the Middle Pleistocene caused substantial acceleration of groundwater circulation within the Miocene artesian system. The majority of passage growth, as well as breakdown formation, probably occurred during this transitional period. Where the water table was established in the gypsum for a prolonged time, further widening of passages occurred. Eventually, with the lowering of the water table below the lower gypsum contact, cave systems in the entrenched karst zone became entirely fossilized. Cave development under confined or semi-confined conditions continues today within the zones of deep-seated and subjacent karst (the 4th and 3rd zones).

4. Speleological observations of the breakdown formation and development: methods and criteria

The accessibility of numerous laterally extensive cave systems in the Western Ukrainian gypsum karst provides an excellent opportunity for direct mapping and examination of breakdown structures at the level of their origin. This allows almost all breakdown structures, which have evolved within a cave field, to be mapped, including those that are still hidden within the coverbeds and not manifested on the surface. Such mapping makes it possible to investigate the relationship of breakdown structures with particular morphogenetic and geologic features in a cave and to reveal stages of breakdown development. The state (quasi-equilibrium or non-equilibrium) of a breakdown structure can be judged and a degree of its propagation toward the surface through the cover (the height of a breakdown column – the depth of a migrating void below the surface) can be determined. Together with detailed data on lithostatigraphy, thickness and hydrogeology of the overburden, this reveals the breakdown mechanisms and facilitates subsidence hazard assessment for the respective areas with a precision and certainty unachievable by the approaches of conventional engineering geology. Such investigations make it possible to test the validity and adequacy of various indirect approaches to subsidence hazard assessment and the assumptions on which such approaches are based.

The following features were identified and mapped as breakdown structures in the caves (Fig.4):

1) Any outlet features (domes, cupolas and domepits in cave passages) indicating considerable breakout in the vault. Breakdown is identified by predominantly gravitational morphology of the vault and by the presence of disarticulated fragments of bedrock and coverbed materials beneath it.

2) Breakdown taluses in cave passages consisting of the fallen bedrock and
covered material. Depending on the initial dome diameter and the distance of upward stoping, such taluses can plug an access to the breakout cupola and separate the migrating void from the cave.

Breakdown structures in the Western Ukrainian gypsum karst normally develop in a number of stages through a prolonged period of time. The multi-stage development is determined by the stratified nature of the overburden which has varying lithological, geomechanical and hydrogeological properties of individual units. The stages are identified from a position of a cupola or a migrating void within the cover that, if not directly observed, can be inferred in most cases from the size, shape and composition of breakdown taluses. The state (quasi-equilibrium or non-equilibrium) of a breakdown structure can be additionally determined from the presence or absence of signs of recent activity in a breakdown talus (water seepage or flow, dampness of sediments, signs of creep or extrusion, etc.).
Such surveys were performed in several caves developed in different geological and hydrogeological settings and representing different morphological character: in Zoloushka Cave (subjacent karst settings), Mlynki, Slavka and Verteba caves (entrenched karst settings).

5. Breakdown development in the subjacent karst zone: Zoloushka Cave and the Dankivsky Collapse

Zoloushka Cave (Fig. 5A) is the third longest gypsum cave in the world with 92km of passages mapped since 1976 when few entrances were opened in the face of an active gypsum quarry. The cave area lies generally in the confined karst zone, although in some of the more uplifted tectonic blocks (where the gypsum was partially entrenched by the nearby major Prut Valley during the Holocene) the groundwater surface is some 2 to 3m below the gypsum top. The quarry operation and accompanied groundwater withdrawal since 1950s caused the water table to further drop 17 to 19m below the gypsum top and brought about considerable transformations in the karst system. The cave was thoroughly studied in various aspects (Andrejchuk, 1984, 1988, 1999; Andrejchuk and Korzhik, 1984) and provides an excellent playground for examination of karst breakdown mechanisms.

5.1. Local settings

Local geomorphological and geological settings are depicted on Fig. 5, B and C. The gypsum in the cave area has a thickness of 23 to 25m, being overlain by the microcrystalline grey - light brown Ratynsky limestone, up to 1m thick. The Kosovsky Formation, 5 to 60m in thickness (depending on the local relief), spreads over the cave area. It comprises mainly argillaceous sediments of grayish-blue color, with some minor sandstone and limestone beds in its lower part. The clays consist predominantly of montmorillonite (up to 38%) and hydro-illite (25 to 30%), and are massive in the lower part of the formation and thinly-bedded in the upper part. The main geotechnical characteristics of the clay are as follows: natural humidity - 17 to 18%, plasticity index - 28, density - 2.1 g/cm³, skeletal volume weight - 1.77 g/cm³, porosity - 35.6%. Above the Kosovsky Clays the Quaternary alluvium of the upper (III to IV) Prut terraces is present, comprising sandy-gravel (immediately above the Kosovsky Clays) and loam sediments. The loams, ranging from a few to 19m in thickness, are light and porous. The soil layer, 0.5 to 1.2m thick and rich in humus (2.7 to 6.4%), lies on the top.

The gypsum rests on the sands and marls of the Lower Badenian (3 to 4m), which in turn overly the eroded Cretaceous limestones and sandstones. Together they form the presently unconfined aquifer, which also includes the lower part of the gypsum. Under natural conditions the aquifer discharged to the Prut River through the terrace sediments. During the quarrying stage a depression cone due to water withdrawal from the quarry deformed the groundwater surface in the cave area. The Quaternary aquifer is also present, being perched on the Kosovsky Clays, although in the cave area it is increasingly drained by breakdown structures that disrupt the clay succession.

5.2. Dewatering of the cave

The quarry that opened the cave started at the end of 1940s. Since then, groundwaters have been continuously abstracted from the quarry and a drawdown cone has
Zoloushka Cave

Fig. 5 - A = The map of Zoloushka cave (courtesy of the Chernovitsky Speleological Club), B = Geomorphological map of the area, C = Geological cross-section across the cave field.
formed around it. In the beginning the withdrawal rate was rather modest amounting about 20 to 50 m$^3$/hour. When the quarry had deepened up to 8 to 10 m, the pumping rates increased to 100 to 500 m$^3$/hour. Since the mid-1960s, with the cutting of the third quarry bench to the depth of 18 to 22 m, groundwater inflow reached 700 to 800 m$^3$/hour and this rate was maintained until nowadays.

Before the quarry, the groundwater level had been situated at about 2 to 3 m below the gypsum top, some 1 to 2 m below the ceiling of Zoloushka’s upper storey passages. The groundwaters circulated slowly toward the Prut River and discharged through the alluvium. They contained considerable amount of H$_2$S and dissolved solids (3.0 to 4.5 g/L). With the start of the operations, the quarry became the drainage focus. Within the drawdown cone that expanded up to several kilometers in diameter, groundwater flow changed to radial, with a considerable increase of flow rates, decrease of TDS content (up to 1.9 to 2.6 g/L) and H$_2$S degassing.

The lowering of the piezometric surface and dewatering of the cave had progressed most during the 1960s. In the first period of the cave exploration (1976 to 1978) passage bottoms were covered by “fresh” wet slippery clay, progressively desiccating and shrinking in the following years with overall decrease in volume and the formation of characteristic crack patterns. The floor level in most passages has lowered by 1 to 2 m and the volume of passages has increased by 25 to 35% since the time of the first exploration. This apparently contributed to an activation of the pre-existing breakdown structures that rested on the cave fill. The lower storey of the cave remains inundated, being located below the water table.

5.3. Cave morphology

Zoloushka Cave is a labyrinth of horizontal passages occurring in two storeys. The upper storey consists predominantly of large passages (average width and height are respectively 2.8 m and 3.0 m; specific volume is 8.0 m$^3$/m) with ceilings located 1 to 3 m below the gypsum top (Fig. 6A and B). Their cross-sections are oval, rhomb-like or hemispherical. Numerous solution domes (1 to 5 m in diameter) in the passage ceilings expose the overlying Ratynsky limestone bed. Such domes were outlets for the water to the overlying aquifer during the period of transverse artesian speleogenesis. In some areas large closely spaced passages coalesce laterally, with only small pillars remaining in between them (Fig. 6C). This is due to horizontal notching by preferential dissolution at the water table during the Holocene (Fig. 6B and C). In this way some quite large (15,000 to 30,000 m$^3$) chambers were formed. In areas where the level of clay filling lowers, it is possible to observe 3 to 10 m-deep rift-like extensions in the bottoms (Fig. 6D), otherwise obscured by the filling. Thus, the entire cross-sections commonly have “keyhole” shapes, with the width of the rift part from 0.3 to 3.0 m. The lower storey of the cave, still inundated and explored only in fragments, lies along the bottom of the gypsum. It is connected with the upper level through large pits (feeders), whose morphology indicates “ascending” hydraulic communication during the cave formation period.

The cave map (Fig. 5A) displays only the upper storey passage network. Sixteen morphological regions are distinguished in the cave, according to characteristic passage size and the structural peculiarities of the patterns. The differences in passage sizes are illustrated by the specific volume parameter varying between regions from 5.1 to 16.1 m$^3$/m (Table 2).
5.4. Breakdown structures

About 70% of the maze has been covered with a special mapping of breakdown structures (BS). At least 700 breakdown structures were found in the cave, over 630 of which were mapped and documented according to the criteria outlined in the previous section. This gives an average density of breakdown structures for the whole cave field of about 1800 per km$^2$.

**Breakdown initiation.** A great majority of breakdown structures initiate and develop where solution domes and cupolas have exposed the bottom of the overlying Ratynsky Limestone bed to the cave. Speleogenetically, such domes and cupolas represent the outlet features through which the water discharged from the cave during the period of transverse artesian speleogenesis. The Ratynsky bed is less than 1m
Table 2: Morphometric characteristics of the regions of Zoloushka cave and breakdown distribution by the regions.

<table>
<thead>
<tr>
<th>Name of the region</th>
<th>Length, m</th>
<th>Averages</th>
<th>Passage area, n1000m²</th>
<th>Passage volume, m³/n1000m³</th>
<th>Specific volume, m³/m²</th>
<th>Area of cave field, n1000m²</th>
<th>Number of BS</th>
<th>BS density per km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Privkhodovoj</td>
<td>5,600</td>
<td>2.7 2.2</td>
<td>15.2</td>
<td>33.8</td>
<td>6.0</td>
<td>39.2</td>
<td>105</td>
<td>2,679</td>
</tr>
<tr>
<td>Zabludshikh</td>
<td>4,330</td>
<td>2.4 2.7</td>
<td>10.5</td>
<td>28.7</td>
<td>6.6</td>
<td>30.3</td>
<td>42</td>
<td>1,386</td>
</tr>
<tr>
<td>Perspektiv</td>
<td>1,237</td>
<td>3.5 3.0</td>
<td>4.4</td>
<td>13.3</td>
<td>10.8</td>
<td>8.7</td>
<td>31</td>
<td>3,580</td>
</tr>
<tr>
<td>Chernovitskij</td>
<td>3,919</td>
<td>3.7 3.2</td>
<td>14.4</td>
<td>45.7</td>
<td>11.7</td>
<td>27.4</td>
<td>68</td>
<td>2,479</td>
</tr>
<tr>
<td>Majsky</td>
<td>1,424</td>
<td>2.1 2.7</td>
<td>3</td>
<td>8.1</td>
<td>5.7</td>
<td>10.0</td>
<td>15</td>
<td>1,505</td>
</tr>
<tr>
<td>Central'ny</td>
<td>7,880</td>
<td>2.6 2.9</td>
<td>20.3</td>
<td>59.7</td>
<td>7.6</td>
<td>55.2</td>
<td>14</td>
<td>254</td>
</tr>
<tr>
<td>Zapadny</td>
<td>5,015</td>
<td>2.8 2.7</td>
<td>13.6</td>
<td>38.4</td>
<td>7.7</td>
<td>35.1</td>
<td>26</td>
<td>741</td>
</tr>
<tr>
<td>Anakonda</td>
<td>3,891</td>
<td>2.7 2.9</td>
<td>10.5</td>
<td>30</td>
<td>7.7</td>
<td>27.2</td>
<td>50</td>
<td>1,836</td>
</tr>
<tr>
<td>Vesely</td>
<td>5,317</td>
<td>2.2 2.3</td>
<td>11.8</td>
<td>27</td>
<td>5.1</td>
<td>37.2</td>
<td>59</td>
<td>1,585</td>
</tr>
<tr>
<td>Metropoliten</td>
<td>2,337</td>
<td>3.7 3.7</td>
<td>8.3</td>
<td>37.6</td>
<td>16.1</td>
<td>16.4</td>
<td>5</td>
<td>306</td>
</tr>
<tr>
<td>Ozerny</td>
<td>4,228</td>
<td>3.1 3.8</td>
<td>12.9</td>
<td>49.1</td>
<td>11.6</td>
<td>29.6</td>
<td>38</td>
<td>1,284</td>
</tr>
<tr>
<td>Goticny</td>
<td>4,091</td>
<td>3.4 4.5</td>
<td>12.4</td>
<td>56.2</td>
<td>13.7</td>
<td>28.6</td>
<td>63</td>
<td>2,200</td>
</tr>
<tr>
<td>Vostochny</td>
<td>4,769</td>
<td>3.1 3.6</td>
<td>14.7</td>
<td>53.1</td>
<td>11.1</td>
<td>33.4</td>
<td>60</td>
<td>1,797</td>
</tr>
<tr>
<td>Dal'nevostochny</td>
<td>2,414</td>
<td>2.3 3.4</td>
<td>5.6</td>
<td>19</td>
<td>7.9</td>
<td>16.9</td>
<td>21</td>
<td>1,243</td>
</tr>
<tr>
<td>Kamchatskii</td>
<td>1,084</td>
<td>2.4 2.4</td>
<td>2.6</td>
<td>6.3</td>
<td>5.8</td>
<td>7.6</td>
<td>40</td>
<td>5,271</td>
</tr>
<tr>
<td>Geochemichesky</td>
<td>5,000</td>
<td>2.6 2.5</td>
<td>16</td>
<td>30</td>
<td>6.0</td>
<td>35.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>62,536</strong></td>
<td><strong>176.5</strong></td>
<td><strong>536</strong></td>
<td><strong>637</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td><strong>2.8</strong></td>
<td><strong>3.0</strong></td>
<td><strong>8.8</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>1,876</strong></td>
</tr>
</tbody>
</table>
| Correlation between BS number and the variables | 0.31 | 0.05 | -0.16 | 0.36 | 0.2 | -0.14 |}

thick and is normally rather densely fissured and brecciated. It falls readily when exposed from below by the outlet features, giving rise to the formation of BS. In places where the Ratynsky bed is coarsely fractured and exposed by occasional block fall-ins, it provides an effective support for the ceiling. It is likely that most of BS in the cave was initiated during the period of transition from confined to unconfined conditions, due to the loss of buoyant support.

Mechanisms of the breakdown development. Among the structures examined, none was found to display signs of a single massive collapse of the cave roof and overburden. All BS demonstrate more or less prolonged multi-stage development. This is determined mainly by the stratified nature of the coverbeds. Five to six distinct stages are distinguished in the breakdown formation (Fig. 7).

The preparatory stage is not considered as a part of the breakdown mechanism proper, although it creates distinctive morphogenetic features, namely the outlet features (dome shafts, domes and cupolas) favoring breakdown occurrence. This stage coincides with the late artesian speleogenetic stage, and is marked by the growth in the area of the Ratynsky bed exposures at the vaults of outlet domes and cupolas.

The first stage of breakdown-proper is the failure of the Ratynsky bed into the cave and the formation of a breakout (gravitational) cupola in the lower part of the Kosovsky Formation (up to 1 to 2m above the gypsum top). It is, therefore, the stage of active development. A breakdown pile consisting of the limestone blocks and
some clayey debris is formed beneath a cupola. The first stage itself can be short, probably one fall-in event in many cases, but it is followed by a prolonged period of relative stability (second stage).

The second stage is marked by gradual upward stopping of a breakout cupola through the Kosovsky Clays. Destruction of the material at the cupola vault occurs as slab and chip breakdown, rarely as block breakdown (i.e. fallen rock masses span more than one bed; White and White, 2000). The fallen argillaceous material forms distinct breakdown taluses (cones) that can vary in volume from a few to many tens of cubic meters. This stage can span quite long periods, probably in the order of thousands to tens of thousands of years. Its duration depends upon the local properties of the Formation and its thickness in a given cave region; the latter varies between a few to 60m, depending on the local relief. Many breakdown structures at this stage still provide access from the cave to a stopping cupola, although when the structure reaches some height, it gets separated from the cave by a breakdown pile. Because of this, one can estimate further migration of the void and passage of BS to the next stage only on the basis of the composition of the talus material at the base. If it contains some admixture of sandy-gravel material, then the BS has reached the Quaternary bed and passed to the next stage.

The third stage begins when a migrating void has reached the sandy-gravel bed of Quaternary alluvium. Two distinct mechanisms of the further development are revealed (Figs. 7, A and B). Which one occurs in a given locality depends on the presence of groundwater in the Quaternary sandy-gravel bed. Mechanism A predominated in the past, probably during the period commencing some tens of thousands years
ago when the Miocene aquifer lost its confinement (i.e. when breakdown processes had intensified for the first time due to the loss of buoyant support). This continued until some 40 to 30 years ago, when breakdown development intensified again due to the start of quarrying and pumping, and related lowering of the water table and subsequent transformations in the cave system. Mechanism B predominates now, when the Quaternary aquifer is largely drained across most of the area, as breakdown structures and exploration boreholes provided numerous points of vertical leakage through the Kosovsky Formation.

Mechanism A: When a migrating void reaches a sandy-gravel bed that contains groundwater, hydrodynamic component processes, such as liquefaction, piping and erosion become involved in the overall breakdown development and become predominant during the third and fourth stages. Breakdown of the last remaining portion of the Kosovsky Clays, along with some sandy-gravel material, causes liquidation of a void at the top of the BS because of sand liquefaction and the formation of a zone of thinning that extends laterally along the sandy horizon as a reversed wide-angle cone (the fourth stage; see Fig. 7A). The vertical breakdown structure enables leakage of the water from the aquifer, accompanied by further material removal by piping and erosion. Wetting of the clayey column causes its settlement down into the cave, further increasing the zone of thinning. All this leads to sagging of the overlying loam sequence, with the eventual appearance of surface deformation in the form of gradual subsidence. The rate and the depth of surface subsidence depend on the intensity of the leakage and piping, and on the rate of the erosion and settling of the breakdown column.

It is important to stress that Mechanism A results in a gradual subsidence type of surface deformation, not collapse. Analysis of historical data and large-scale topographical maps for the pre-quarrying period supports the view that gradual subsidence was the prevailing type of deformation in the recent past. However, Mechanism A is still operative in a few breakdown structures where Quaternary beds still host lenses of groundwater. This is indicated by active filtration along some breakdown columns. There have been occasional direct observations of drastic activation of a breakdown cone, with apparent settlement and extrusion of wet clays down into the cave and release of a considerable amount of water within few hours. On the surface the related pre-existing gentle subsidence was reactivated, with the formation of fresh concentric cracks up to 2m deep and up to 0.3m wide.

Mechanism B: This occurs where the Quaternary sandy-gravel horizon is drained and does not contain water. This situation has become increasingly predominant in the cave area since the start of quarrying and related groundwater abstraction from the main Miocene aquifer. This caused reactivation of pre-existing breakdown structures and formation of new ones that, together with numerous exploration boreholes, created a closely spaced pattern of leakage points from the perched Quaternary aquifer. This eventually caused the aquifer to drain throughout most of the area.

The differences between the mechanisms start from the third stage (see Fig. 7B), which begins when a stoping void reaches the sandy-gravel bed. This stage signifies a non-equilibrium state. The void does not transform into a thinning zone as in Mechanism A but instead it grows quickly by crumbling until it reaches the overlying loam horizon that is able to support arching.
The fourth stage (quasi-equilibrium state) includes further void stoping through the loam horizon. It occurs gradually by crumbling. As the void approaches the soil horizon, the destruction process is increasingly influenced by daily and seasonal changes of temperature and moisture content.

The fifth stage (non-equilibrium state) occurs in most cases as a single catastrophic event, i.e. as a collapse of the remaining roof of a void, with eventual appearance of the surface feature. Depending on local conditions, it can occur either when some part of the loams still remains at the roof or when arching is supported solely by the soil horizon. The latter case is common (with a roof thickness of about 0.3 to 1.0m), as rhizomes reinforce the soil in unploughed areas. Failure can be induced by extreme wet or dry periods, seismic events (blasting in a nearby quarry), application of additional load and ploughing. It is quite common that formation of concentric cracks and shallow subsidence precedes collapsing. Final collapse events are commonly accompanied by noise and dust ejection. This indicates that the roof collapses into a void that is already separated from the main cave. The newly formed collapses have a diameter of 3 to 5m, depth of 2 to 5m and a bottle-like cross section (the diameter at the base is 10 to 40% larger than the diameter at surface level).

The full development sequence is described above. However, some variations are possible toward the reduction of the number of stages due to: 1) the presence of structural or lithological discontinuities and irregularities in the overburden and, 2) incomplete thickness and composition of the overburden, such as in the lower (IId) terrace, where the Kosovsky Formation is only a few to 10m thick and the sandy-gravel and loam beds are entirely removed. Also, the last stage, that is the appearance of the subsidence or collapse at the surface, may never occur where the thickness of the overburden is large enough to cause self-liquidation of the stoping void (this point is discussed further below).

Distribution of breakdown structures. The resultant map shows most of the breakdown structures existing in the cave field, regardless of whether or not they are expressed at the surface (Fig. 8A). The mapped breakdown structures were classified according to their stages of development, as described above.

The survey data suggest that the overall density of breakdown structures for the whole cave field is more than 1800 per km$^2$. However, this parameter varies substantially between cave regions, from 254 BS/km$^2$ in the Central’ny region to 5271 BS/km$^2$ in the Kamchatka region. As the regions differ in size and morphology of passages and in the characteristics of their patterns, it is important to examine possible relationships between the number of breakdown structures and parameters of passages and their patterns in particular regions. Respective correlation coefficients are given in the last row of Table 2.

As can clearly be seen all the variables characterizing passage size show no appreciable correlation with the BS number. This agrees well with observations in the caves. Whereas some of the largest cave passages (up to 20m wide and 10m high; see photos on Fig. 6 for instance), being closely spaced and separated by only small pillars, host no or few breakdown structures, other much smaller passages contain many breakdowns. It is further illustrated by some details of the dataset under examination. The Metropolitan region, which consists of large passages (specific volume 16.1 m$^3$/m) has one of the lowest breakdown structure densities (306 per km$^2$), whereas the Kamchatka region, with a specific volume of 5.8m$^3$/m has the highest
Fig. 8 - The fragment of the map of breakdown structures in Zoloushka cave (A), the profile showing different stages of their development - the heights of their propagation to the surface (B) and the map of micro-zoning of the territory according to subsidence hazard. A key to the Fig. 7A:
1 = cave passages;
2 = passages destroyed by the quarry;
3 = isopachytes;
4 - 7 = breakdown structures with the breakout cavities positioned at various levels: 4 - at the bottom of the Ratynsky bed, 5 - within the Kosovsky Clays, 6 - within the sandy-gravel bed, 7 - within the loam bed;
8 = surface karst features; 9 = the quarry faces

Areas of:
- very high hazard
- high hazard
- medium hazard
- low hazard
- non-classified
- sinkhole
breakdown density. The above finding is in striking contrast with established views, which suggest that breakdown formation is controlled primarily by passage size.

The lack of correlation between BS number and passages size agrees well with the observation, mentioned above, that the vast majority of breakdowns in the cave initiate and develop from solution domes and cupolas that expose the bottom of the overlying Ratynsky limestone bed to the cave. Even a rather small-sized outlet cupola that exposes a few m² of the Ratynsky bed may give rise to the formation of breakdown structures. In contrast, large spans of master passages tend to remain stable if no outlet features occur. The causal relationship of breakdown formation and the outlet features is discussed further below, in more general speleogenetic terms.

**Site-specific collapse/subsidence hazard assessment.** As the BS development stage signifies a certain level reached by a stoping void in a given geological cross-section, one can readily deduce the depth of a void position below the surface by superimposing the isopachyte map on the breakdown map (Figs 9, A and B). These data allow the main questions of engineering karstology, about where and at what depth voids stoping through the overburden located, to be answered with great precision. Adopting a hazard categorization based on an understanding of the breakdown mechanisms, one can produce a map of the micro-zoning of the territory according to the degree of subsidence/collapse hazard presented at the surface (Fig. 8C). On this map some arbitrary categorization of the hazard is used that reflects the depth of the stoping void below the surface and a relative probability of the collapse/subsidence deformation at the surface. Areas of low, moderate, high and very high hazard are distinguished. Depending upon the overburden thickness, the same breakdown stages can cause different degree of hazard: the lower thickness, the earlier stage can result in the surface appearance of the collapse. The blank areas within in the cave field are non-hazardous, although the blank areas outside the cave field limits are non-classified, and because of this, evaluation is based on the direct mapping in the cave. Hence, the areas outside cave field cannot be assessed in the same way.

Another question important to hazard assessment is that of the possible size of collapse/subsidence when it appears to the surface. The answer can be inferred from the above description of the breakdown mechanisms. The main gauging factor is the diameter of the outlet domes/cupolas, initiating breakdown at the level of the cave. Most commonly it varies between 1 and 5m. The processes involved during the first three stages result in upward stoping without appreciable increase of the void at the top of the breakdown column. Mechanism A (the subsidence mechanism) implies a possible increase of the subsidence-prone zone of 2 to 3 times, because of lateral extension of the thinning zone in the aquiferous sandy horizon. This determines the expected size of subsidence at the surface to be within a few to 15m. Development according to Mechanism B (the collapse mechanism) can cause an increase in the expected diameter of the surface collapse in only 30 to 50% of the initial breakdown column diameter. Hence, the possible collapse size is 2 to 8m, which agrees well with the actual sizes of newly formed collapses.

**5.5. The Dan’kivsky collapse**

The Dan’kivsky area is located 12km north of Zoloushka Cave, still within the subjacent karst zone. The Collapse formed suddenly, on January 11 1998, on a gen-
tle slope of a small stream valley. According to local people the noise of the collapse was heard at a farm lying about 1km from the site. A 22m-deep shaft has formed, with an open entrance to a cave at the bottom (Fig. 9A). The shaft walls exposed the clays of the Kosovsky Formation, which graded into loams in the upper part. The walls displayed fragments of slickensided rock, which suggests that the collapse occurred along a fault. This is also supported by the presence of leakage patterns at the contact between the soil and loams in the upper part of the walls, which indicate prolonged vertical percolation along the fault at the site of the subsequent collapse.

The bottom of the shaft was almost entirely occupied by breakdown material. Its arrangement (the presence of large blocks of clay with fragments of slickensided material) suggests a single-event collapse. From the top of a breakdown pile it was possible to climb down into a chamber, a widened and domed part of the passage where 1.5m airspace occurred in the otherwise totally inundated cave (see plan and profile on Fig. 9, B and C). A water-filled passage, about 8to 9m wide and 7m high
continued in a NE direction. The cave was surveyed in April, and in May it became inaccessible due to the continuing filling of the entrance shaft by loose sediments. By October, the shaft was already transformed into a bowl-shaped sinkhole 4m deep. It is evident that this surface feature will soon assume a gentler shape, quite similar in morphology to numerous subsidence features identified in the vicinity.

The sinkhole mouth lies at an altitude of 173m, some 8.3m above the bottom of the small valley and 67.3m above the floor of the Dniester Valley some 5km to the north. The bed of the surface stream in the local valley is 19.2m above the groundwater table exposed in the cave, so that the stream is perched on the clays above the vadose zone. In April, the water table was at 2.7m below the top of the gypsum.

The form of the documented part of the cave suggests that it is a fragment of an extensive maze cave system analogous to Zoloushka Cave. Morphology and passage size are quite similar. This analogy is also supported by geophysical survey results indicating a labyrinthine pattern in the vicinity of the collapse.

The Dan’kivsky collapse exemplifies a rare case of a sudden single-event collapse. It occurred along a prominent fault (probably two closely related faults) at a locality where the presence of the underlying enlarged cave passage with a cupola (an outlet?) had reduced stability to a critical level. Percolation along the fault had reduced friction within the clay along the fault plane, and this further conditioned the collapse to occur through the entire thickness of the clays.

Another important lesson from the Dan’kivsky case is that the shape of a surface form is not necessarily indicative of its collapse (sudden) or subsidence (gradual) origin. With the presence of soft sediments within the overburden, an original collapse shaft can be transformed into a gentle-sloped doline within few years.

6. Breakdown development in the entrenched karst zone: Mlynki, Slavka and Verteba caves

The zone of entrenched gypsum karst in the Western Ukraine lies mainly to the north of the Dniester valley (Podol’sky region). The deeply incised river valleys of Dniester and its left sub-parallel tributaries separate the Miocene sequence into a number of isolated deeply drained interfluves where the gypsum and clay overburden remain largely intact. The Miocene sequence is almost entirely drained and only in the central parts of the inter-valley plateaus do the sub-gypsum units contain unconfined underground water, locally occupying also the lowermost part of the gypsum. Maze cave systems in the gypsum are presently relict. Modern dissolution is restricted to the lower part of gypsum, where the water table is present, at rare points of focused vertical percolation (where vertical dissolution pipes develop) and along short linear underground streams that are fed via swallow holes that receive periodic surface flow. Sinkholes are generally few within the high interfluves, but their density increases locally where the capping clays are removed, as within high river terraces or the floors of perched valleys.

When compared to the settings of the Zoloushka area there are some distinctly different features in the litho- and hydrostratigraphy of the overburden, and these are important to breakdown development:

- The 2 to 5m-thick Upper Badenian unit, which immediately overlies the Ratynsky bed, is composed of marly lithothamnion carbonates (the Ternopol’sky
This material is capable of crumbling gradually, to support breakout cupola development.

- The formation lying next above is represented by massive, rather homogenous, fine marine clays (the Lower Sarmatian) up to 60m in thickness depending on local relief. This material is quite coherent when dry, and if it is thick enough it can prevent further upward migration of a void. However, where wet (along tectonic or stratigraphical discontinuities that support groundwater percolation across the otherwise almost impervious thickness), it demonstrates a kind of viscous-flow behavior, and can be extruded into the cave through breakdown structures, like toothpaste from a tube. Also, the Sarmatian clays can shift down as blocks, by sliding between two closely spaced faults if cave and breakdown development result in a decrease of support from below.

- Alluvial pebble/gravel sediments of the ancient upper terraces of Dniester occur overlying the clays. In most of the region these are effectively drained due to the high degree of erosional dissection. Hence, Mechanism A of the breakdown development described for the Zoloushka Cave area does not operate in the Podol'sky region.

These peculiarities lead to some distinctive variations in the breakdown development in the entrenched karst zone, as compared to the development in the subjacent and deep-seated karst zones described above.

6.1. Mlynki Cave

The cave lies at the northern edge of the entrenched karst zone. The entrance opens into a valley slope within the gypsum outcrop. The thickness of the overburden increases to 25 to 30m towards the plateau. Only two sinkholes are recorded at the surface within the explored cave field.

The cave is a maze, currently surveyed for 26km, in which passages occur on two levels. In the upper level the passages are mainly slot-like in shape, 1 to 2m wide and up to 5m high. In the lower level passage cross-sections are commonly wider, and many have a rift extension down to the base of the gypsum.

Complete mapping of breakdown structures has been performed for five cave regions, enabling estimation of density values. In total, 144 breakdown structures have been mapped (Fig. 10). In 57 cases breakout cupolas at the top of BS are positioned within the Ternopol'sky carbonate bed and are accessible from the main cave. In 87 cases migrating voids are separated from the cave by breakdown talus. Only in few breakdown structures is the Sarmatian clay identified in the talus, indicating unambiguously that the stoping void had entered the clay thickness above the Ternopol'sky bed. Almost all breakdown structures in Mlynki Cave developed from outlet cupolas (see photos on Fig. 4, A and B).

The extrapolated density of breakdown structures varies from 700 to almost 3000 per km² between cave regions, with the average value for the whole set being 1609. These characteristics are quite similar to Zoloushka Cave despite the many differences in passage size, morphology and geohydrological setting. This can be explained by the similarity of the initiation conditions, by the fact that in both cases breakdown structures initiate from outlet cupolas/domepits. Hence, these morphogenetic features impose the most important control of breakdown initiation and distribution. However, in contrast to the Zoloushka area, most of the breakdown struc-
Breakdown talus, no access to a stoping cavity
○ Breakout cupola in the overburden

Density of breakdown structures in different cave regions, n/km²:
- Central'ny 700
- Pivnichny 1610
- Peremoga 1365
- Rizdvjany 1418
- Schasttyvy 2951
- Average 1609

Fig. 10 - Breakdown structures in Mlynki Cave. The cave map is a courtesy of the Chortkiv Speleological club. Breakdown survey has been performed with an assistance of Vladimir Snigur

Breakdown structures do not reach the surface and they remain stable and hidden in the subsurface after reaching the base of the Sarmatian clay. This reflects the fact that both the cave and the overburden are fully drained and do not demonstrate any considerable hydrogeological activity.

6.2. Slavka Cave

The cave lies within a spur of the interfluve plateau, bordered by a stream valley and its two small tributaries – perched karst valleys. The entrance is a collapse sinkhole on the slope of one such valley. Overburden thickness increases to 20 to 25 m toward the interfluve. The cave is currently explored for 9.2 km and consists mainly of high (3 to 10 m) slot- and rift-like passages. Feeder conduits, commonly separate, form a lower level, relative to the master passages; in places they form small networks.

Breakdown structures in Slavka Cave are of two types: 1) “common” breakdowns formed from outlet features, and 2) breakdowns related to “rhythmolitic” bodies (see below). The latter represent a special case of breakdown formation, occurring widely in Slavka Cave but rare in other caves.
“Rhythmolites” is the local term for highly gypsiferous bodies of closely interbedded aleurolits, sands and coaly streaks occurring within the upper part of the gypsum. Such bodies can be of 5 to 10m across and 3 to 4m in vertical thickness. Although “rhythmolite” bodies are found in many other caves in the region, they are unusually abundant throughout the Slavka cave field. Their contact with the gypsum is irregular and generally has a cone- or bowl-like shape. The nature of the “rhythmolite” bodies is not well understood, but one can assume that they are paleokarstic (syngenetic?) features.

Being particularly brittle, closely stratified and fissured, slabs of rhythmolitic material fall readily into any passage whose ceiling has intersected the bodies from below, giving rise to breakout cupolas/domes (see Fig. 4C). Breakdown piles beneath these consist almost entirely of rhythmolite slabs. In total 42 breakdown structures of this type were mapped within the cave (Fig. 11), giving an extrapolated density of about 480 features per km². Most breakout forms are confined to the rhythmolite bodies or terminate at their contact with the overlying Ratynsky limestone or Ternopol’sky unit. Examination of such cupolas and domes suggests that breakdown structures of this type are not related to any discontinuities in the overlying formations; the latter remain largely intact above such breakdown. The scarcity of surface subsidence and collapse features above the Slavka Cave suggests that this type of breakdown structure is generally not sufficiently potent to produce a surface expression, despite the overburden being of rather small thickness. Considering that rhythmolite bodies are not common in other cave areas examined, this type of geological influence on breakdown initiation can be regarded as site-specific.

“Common” breakdown structures, i.e. those formed from outlet features, are quite similar to those in Mlynki Cave. Only 13 structures of this type were found, which suggests an extrapolated density of about 150 features per km². Both density values given above are somewhat underestimated, because some structures have probably been overlooked in the marginal parts of the labyrinth. However, it is evident that in this particular case breakdown structures related to “rhythmolites” predominate over structures related to outlet features.

6.3. Verteba Cave

Verteba Cave lies in the neck of a large meander of the Seret River, where the cover sediments are almost entirely denuded. Only isolated patches of the Ratynsky limestone and Ternopol’sky beds, from 1 to 3m in thickness, remained within the meander, but through most of the area the gypsum is covered only by soils. Many sinkholes of cone-, bowl- and plate-like shapes are scattered throughout the area (Fig. 12).

The cave is a shallow-lying labyrinth with 7820m of closely-spaced, wide but low passages (primarily due to the high level of clay cave filling) that occur within a narrow strip. Numerous breakdown structures examined in this cave fall into three groups:

1) “Common” breakdowns formed from outlet cupolas;
2) Breakdowns formed from vertical dissolution pipes;
3) Breakdowns formed along prominent vertical cracks in the cave ceiling.

Massive fall-ins of blocks are rare. Even in this shallow cave they do not cause total breakdown of the cave ceiling with sudden collapsing at the surface. Gravitational breakdown of any remaining “bridges” at the top of the cupolas and the
vertical pipes is also infrequent, because of low lithostatic loads. The vast majority of breakdown structures in Verteba Cave is associated with prominent vertical cracks in the cave ceiling and involve mainly filtrational mechanisms, such as suffosion and erosion. Through such cracks, poorly consolidated fragments of the Ternopol’sky beds and remnants of the soil cover are washed into the cave, giving rise to numerous suffosion sinkholes at the surface and related breakdown piles in the caves (see Fig. 4G). The breakdown piles are rather small in size and consist of mainly (sometimes solely) of washed-in soil. Artifacts have been found in some piles, originally dumped into the sinkholes by inhabitants of the Tripil’sky settlement (about 5000 years BC) located above the cave. This gives some idea of the rate of filtrational mass flux from the surface to the cave.

7. Discussion and conclusions

Speleological observations have allowed the identification of several different mechanisms for breakdown development in the gypsum karst of the Western

---

Fig. 11 - Breakdown structures in Slavka Cave. The cave map is a courtesy of the Kiev Speleological club. Breakdown survey has been performed with an assistance of Natalia Yablokova
Ukraine. Distribution of breakdown structures and the mechanisms of their development are influenced mainly by:

1) Speleogenetic factors (distribution, type and size of the breakdown-initiating cavities or their particular components);

2) Lithological and structural discontinuities in the gypsum encountered by caves (combined speleogenetic and geological guidance);

3) Lithostratigraphy of the overburden and the geotechnical properties of its individual units;

4) Lithological and structural discontinuities in the overburden;

5) Hydrogeological conditions at the level of the gypsum and in the overburden.

7.1. Breakdown initiation

Ultimately karst breakdown development is related to the presence of karstic cavities and dissolutionally enlarged fissures. However, in contrast to established views, this study suggests that breakdown initiation in the Western Ukraine is not guided directly by the size of cavities. Some of the largest passages and chambers in the major caves remain stable and untouched by gravitational destruction. In many other cases breakdown of large gypsum blocks occur from the ceiling of passages, but the

Fig. 12 - Distribution of sinkholes above Verteba Cave. The cave map is a courtesy of the Ternopil' Speleological club.
respective breakout surfaces remain stable, still within the gypsum (corresponding to particular prominent bedding planes). Even when the breakout surface occurs along the base of the Ratynsky bed, it remains stable in many cases. Only in rare situations can the massive breakdowns terminating some large passages be assumed to form as single-event collapses of the cave roof. Apparently, such cases are guided mainly by geological factors. This survey suggests strongly that the great majority of breakdowns initiate at specific speleogenetically or geologically “weakened” localities (factors 1 and 2 in the list above) that classify into few distinct types.

**Speleogenetic controls.** In the Western Ukrainian caves, two types of speleogenetic situations that favour breakdown initiation are distinguished, both creating exposures of the Ratynsky bed in the caves: 1) outlet features (cupolas, domes and domepits of “ascending” origin) and, 2) vertical pipes formed by free downward percolation.

In all the caves examined most of the breakdown structures initiate from outlet features. Such features represent places where water has discharged from a cave to the upper aquifer during a period of transverse artesian speleogenesis. By virtue of their hydrological function, the outlet features tend to form at places where the integrity of the immediately overlying Ratynsky bed and of the next higher formation are somewhat disrupted and, hence, permeability is enhanced. In other words, all of the most weakened zones at the gypsum/Ratynsky limestone contact were exploit ed speleogenetically, to form outlet features during transverse artesian speleogenesis. This is the single fundamental cause of breakdowns initiating predominantly from outlet features. Therefore, distribution of outlet features is the most important influence upon breakdown initiation. By way of contrast, the above reasoning is supported by the fact that the Ratynsky bed commonly forms relatively stable ceiling in large exposures created by occasional separation and breakdown of gypsum blocks into the underlying master passages, if this does not relate to outlet features.

The second speleogenetic situation favouring breakdown initiation is where vertical dissolution pipes form under present unconfined settings in the entrenched and subjacent karst zones. Such pipes develop at points of a focused descending percolation to the gypsum from the overlying beds. They are 1 to 3m wide, extend downwards from the gypsum upper contact through the full thickness, and are commonly superimposed upon relict artesian passages (Fig. 13). Although in a different way, the vertical percolation pipes also expose the base of the Ratynsky limestone to the caves. Also, as in the case of the outlet features, the vertical percolation pipes commonly indicate weakened zones in the Ratynsky limestone bed and in the overlying formations. This is why breakdown structures are readily initiated from such pipes. The mechanisms for breakdown development remain largely the same as for the structures formed from outlet features, although some differences can be imposed by continuous active percolation, hence the erosion of breakdown structures. Active percolation facilitates upward stoping through larger overburden thicknesses. The density of vertical pipes in the main caves of the region (a few to a few tens of pipes per km²) is much lower than that of outlet features. However, in other regions their density is known to be much higher, for instance about 300 pipes per km² in the Kungursky Cave area of the Urals, Russia (Andrejchuk, 1999). There, breakdown development from vertical pipes is considered to be the main cause of collapse/subsidence development at the surface.
Geological factors. Some kinds of geological discontinuities occurring within the gypsum can initiate breakdowns in the ceilings of “normal” passages.

One type is exemplified by Slavka Cave, where most of the breakdowns relate to (palaeokarstic?) bodies of gypsum-rich “rhythmolites”. Generally breakdown structures of this type are not sufficiently potent to produce an expression at the surface, even if the overburden has a relatively small thickness. Considering that “rhythmolite” bodies are not common in other cave areas that have been examined, this type of geological influence on breakdown initiation can be regarded as site-specific.

Another type of geological influence is where breakdown is initiated at points where prominent tectonic faults disrupt both the gypsum and the overburden. If faults are pre-speleogenetic, they can cause development of larger passages that may collapse suddenly when their ceiling strength is exceeded by the load of the overburden. The presence of prominent sub-vertical discontinuity planes in the overlying clays facilitates massive breakdown. It is the presence of such guiding discontinuities that allow overburden material to collapse in a single event, even where there is a considerable thickness of overburden. It is presumed that all the deep collapses known in the region are of this type. They appear at the surface suddenly, as catastrophic collapses, forming 10 to 30m shafts, as exemplified by the Dan’kivsky collapse. Such collapses are quite rare both throughout this region and more generally, but they are the most hazardous, due to their considerable vertical magnitude (energy involved) and the difficulties inherent in their prediction.
7.2. Breakdown propagation through the overburden

The propagation of a void through the overburden by stoping and the possibility that a breakdown structure will eventually manifest itself at the surface as a subsidence or a collapse depend on the thickness and lithostratigraphy of the overburden and on the particular mechanism involved.

**Lithostratigraphy of the overburden.** The presence, layered structure and lithological composition of an overburden are among the major factors that determine stages of karst breakdown development and the component processes involved, i.e. the mechanisms of karst breakdown.

Multi-stage development is governed by the stratified nature of the overburden, with varied lithological, geomechanical and hydrogeological properties for individual units. Generalizations, derived from the major publications on the problem and supported by this study, are as follows. Beds of loose, permeable sediments (i.e. sands) serve as predominantly as a setting for processes of hydrodynamic decomposition (such as suffosion, liquefaction, erosion, etc.). In contrast, low-permeability or fully-drained beds of more coherent sediment or solid rock promote arching to support void development by stoping, and serve as the setting for mainly gravitational destruction. Consequently, in the overall propagation process some non-equilibrium stages give way to quasi-equilibrium stages. The capability of some beds within the overburden to bridge a void is the main pre-requisite for collapse-style in the eventual surface deformation (as against gradual subsidence).

**Hydrogeological conditions.** The role of hydrogeological conditions in creating solution cavities that initiate breakdowns (speleogenetic factors) is not discussed here. However, these conditions play an important role in determining breakdown initiation (triggering) and development. In the Western Ukrainian gypsum karst, one of the most important effects that triggered breakdown development was the loss of buoyant support when the Miocene aquifer had been losing its confinement due to geomorphic development. The loss of buoyant support can disturb the metastable state of a cave roof at points where speleogenetic and geological factors have already brought its bridging capacity (resistance to failure) close to a critical level. This situation generally signifies the transition from deep-seated karst to subjacent karst. The effect is illustrated by many quarries in the deep-seated (confined) karst zone (Jazovsky sulfur quarry, Nikolaevsky clay quarry, etc.), where overburden removal and massive groundwater withdrawal from the Miocene aquifer resulted in an abrupt drop of potentiometric surfaces and dramatic intensification of collapse/subsidence formation in the vicinity of the quarries (Klimchouk and Andrejchuk, 1996).

In unconfined settings, hydrodynamic activity at the gypsum level promotes destabilization of breakdown columns that rest on the clay cave fill. Their basements can settle down, due to shrinkage and compaction of bulk cave fill, and be eroded by focused streams. In all cases this causes settlement of the breakdown columns. This is why lowering or fluctuation of the water table in the gypsum commonly activates breakdown development and subsidence formation at the surface, a case that is well exemplified by the Zoloushka Cave area. A complete draining of the gypsum promotes stabilization of the breakdown structures and slows down their propagation to the surface (the Mlynki Cave).

Another important consideration is the presence of perched aquifers within the
overburden. In the region, an aquifer hosted in the sandy-gravel alluvial terrace sediments perched on the Kosovsky/Sarmatian clays is present in many places. In the confined karst zone it contains groundwaters almost universally throughout the area, but in the subjacent and, especially, in the entrenched karst zones it is drained in part or in full by erosion valleys and subsurface breakdown structures. Where a stopping void at the top of a breakdown structure reaches the bottom of this water-bearing horizon, the set of hydrodynamic destruction processes evolves, such as suffosion, liquefaction, erosion, etc. Besides suffosion, liquefaction and thinning occurring at the sandy horizon itself, leakage along the breakdown structure, if continuous and intense enough, may cause considerable destabilization and settling of the breakdown column due to erosion and damping, hence promoting activation of the overall process.

7.3. Breakdown mechanisms

The factors considered above (initiation conditions, lithostratigraphy and hydrogeological conditions) together determine the mechanisms of breakdown propagation and surface deformation. Five mechanisms identified by this study are summarized on Fig. 14. In two of them (2nd and 5th) the processes of gravitational destruction overwhelmingly predominate, but in the other three the processes of filtrational (or hydrodynamic) destruction play an important part, either in particular stages or during the entire breakdown development. Consequently these mechanisms are termed “gravitational” and “gravitational/filtrational”. Note that the initiating situation only directly determines Mechanism 5, whereas other mechanisms strictly do not depend on the ways in which breakdown started. The specifics of the mechanisms are determined mainly by lithostratigraphical and hydrogeological conditions.

7.4. The critical thickness of the overburden

The ability of a breakdown structure to reach the surface in the form of a collapse or subsidence depends on: 1) the size of the initial “breakdown window” at the gypsum/Ratynsky bed contact and the receptacle capacity of a master cavity beneath it, 2) the coefficient of loosening of the fallen material, 3) the thickness of the overburden and, 4) the involvement of the processes of hydrodynamic destruction. As most breakdowns in the region initiate where artesian outlet features or vertical percolation pipes expose the Ratynsky bed to a cave, the diameter of such exposures is the main gauging factor that determines the cross-sectional size of the breakdown column. The receptacle capacity of a master passage beneath the initiating feature is determined by passage width and height. Hence, these parameters influence the initial size of a stoping void at the top of the breakdown structure.

When a breakdown talus reaches the gauging “window” and separates the migrating void from the main cave, the height of the void decreases in the course of its further upward migration, because of the loosening of the fallen material. This means that at a certain height of breakdown column void propagation may cease and the breakdown will never manifest at the surface. Hence, given some maximum parameters for the initial receptacle capacity of a cave, and a characteristic coefficient of loosening for the overburden material (it commonly varies from 1.1 to 1.3 for the region), one may speak about the critical thickness of the overburden, above which surface deformation will never occur, regardless of the degree of underground karstification. Empirical study of the relationship between sinkhole density and the thick-
ness of the overburden performed for the three different areas (Fig. 15), seemingly supports this assumption. The critical thickness of the coverbeds is found to vary from 45 to 55m between the three different areas. The shape of the curve for area 3 (Zoloushka Cave) differs from the other two because of the intensification of collapse and subsidence formation caused by man’s impact (quarrying activity).

Apparently, the critical thickness of the overburden will be specific for each region. It depends on the size of the cavities and the structure and composition of the cover. This scheme is strictly valid, however, only for purely gravitational mechanisms that do not involve the processes of hydrodynamic destruction and removal, as the latter can maintain the non-karstic growth of a stoping void or restoration of the receptacle capacity of an initial karstic cavity. And, finally, it does not apply for situations where the cover is made of sediments that have a coefficient of loosening close to 1.0, such as sands. In sands, a stoping void can propagate through great thicknesses of up to 100m or more.

7.5. Synopsis

Breakdown initiation at the karstified horizon (at the cave level) occurs due to various causes. Simple gravitational breakdown of blocks and slabs from the cave ceil-
Fig. 15 - The density of sinkholes versus thickness of the overburden: 1 = in the Seret-Nichlava interfluve (entrenched karst), 2 = in the Cherny Potok area (subjacent karst), 3 = in the Zoloushka cave area (subjacent karst).

breakdown rarely gives rise to destruction of the overburden. The most important conclusion of general significance derived from this study is that breakdown of the overburden is caused predominantly by structures related to specific morphogenetic features in cave systems (outlet features), or to specific genetic types of conduits (vertical solution pipes), not merely to large unsupported roof spans. This is because, by virtue of their origin and hydrogeological function, such features exploit the points of lowest integrity within the main bridging unit (the Ratynsky bed in the Western Ukraine) and the entire overburden. This is also the reason why such breakdown structures are sufficiently potent to propagate through the overburden, whereas those related to occasional block breakdown of the cave ceilings are commonly not. Therefore, passage size is not an important influence upon breakdown initiation.

Breakdown formation can proceed through a variety of mechanisms. In the intrastratal and covered karsts, manifestation of karstic features at the surface does not adequately reflect the degree and character of karstification at depth. The shape and size of sinkholes is not indicative of their origin. Structure and composition of the cover and the processes therein play the major role in transmission of breakdowns to the surface.

This study demonstrates that speleogenetic analysis plays one of the most important roles in understanding breakdown pre-conditions and mechanisms, and in eventual subsidence hazard assessment. Direct cave observations aimed at both speleogenetic investigation and breakdown characterization at regional or site-specific levels should be employed wherever possible.
Acknowledgement

This study was partially supported by the ROSES (Risk of Subsidence due to Evaporite Solution) Project ENV4-CT97-0603 funded by the EC Framework IV Programme. The authors sincerely thank Dr. David Lowe and Dr. Armstrong Osborne for the correction of English.

REFERENCES


MECHANISMS OF KARST BREAKDOWN FORMATION IN THE GYPSUM KARST OF THE FORE-URAL REGION, RUSSIA (FROM OBSERVATIONS IN THE KUNGURSKAJA CAVE)

Vjacheslav ANDREJCHUK and Alexander KLIMCHOUK

ABSTRACT
The fore-Ural is a classical region of intrastratal gypsum karst. The intensive development of karst in the Permian gypsums and anhydrites causes numerous practical problems, the subsidence hazard being the most severe.

Mechanisms of karst breakdown formation were studied in detail in the Kunguskaya Cave area. The cave and its setting are characteristic to the region and, being a site of detailed stationary studies for many years, the cave represents a convenient location for various karst and speleological investigations.

Breakdown structures related to cavities of the Kungurskaya Cave type develop by two mechanisms: gravitational (sagging and fall-in of the ceilings of cavities) and filtrational/gravitational (crumbling and fall-in of the ceilings of vertical solution pipes, facilitated by percolation). The former implies upward stoping of the breakout roof and cessation of the process at some height above the floor of the cave due to complete infilling by fallen clasts. This mechanism cannot generate surface deformation where the overburden thickness exceeds a certain value. The latter mechanism implies that breakdown will almost inevitably express itself at the surface, most commonly as a sudden collapse, even where the thickness of the overburden is large. These mechanisms result in different appearance, distribution and further evolution of the respective surface forms, so that subsidence hazard assessment should be performed differently for these types of breakdown.

The conclusions reached by this study are representative for the region, although some of them bear more general validity for intrastratal karst conditions. This study underlines the ultimate importance of speleological investigations to the understanding of karst breakdown mechanisms.

KEYWORDS: gypsum karst, karst subsidence, subsidence hazard, cave breakdown, speleogenesis, Ural region.

1. Introduction
Aimed at characterization and understanding of subsidence phenomena and underlying karst breakdown processes in the fore-Ural region, this study also seeks to contrast these with another well-known region of gypsum karst, the Western
Ukraine (see Klimchouk and Andrejchuk, this volume). Subsidence phenomena are widespread in both regions, and comparing them can help to reveal specific and general features. Like the Western Ukraine, the fore-Ural region is located on the margin of the craton (the eastern limit of the Eastern European Platform), in the zone of its junction with the foreland structure of a large folded region (the Ural Mountains), the Ural Foredeep. The sulphate karst in the fore-Ural develops in gypsum and anhydrite beds of the Lower Permian evaporitic sequence, which spreads through both the platform margin and the foredeep. Besides similarities in the lithology of the karstifiable rocks and their geostuctural position, the two regions have some other features in common. Both display temperate climatic conditions and transitional forest-to-steppe landscape, the subhorizontal or monoclinal occurrence of the soluble beds, and the presence of a loose sediment cover of variable thickness.

Equally, there are also substantial differences between the conditions of gypsum karst development in the Western Ukraine and the fore-Ural regions (Andrejchuk, 1996; Andrejchuk and Klimchouk, 1996), which determine some specific aspects of subsidence phenomena and processes in the two regions. In particular, these differences appear in:

- The nature and character of the fissuring in the sulphate strata (prevalence of vertical fissures arranged in superimposed networks confined to particular horizons of the gypsum bed in the Western Ukraine, versus complex polygenetic networks in the fore-Ural);
- Density and permeability of fissure networks (lower and more anisotropic in the Western Ukraine versus higher and more isotropic in the fore-Ural);
- The age of karstification (Pliocene-Pleistocene in the Western Ukraine versus Mesozoic-Cenozoic, polycyclic in the fore-Ural);
- The thickness and lithostratigraphy of the karstifiable strata (10 to 40m-thick single gypsum bed in the Western Ukraine, versus 60 to 90m-thick interbedded sequence of gypsum, anhydrite and dolomite in the fore-Ural);
- The nature of the overburden (low permeability clays in the Western Ukraine versus a freely permeable breccia horizon and loose loamy sediments in the fore-Ural);
- The structure of the sulphate rocks (recrystallized, predominantly coarsely-crystalline, gypsum in the Western Ukraine versus micro- and crypto-crystalline gypsum and anhydrite in the fore-Ural).
- The history of karst development (the karst in the Western Ukraine has evolved since the Pliocene in one major phase of uplift. In the fore-Ural, continental conditions were established during the Mesozoic, and the region has experienced repeated oscillations of tectonic movement, resulting in repeated overdeepening of river valleys and subsequent changes in the conditions of karst development).

Breakdown development mechanisms have been studied in detail in Kungurskaya Cave, the largest gypsum cave in the region (Fig.1). The cave developed in conditions typical of the fore-Ural, and the pattern and morphology represent well the style of underground karstification of sulphate massifs in the region. Hence, the general conclusions inferred from this study can reasonably be extended to most of the fore-Ural gypsum karst, at least to the zone of entrenched and subjacent karst.
The Kungurskaya Cave is well-suited for detailed studies of mechanisms of breakdown formation. It is easily accessible and horizontal, and consists of passages and chambers of considerable size. It has permanent lighting as it is used as a show cave (Dorofeev and Andrejchuk, 1990). The massif in which the cave is developed is well documented geologically and hydrogeologically. The breakdown structures, occurring widely in the cave, represent different types and stages of development.

2. The Kungurskaya Cave and settings of karst breakdown development

The cave lies in the Perm administrative region, on the northern outskirts of Kungur town. The area belongs to the north-west margin of the Ufimsky Plateau, with elevations ranging from 300 to 400m asl. The plateau surface is entrenched for 50 to 150m by river valleys (Fig.2), which separate the gypsum/anhydrite sequence into numerous interfluve massifs.

2. 1. Geomorphological and geological settings

Historically the massif in which the Kungurskaya Cave is developed is known as the Ice Mountain, because the entrance series of the cave contains ice formations during all seasons. The Ice Mountain represents an elevated plateau-like massif (about 10km²) bounded by the valleys of the Sylva River and its tributary, the Shakva River.
Fig. 2 - Characteristic landscape of the pre-Ural gypsum karst region, with riverside exposures of the sulphate rocks. The Sylva River near the Podkamenskaya village.
MECHANISMS OF KARST BREAKDOWN FORMATION IN THE GYPSUM KARST OF THE FORE-URAL REGION, RUSSIA

(Fig. 3A). The southern flank of the massif, where the entrance is located, is steep and has numerous rocky ledges (Fig. 4B). The western and northern flanks are gentle, terraced, and have some protruding residual gypsum hills. The Sylva River is 110 to 120 m wide and 2 to 3 m deep near the cave, and it carries 16 to 24 m$^3$/s of water during the summer and winter seasons and up to 1300 m$^3$/s during spring floods.

The massif comprises the >70 m-thick sequence of gypsum and anhydrite beds of the Kungursky Stage of the Lower Permian. These rest on the dolomite and limestone beds of the Filippovsky Formation, which is up to 50 m thick. The formation hosts a

---

Fig. 3 - Geomorphological map of the Ice Mountain (A) and the geological section (B) showing occurrence of the Kungurskaya Cave.

A: 1 = terraces, 6 = ravines, 7 = erosion ditches, 8 = river trench, 9 = steep slopes with gypsum ledges, 10 = modern and former riverbed, 11 = swallets, 12 = dolines, 13 = lakes, 14 = swamped dolines, 15 = cave entrance, 16 = cave field.

B: 1 = loam/soil, 2 = karst breccia horizon, 3 = sulphate rocks, 4 = carbonate rocks, 5 = water table, 6 = clay, 8 = breakdown material.
Fig. 4 - Surface karst features above Kungurskaya Cave, superimposed on the cave map (A) and the view (B) of the Ice Mountain from the Sylva River (from the south). 1 = dry cave passages, 2 = cave lakes, 3 = contours by the breakdown material, 4 = suffosion dolines, 5 = karst collapse/subsidence dolines.
good aquifer, with fissure and porous permeability, although at present it represents a relatively less permeable sequence than the overlying sulphates.

The sulphate sequence is known as the Irene Formation and comprises a sequence of gypsum and anhydrite beds alternating with minor layers of limestones and dolomites. Several units are distinguished in the formation, each having its own name. The lowermost sulphate unit (up to 28m thick), which rests on the Filippovsky dolomites, is called Ledjanopeshcherskaya (the Ice Cave Unit) and consists of blue-greyish anhydrites and grey gypsum. The dolomite intercalations of 5 to 10cm in thickness divide it into three sulphate beds differing in thickness, bedding, structure and fissuring. The cave lies mainly within the Ledjanopeshcherskaya Unit and the different properties of the beds considerably influence the character of breakdown processes.

The Ledjanopeshcherskaya Unit is overlain by the Nevolinsky Unit (4 to 5m), which comprises four beds: grey dolomite (1m), oolitic limestone (1.7 – 1.9m), pale-grey cavernous limestone (1.5m) and dark-grey pelitomorphic dolomite (0.7m). Above this is the Shalashinskaya Unit, which comprises a fissured grey gypsum 23m in thickness. This unit displays a highly kartsified and irregular rockhead. It is overlain by the Elkinskaya Unit, made up of alternating oolitic limestones, pelitomorphic dolomites and argillites. The uppermost (Demidkovskaya) unit of sulphates (light-grey friable gypsum) is present only in the highest areas of the massif, where it crops out in the flanks of large sinkholes.

The upper part of the geological section of the Ice Mountain massif is substantially destroyed by karstification. Carbonate beds within the sequence, being more resistant to dissolution, experienced uneven settling, disarticulation and mixing, and formed a breccia horizon consisting of dolomitie, limestone, marls, argillite and gypsum clasts. Voids between clasts are infilled by clay. In places clasts are cemented by calcite. Above the breccia horizon, there are clayey-loamy sediments of mixed (alluvial-deluvial) origin, which were formed during extended timescales.

The conditions described, namely the pronounced stratification of the overburden, its lithologic heterogeneity and high degree of fissuring, favour breakdown development.

2.2. Hydrogeological settings

The sulphate sequence of the massif is almost entirely in the vadose zone. The groundwater table is located in the lowermost sections of the cave labyrinth, where it is observed in more than 50 cave pools. The aquifer is well connected to the Sylva River due to the high degree of karstification and fissuring. The cave pools are located 120 to 580m from the river. In the low regime the river drains the groundwaters through the cave area. During spring floods the high level of water in the river props up the underground waters, causing a rise 3 to 4m in the water table and even backflooding. During these periods intense dissolution takes place in the massif, causing concentrated lateral enlargement of the cave.

In Spring time and after rainfalls, a considerable amount of water is retained in the friable loamy sediments and the breccia horizon above the cave, forming a perched aquifer. Its water then leaks slowly down to the cave via fissures. As demonstrated below, this percolation is one of the main factors of the breakdown formation.
2.3. Cave morphology and speleogenesis

The cave is a maze (Fig.4A), developed mainly within gypsiums and anhydrites of the Ledjanopeshcherskaya Unit. The total length of the explored cave is of 5.6km, and its volume is 350,000m³.

In general the passages are horizontal, but their floors lower gradually from east to west and from the entrance series to depth within the massif. This is due to accumulation in the entrance series (which is the cold part of the cave) of large amounts of clasts generated by frost weathering. In this section both the floors and ceilings of the passages and chambers lie 5 to 6m higher than in the far reaches of the cave. Breakout domes are common here, but passages are generally smaller.

Passages in the distant parts of the cave are generally larger, 20 to 40m wide and 5 to 10m high, with corroded walls. Gravitational processes affect ceilings to varying degrees. The original dissolutional morphology is not preserved at the ceilings. Slab breakdowns occur almost everywhere, and ceilings rise to a height of 10 to 15m above the water table. There are many breakout domes with talus or piles of breakdown material below them. In three places large, 20 to 24m-high breakout domes have formed (the Vyska-1, Vyska-2 and Cosmic domes). Because of the breakdown piles below, the actual height of the cave space in these domes remains below 10m. The ceiling is flat in places, where it reaches the base of the scarcely-fissured anhydrite bed (e.g. in the Smelykh, Velikan, Zapadny and Geologov chambers).

Breakdown domes are commonly separated by breakdown structures, forming elongated chambers 40 to 100m long. They are connected with smaller horizontal conduits, 1 to 20m wide and 1 to 6m high, which occur along the water table or below it. In contrast to large passages, these conduits have clear dissolutional morphology, almost untouched by breakdown processes.

The cave has a long and complex history of development. During the early stage the cave was developed under confined conditions, by waters rising from the underlying Filippovsky carbonate formation. In the past the nearby river valleys were repeatedly overdeepened relative to the present position, and this imposed vadose conditions within the cave massif. Recent development has occurred mainly at the fluctuating water table, particularly at the expense of aggressive backflooding waters entering the cave from the river during high stands.

3. The formation of breakdown structures

The intense breakdown processes in the Ice Mountain massif are evident from both observations in the cave and the wide presence of subsidence sinkholes at the surface (Figs 3A, 4A and 5). Before considering the mechanisms of their formation, it is appropriate to characterise the surface features above the cave.

3.1. Collapse sinkholes above the cave

There are more than 3000 hollows of various shapes and sizes on the surface of the massif (Dorofeev, 1979), which makes the density about 300 forms per km². Among 935 forms mapped in detail on the large-scale plan, cone-shaped dolines are predominant (57%). Bowl-shaped dolines comprise 26.8% and saucer-like dolines 9.5%. The rest are trenches and pits formed along unloading fissures near the plateau edges (6.2%), or large depressions (0.5%) and other forms.
Of the total number of mapped hollows, 640 (68.5%) are located on the surface of the Ice Mountain massif, 197 (21.1%) lie on its slopes, and 98 (10.5%) are in the thalwegs of ravines. According to the density and character of hollows four zones are distinguished (Dorofeev, 1968, 1970): steep slopes (<200 forms/km²), edges (500-1000 forms/km²), gentle (upper) slopes (200-300 forms/km²) and terrace/watershed (<200 forms/km²). Concentration of karstic hollows in the edge zones is linked to the development of unloading fissures, removal of cover sediments and exposure of the sulphate rockhead. Small and randomly distributed forms predominate in this zone. In the gentle slope zone (200 to 400m away from the edges) karst hollows are relatively large. For instance, dolines 10 to 30m wide and 4 to 10m deep predominate on the surface above the cave, the largest reaching 60m in diameter and 13m in depth. Most of the dolines are separate, and randomly distributed. An increase of doline size towards the watersheds is explained by the increasing thickness of friable sediments, in which the dolines develop.

On the plateau, small- and medium-sized dolines predominate (Fig.5; see also Fig.13), commonly with signs of periodic activation. These dolines are clustered. Old saucer-shaped waterlogged dolines are widespread, but fresh collapses are also common. Between 1943 and 1986 134 new collapses were recorded within the Ice Mountain (Dorofeev, 1979; Dorofeev and Anrejchuk, 1990). Most of these were less than 4m in diameter and 2m in depth (Table 1). Fresh collapses commonly occurred at the bottom or on the slopes of the older dolines (54%) or less than 20m from them.
Table 1. Distribution of 134 collapses formed between 1943 and 1986, in terms of diameter and depth (after Dorofeev, 1979)

<table>
<thead>
<tr>
<th>Diameter, m</th>
<th>%</th>
<th>Depth, m</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1</td>
<td>34</td>
<td>&lt;1</td>
<td>68</td>
</tr>
<tr>
<td>1-2</td>
<td>21</td>
<td>1-2</td>
<td>18</td>
</tr>
<tr>
<td>2-4</td>
<td>27</td>
<td>2-4</td>
<td>12</td>
</tr>
<tr>
<td>4-6</td>
<td>15</td>
<td>&gt;4</td>
<td>2</td>
</tr>
<tr>
<td>&gt;6</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(25%). This is considered to be an important diagnostic indication of a particular breakdown mechanism.

Thorough underground observations have revealed that collapse/subsidence features above the cave have different origins, which explain peculiar features of their distribution on the Ice Mountain massif. Most of the breakdown structures develop according to a vertical dissolution pipe mechanism (infiltrational/gravitational) or, less commonly, by failure of the ceilings of large cavities (gravitational mechanism). Some features originate due to the suffosional mechanism. These three types are considered below, starting with the “classic” gravitational mechanism.

3.2. Breakdown development by the gravitational mechanism

Whereas it is appreciated that all types of karst breakdown involve the action of gravity forces, the term “gravitational mechanism” is used here to denote “purely” mechanical failure of cave roofs under load, without significant involvement of other processes such as percolation, erosion, suffosion, liquefaction, etc.

In Kungurskaya Cave 64 rock failure events were recorded during the period from 1963 to 1986 (Dorofeev, 1987). The actual number of failures was probably far greater, as only the largest events in easily accessible areas of the cave were documented. The prevailing type of failure is slab breakdown (sensu White and White, 2000), although less frequent breakdowns of blocks measuring 3 to 5m also occur. Continuous failures of passage ceilings result in clast accumulation at the bottom and upward migration of voids. Many parts of the cave are completely filled with breakdown clasts. In some places large breakout domes form, with dome-like or conic piles of clasts below, e.g. in the Velikan, Meteorny and Geografov chambers (Fig.6).

The most intense contemporary breakdowns are found within the entrance series, where seasonal and daily ranges of temperature are substantial and repeatedly pass through zero. Ice wedging in cracks and fissures ruptures the rock during cold days, with noise that resembles muffled gunshots. In the warmer part of the cave (the main part, which exhibits a constant positive temperature) failures are most frequent in those chambers with large ceiling spans. These include the Velikan Chamber (40m span and 7 failure events during the above-mentioned period) and the Vyshka Chamber (30m span and 11 failure events). Stratification and the degree of fissuring of particular rock packages also influence the intensity of breakdowns. A layer of the lumpy gypsum in the upper part of the Ledjanopeshcherskaya Unit is most suscepti-
Fig. 6 - Breakout domes and breakdown taluses originated by slab and block breakdown in Kungurskaya Cave. A = Velican Chamber, B = Casteret Chamber.

ble to failure. Much less commonly breakdowns affect a bed of massive anhydrite within the same unit, which fails by collapse of large blocks.

Continuous elastic sagging of beds across large passage spans is common throughout the cave (Fig.7). It normally precedes and accompanies the failure (Fig.8).

Almost the full thickness of the rocks above the cave is characterised by undulating beds, representing a vivid example of “karst tectonics”. The amplitude of bend-
Elastic sagging of gypsum beds in the ceiling of Ruiny Chamber.

Fig. 7 - Elastic sagging of gypsum beds in the ceiling of Ruiny Chamber.

...ing reaches 3 to 5m. It is noteworthy that the observed dip of beds at the ceiling is not always directed towards the centre of the span, but commonly towards the walls. This is due to polycyclic karstification and the presence of various generations of cavities of different ages, including paleokarstic cavities filled with karst breccia.

It appears that ceilings have not achieved a stable morphology, even in well developed large breakout domes, and the domes continue to grow. Despite this and the fact that gravitational breakdown mechanism is the most common through the cave area, it does not result in collapses at the surface. Gradual upward stoping of cavities due to breakdown and consequent accumulation of fallen clasts bring about reduction of stoping voids in volume and self-arrest of the breakdown process (Fig.9). This is because the bulk volume of the accumulated breakdown material is larger than the volume of the solid source rock, an effect previously noted by Šušteršič (1973, 1974). Growth of a breakdown pile surpasses upward growth of the void ceiling, and the rate of the advancing growth of the pile depends on the coefficient of rock loos-
Fig. 8 - Diagram showing conjugate sagging and slab fall-in processes.

...ening. The latter is the ratio of the volume of the bulk mass of fallen clasts to the volume of the solid source rock. This coefficient ($K_{loos}$) may vary from 1 to >2, increasing from friable sandy-clayey materials to solid rocks, and from crumble breakdown to block breakdown. Provided the overburden is sufficiently thick, the breakdown pile overtakes the breakout vault at a certain height. This relieves the stress and arrests the process of void propagation. The breakdown structure will not reach the surface in this case and no collapse will appear.

The described phenomenon of self-regulation of the breakdown process, vividly displayed in Kungurskaya Cave, explains the absence of large collapses above the cave, despite the large spans of cave passages. It also accounts for the formation of karst breccia. Elastic sagging of the sulphate rock continues for some time after the breakdown pile has reached the ceiling, causing some loading of the pile and compaction of the breakdown material. With time the latter transforms into brecciated rock. Brecciated zones and bodies of breccia ("fillings" of former cavities of various ages) are observed widely in the cave, intersecting with the present passages in different ways. For instance, between Ruin Chamber and Meteorny Chamber a 60m-wide breccia zone stretches northeast for 100m. The large size of the ancient cavity is evidenced by the presence of 1 to 2m-wide blocks of Nevolinskaya Unit dolomite, encased in the breccia, some 20m below the source bed. The lowermost parts of the breccia zones lie below the modern floor of the passages in places. This indicates a possible Pliocene age for the self-sealing of such cavities, which could be related to the period 3 million years ago when the Sylva river and its tributaries were entrenched below the modern position.
Walls with exposed karst breccia can easily be recognized by chaotic interrupted bedding and encased broken pieces and blocks of dolomite (Fig. 10A), and by a spongework pattern of small dissolution voids (Fig. 10B).

3.3. Breakdown development by the vertical solution pipe mechanism

Vertical solution pipes (VSP) are rounded channels that perforate the sulphate thickness vertically above the cave. They are also known as “organ pipes” and “comins”. VSP are common in many entrenched gypsum karsts such as the Pinego-Severodvinsky region in Russia and the Western Ukraine. They form by aggressive waters leaking through the vadose zone from perched aquifers above (Fig. 11A), become superimposed upon horizontal cavities developed earlier and play an important role in initiating and guiding the breakdown processes (Klimchouk and Rogozhnikov, 1984; Andrejchuk, Dorofejev and Lukin, 1997; see also paper by Klimchouk and Andrejchuk in this volume).

In the Kungurskaya Cave 146 VSP have been mapped (Fig. 11B) with diameters ranging from 0.2 to 10m. They reach a height of 10 to 20m. Most of the pipes are wider at the mouth, although cylindrical pipes are also common. The walls are entrenched by corrosion flutes. VSP form along paths through which water leaks from the perched aquifer. Almost all percolation in the vadose zone is concentrated in VSP, the blocks between them being completely waterless. Dripping of water commonly occurs in pipes superimposed on horizontal passages. In some pipes dripping intensity increases considerably during snowmelt at the surface, whereas in others it oscillates with no pronounced correlation to seasons or weather. These variations reflect differences in capacity and retention characteristics in different parts of the perched aquifer, and in configuration of leakage paths. Total dissolved solids in drip-
ping water varies between pipes and intensity regimes from 0.6 to 2.0 g/L, depending on the length (time) of immediate contact of the water with the sulphate rock. A few dripping spots in the cave, associated with cracks in ceilings and yielding supersaturated water, probably indicate recent VSP that started to develop above but have not yet reached the cave.

Carbonate beds within the otherwise sulphate sequence divide the pipes into 2- or 3-sections in the vertical profile. Being fissured, these beds let water percolate downwards into the next pipe section but retain loose material, thus preventing the lower sections from being filled (Fig. 12A). Different sections of a pipe can be aligned along the same vertical fissure and match each other in plan view, or they can be shifted laterally up to few metres after crossing a carbonate bed according to fissure guidance in respective sulphate beds.

The growth in pipe diameter and attendant filtration cause collapse and subsidence development at the surface (Fig. 11A). The overwhelming majority of dolines above the Kungurskaya Cave were formed by breakdown processes related to the development of vertical solution pipes. This is confirmed by the coincidence of almost all dolines in the cave field with pipes and related breakdown piles mapped in the cave (compare Fig. 4A and Fig. 11B), a fact noted by Dorofeev (1968). A mismatch of a few metres between the centres of some dolines and the pipes mapped in the cave is explained by the lateral shift of different vertical segments in some pipes where they cross the carbonate beds. Some pipes, however, do not have dolines above them. These have not yet reached the uppermost unit. The position of the top of the pipe in the vertical section can be inferred from the composition of the breakdown pile below the pipe.

The mechanisms of breakdown development along VSP may vary depending on
Fig. 11 - Doline formation due to the gravitational/filtration mechanism, after vertical solution pipes (A), and distribution of the biggest pipes in Kungurskaya Cave.

A: 1 = loam, 2 = karst breccia horizon, 3 = gypsum, 4 = limestone/dolomite, 5 = gypsum/anhydrite, 6 = breakdown material.

B: 1 = gypsum scarp, 2 = cave entrance, 3 = cave lakes, 4 = infilled VSP, 5 = open VSP, 6 = chain of pipes
which particular horizon (perched aquifer) gave rise to the pipe. If the pipe is fed from the carbonate beds of the Nevolinsky Unit, it develops only in the underlying sulphates. Growth of the pipe diameter will cause collapse of the bridging Nevolinsky Unit at some stage and further growth by upward stoping through the overburden. The surface feature will most likely evolve as a collapse.

More commonly pipes evolve due to leakage from the uppermost horizons of breccia and loams, supporting a perched aquifer. In such cases, small conic sinkholes form at the surface due to suffosion of the friable cover, starting during early stages of pipe growth. Formation of initial suffosion dolines accelerates the development of pipes below, due to piracy of surface runoff. Subsequent increase of the pipe diameter in the sulphate strata causes internal collapse of the separating carbonate beds and eventually the final collapse of the bridging breccia and loams. Where the thickness of the friable cover is small, pipes may open to the surface as shafts. If the thickness is considerable, the pipe can be filled completely by breakdown material after collapsing, and collapse dolines appear at the surface.

The breakdown mechanisms after vertical solution pipes, inferred from observations in the Kungurskaya Cave, can be extrapolated across the entire region. This is supported by the wide presence of VSP (they can be observed in valley outcrops and quarries as well as in caves) and also by the characteristics of fresh collapses. As the main gauging factor for the size of fresh collapses is the diameter of guiding pipes below, their diameters should correspond to the diameters of pipes. According to Lukin and Ezhov (1975), the initial diameters of the collapses that occurred in the Kungur region during many years were 0.5 to 5.0m. In the Kungurskaya Cave diameters of 83% of pipes fall in this range.

Further evolution of dolines evolved through the VSP mechanism is guided by the processes in the pipes. Pipes continue transporting breakdown and wash-out material underground, and the process is facilitated by continuing filtration through them. In addition to draining the perched aquifer, pipes now receive an increasing amount...
of surface run-off. The upper part of the pipes enlarges more quickly and generally the pipes assume a funnel-shape, with more complex relief in detail. Breakdown filling settles in the pipe due to dissolution and erosion in the breakdown column, and so both the depth and diameter of the doline increase. Periodically, fresh concentric cracks and small collapses may appear in the floor of the doline. This continues until the passage below is completely filled. Erosion at the base of the breakdown column may further facilitate doline growth, but eventually the breakdown column is sufficiently compacted to suppress active filtration, and doline growth ceases. Any further modification is mainly directed towards the softening of slopes and decrease of depth, although re-activation of settlement in the pipe may occur.

So, the size of the passage, though not influencing the initial diameter of collapse, does exert an influence, through its receptacle capacity, upon the size of a mature doline. This is why dimensions of mature dolines are commonly equal to the widths of cave passages below them, or are slightly less (Table 2). Only two dolines (above the Efirny and Geografov chambers, lines 9 and 17 in Table 2) have diameters substantially less than the widths of cavities below them, which indicates their immaturity and continuing growth. This is also evidenced by the steep slopes of these dolines and the apparent activity of the related breakdown piles in the cave. The correspondence of doline dimensions and their related receptacle cavities, which can be expressed by their ratio (the final column in Table 2), indicates the morphological maturity of dolines. If the $D/B$ ratio is higher than 1, sedimentation processes and morphological smoothing predominate. Most dolines within the cave field have stopped growing.

The ratio of doline depth to diameter ($H/D$) also indicates the evolutionary state of the feature. This ratio is 0.25 to 0.30 for the most of the dolines above the cave, whereas it is 0.38 and 0.52 for the two dolines mentioned above that are still growing.

The volume of dolines always exceeds the volume of the breakdown piles below the pipes, despite of loosening of the breakdown material (Table 3). Volume discrepancy is explained by that part of the breakdown material that fills the pipe. The difference characterizes the volume of the pipe.

The above characteristics of breakdown formation related to vertical solution pipes lead to several important conclusions about related surface forms:

- Initial dimensions of surface collapses (at the time of the event) are determined by the diameters of pipes and the heights of the underlying cavities.
- Dimensions and shape of dolines observed at the surface reflect the evolutionary state of the features.
- Mature (stable) dolines imply cessation of material transport in the pipe, and their dimensions point to the widths of the receptacle cavities.
- Large doline size is not necessarily determined by the large size of the initial collapse and, conversely, the small size of a collapse does not reflect the size of the subsequent mature doline.

3.4. *Dolines formed by suffosion*

Some dolines at the surface of the Ice Mountain were formed without any relation to cavities of the Kungurskaya Cave type, due to suffosion washout of loose
Table 2. The correspondence of dimensions of conjugate dolines and cave passages within the field of influence of Kungurskaya Cave (modified after Dorofeev, 1970)

<table>
<thead>
<tr>
<th>№</th>
<th>Chamber (passage)</th>
<th>Width of doline, m</th>
<th>Diameter of doline, m</th>
<th>Depth of doline, m</th>
<th>Doline depth to doline diameter ratio H/D</th>
<th>Doline diameter to cave width ratio D/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Poljarny</td>
<td>30</td>
<td>22</td>
<td>slope</td>
<td>-</td>
<td>0,73</td>
</tr>
<tr>
<td>2</td>
<td>Skandinavsky</td>
<td>16</td>
<td>15</td>
<td>4,0</td>
<td>0,27</td>
<td>0,94</td>
</tr>
<tr>
<td>3</td>
<td>Sklep-Zapadny</td>
<td>45</td>
<td>42</td>
<td>14,0</td>
<td>0,33</td>
<td>0,93</td>
</tr>
<tr>
<td>4</td>
<td>Krestovy</td>
<td>35</td>
<td>30</td>
<td>3,8</td>
<td>0,13</td>
<td>0,86</td>
</tr>
<tr>
<td>5</td>
<td>Smelykh</td>
<td>25</td>
<td>32</td>
<td>9,8</td>
<td>0,30</td>
<td>1,28</td>
</tr>
<tr>
<td>6</td>
<td>Geologov</td>
<td>19</td>
<td>20</td>
<td>5,0</td>
<td>0,25</td>
<td>1,05</td>
</tr>
<tr>
<td>7</td>
<td>Grozny</td>
<td>30</td>
<td>30</td>
<td>9,5</td>
<td>0,32</td>
<td>1,00</td>
</tr>
<tr>
<td>8</td>
<td>Kolizej</td>
<td>33</td>
<td>30</td>
<td>9,0</td>
<td>0,30</td>
<td>0,90</td>
</tr>
<tr>
<td>9</td>
<td>Efimy</td>
<td>30</td>
<td>12</td>
<td>6,3</td>
<td>0,52</td>
<td>0,40</td>
</tr>
<tr>
<td>10</td>
<td>Mokraja Kochka</td>
<td>20</td>
<td>15</td>
<td>5,0</td>
<td>0,33</td>
<td>0,75</td>
</tr>
<tr>
<td>11</td>
<td>Atlantida</td>
<td>13</td>
<td>30</td>
<td>7,5</td>
<td>0,25</td>
<td>2,03</td>
</tr>
<tr>
<td>12</td>
<td>Khlebnikoviykh</td>
<td>40</td>
<td>39</td>
<td>10,9</td>
<td>0,28</td>
<td>0,98</td>
</tr>
<tr>
<td>13</td>
<td>Zaozerny</td>
<td>37</td>
<td>38</td>
<td>13,2</td>
<td>0,35</td>
<td>1,03</td>
</tr>
<tr>
<td>14</td>
<td>Dlinny</td>
<td>27</td>
<td>35</td>
<td>5,0</td>
<td>0,25</td>
<td>0,74</td>
</tr>
<tr>
<td>15</td>
<td>Velikan</td>
<td>31</td>
<td>37</td>
<td>6,9</td>
<td>0,23</td>
<td>1,19</td>
</tr>
<tr>
<td>16</td>
<td>Kosmichesky</td>
<td>60</td>
<td>55</td>
<td>12,0</td>
<td>0,25</td>
<td>0,92</td>
</tr>
<tr>
<td>17</td>
<td>Geografov</td>
<td>40</td>
<td>20</td>
<td>7,5</td>
<td>0,38</td>
<td>0,50</td>
</tr>
</tbody>
</table>

Table 3. Relationship between doline volume and the volume of breakdown piles in Kungurskaya Cave (after Dorofeev, 1970)

<table>
<thead>
<tr>
<th>№</th>
<th>Chamber (passage)</th>
<th>Volume of breakdown piles in the cave, m³</th>
<th>Volume of doline, m³</th>
<th>Volume of material in the pipe, m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Efimy</td>
<td>500</td>
<td>670</td>
<td>170</td>
</tr>
<tr>
<td>2</td>
<td>Velikan</td>
<td>3520</td>
<td>4210</td>
<td>690</td>
</tr>
<tr>
<td>3</td>
<td>Smelykh</td>
<td>3020</td>
<td>4880</td>
<td>1860</td>
</tr>
<tr>
<td>4</td>
<td>Sklep-Zapadny</td>
<td>10780</td>
<td>13480</td>
<td>2700</td>
</tr>
</tbody>
</table>

Quaternary sediments into small cavities and large fissures in the breccia horizon that immediately underlies the cover. The main diagnostic feature of this type of dolines is their small size (diameter 0.5 to 2m and depth 0.5 to 1.0m; Fig.13), which is determined by the small sizes of receptacle cavities and fissures between boulders in the breccia horizon. They commonly appear as gradual subsidences, although small collapses also occur. With time, such dolines may gain larger diameters (up to 3 to 5m), and their discrimination from dolines formed by the VSP mechanism becomes problematical. The morphometric criteria are ambiguous, and distinguishing this type would be difficult without precise comparison of surface and underground features.
within the cave field. For instance, six small dolines are located immediately above cave passages (see Fig.4A) but there are no percolating fissures, pipes and breakdown piles in the related underground locations.

4. Subsidence hazard assessment

Detailed mapping of breakdown structures in caves facilitates precise hazard assessment with respect to cave-related collapse/subsidence features (see also paper by Klimchouk and Andrejchuk in this volume). However, such an assessment remains site-specific, accomplishable only for the areas of cave fields. Nevertheless, an understanding of the mechanisms of breakdown formation, gained from speleological observations, allows development of more adequate approaches to subsidence hazard assessment in areas holding similar geological, hydrogeological and speleogenetic characteristics.
The sulphate karst of the fore-Ural is generally characterized by:

- incomplete opening of the soluble rocks by river valleys;
- presence of a 10 to 80m-thick vadose zone in sulphate massifs;
- dense fissuring and stratification of sulphate rocks;
- presence of a 5 to 30m-thick karst breccia horizon and loose Quaternary sediment cover at the tops of massifs.

The situation on the Ice Mountain is representative of the sulphate karst of the region as a whole; hence the breakdown formation mechanisms revealed by this study can reasonably be extrapolated across the entire region.

This study suggests that collapse and subsidence dolines in the Ice Mountain evolve through several distinct mechanisms, described above as gravitational, gravitational/filtrational (after VSP) and suffosional. The differences between these mechanisms result in different appearances, distribution patterns and onward evolution of the respective forms at the surface, which necessitates different approaches to subsidence hazard assessment. Based on the Ice Mountain example, an attempt is made below to outline possible approaches to such assessment.

4.1. Hazards imposed by gravitational breakdown

One of the principal goals of the assessment is to distinguish between areas prone to subsidence (collapse) and those where no karst-induced deformations may occur. Considering dolines formed by the gravitational mechanism in intrastratal karst settings with varying thickness of the overburden, this can be performed by evaluating the critical thickness above which breakdowns cease and therefore cannot reach the surface (Andrejchuk, 1994, 1995, 1999). It was shown above that the question of whether a stoping void can reach the surface or not depends upon the height achieved before a breakdown pile and breakout dome meet during the upward stoping process, in relation to the overburden thickness. This height, the height of closure ($h_c$), depends on the coefficient of rock loosening ($K_{loos}$) and the initial height of the receptacle cavity ($h_o$). It can be estimated using a simple formula (Andrejchuk, 1999) accounting for these two factors:

$$ h_c = h_o \frac{K_{loos}}{K_{loos} - 1} $$

where:

- $h_c$ – the height of closure (with reference to the level of the cave floor) of the breakout dome ceiling and the overtaking breakdown pile;
- $h_o$ - the initial height of the receptacle cavity;
- $K_{loos}$ – coefficient of rock loosening.

For example, the height of closure for the breakdown occurring above a 5m-high cavity, where the coefficient of loosening is 1.4, will be 17.5m. One can show that even in cases of receptacle cavities with relatively large vertical dimensions (5 to 10m) and small $K_{loos}$ (1.2 to 1.4), closure occurs at a height of 30 to 60m above the cave floor.
This explains why no large gravitational collapses occur at the surface above Kungurskaya Cave. They are virtually impossible because of the thickness of overburden commonly exceeding 60m. Moreover, $K_{loos}$ is typically >1.5 for predominantly slab and block breakdowns in the cave, which decreases the height of closure further. Therefore, gravitational breakdowns do not pose a hazard within the area of the cave field, as migrating voids cannot reach the subsurface (5 to 10m) zone.

Using this approach an assessment can be made for the whole area of the Ice Mountain (Fig.14). The starting data are as follows:

- Cave passages occur at a level of 115 to 120m asl (a level of 130m is adopted, as it results in a more conservative estimate)
- Average height of chambers and master passages is 5m;
- Coefficient of loosening is 1.3 (minimum).

These data indicate that the level at which typical breakdown structures cease stoping is about 21 to 22m above the passages, at an altitude of 151 to 152m. By taking the 160m map contour as marking the upper limit of gravitational breakdown structures, the massif can be divided into two areas. In the area below 160m the formation of collapse dolines by gravitational mechanism is possible, and no such dolines can occur in the area above 160m (Fig.14A).

The map shows (compare also with Fig.3A) that the greater part of the Ice Mountain, all of the watershed plateau with altitudes of 180 to 215m and the upper parts of slopes, appear to be within the safe zone. The western, gently terraced part and the northern part are slopes of the Sylva and Shakva river valleys, comprising areas prone to collapse due to gravitational breakdown of passage ceilings. The remarkably high density of surface karst features, large dolines in particular, on the western slopes of the Ice Mountain (especially within the area called “Bajdarashki”, a kind of a forested karstic badland) is assumed to relate mainly to the intense gravitational destruction of an underlying cave system.

4.2. Hazards imposed by breakdowns formed after vertical solution pipes

Within the cave field the exact positions of most of the pipes and breakdown talus- es are known from the cave survey. By superimposing the large-scale surface plan on the cave survey the area can be classified according to the probability for new collapses to form by this mechanism. Considering that there could still be unknown pipes and associated breakdown structures, even in close proximity to the mapped passages, the whole cave field area should be treated as potentially hazardous. Locations above pipes and breakdown piles with no visible collapse/subsidence features should be considered as the most hazardous, as well as areas on the continuation of major passages terminated by breakdown, where unknown blind pipes may exist. The potential for re-activation and further growth of pre-existing pipe-related dolines can also be evaluated, based on the predictabilities of their evolution, described above.

Assessment of areas without accessible caves cannot be made in the same way as for the cave field areas. However, the cave field methodology represents a useful model from which some parameters can be derived to help with the evaluation of larger areas displaying similar physiographic and geological conditions.
Fig. 14 - Regionalization of the Ice Mountain area according to the conditions of formation of collapse dolines by gravitational mechanism (A) and profile illustrating these conditions (B). 1 = the area prone to collapses due to gravitational breakdown of passage ceilings; 2 = the area where no collapse dolines due to gravitational breakdown can occur; 3 = the area with an extremely high density of collapse dolines; 4 = entrance to Kungurskaya Cave.
The area of the cave field is 0.5 km². 80 dolines in this area are identified as having formed after vertical solution pipes, which suggests an extrapolated density of 160 dolines/km². There are 150 mapped pipes, suggesting a density of 300 pipes/km². The ratio of the density of this type of doline to the pipe density could be termed the "coefficient of pipe collapse realisation" = $K_{VSP}$. This may be as large as 0.53, indicating that only slightly more than a half of the existing tubes have so far produced collapse/subsidence features. Hence, almost the same number of new features can be expected to form within the study area in the future. This useful qualitative indication of potential hazard can also be applied to similar areas. For instance, in the central part of the Ice Mountain the observed density of dolines classified as having VSP-related origins is 40/km², but the prognostic density is $40 / 0.53 = 75$ dolines/km².

Evaluations performed in other areas of the fore-Ural region where observations in caves were possible, suggest that $K_{VSP}$ may vary between 0.3 (highly hazardous areas with respect to new collapses) to 1.0 (areas highly karstified at the surface but rather safe in terms of probability of new collapses). The VSP density parameter, needed for evaluation of $K_{VSP}$, can also be derived from observations in quarries, mines and riverside exposures.

4.3. Hazards imposed by suffosional dolines

These dolines are not related to caves in the sulphate rocks, and hence no specific approach for evaluation of the relevant hazard can be derived from speleological observations. They can form almost everywhere where the karst breccia horizon underlies the loose sediment cover, but areas situated at lower elevations than this horizon can be regarded as safe with respect to this type of deformation. Because of their prevailing appearance as gradual subsidences rather than collapse features, and because of their small sizes, dolines of this type present the least hazard among the types considered in this paper.

5. Conclusions

Breakdown structures related to the Kungurskaya Cave develop by two mechanisms: gravitational and filtrational/gravitational. The former implies upward stoping of a breakout vault and cessation of the process at some height above the base of the cave, due to its complete filling by fallen clasts. Hence, this mechanism cannot generate surface deformation where the overburden thickness exceeds a certain value. The latter mechanism, stoping of a vault in vertical solution pipes guided by downward percolation, implies that breakdown will almost inevitably express itself at the surface, most commonly as a sudden collapse, even where the overburden thickness is large. Each mechanism results in specific morphologies of dolines and their further evolutionary forms. Subsidence hazard assessment should be performed differently for each type of breakdown.

Deformation and destruction of ceilings due to failure of large unsupported passage spans is more common in the fore-Ural gypsum karst than in the Western Ukraine, because of the dense fissuring and stratification of the sulphate sequence. However, where the overburden thickness is substantial, the main causes of collaps-
es at the surface are breakdown structures evolved after vertical solution pipes.

Thus, this study suggests (see also Klimchouk and Andrejchuk in this volume) that breakdown formation is not related primarily to large passage spans, and that relatively small forms, indicative of hydrodynamically and speleogenetically “exploited” and “weakened” localities (i.e. vertical solution pipes) are the major cause of deformations at the surface. However, size of passages, though not influencing location and the initial diameter of collapse, does exert guidance, through the cavities’ receptacle capacity, over size of mature dolines.

Direct observations in caves, aimed at breakdown characterisation at regional or site-specific levels, are inevitably essential for a more adequate understanding of breakdown mechanisms and assessment of karst subsidence hazard.

Acknowledgement

The authors sincerely thank Dr. David Lowe of British Geological Survey for improving English in this paper.

REFERENCES


DOROFEEV E.P. 1968. Relations between underground and surface karst forms, on the example of the Kungurskaya Cave. 147-151. In: Proektirovanie, stroitel'stvo i explanatatsija zemljanogo polotna v karstovykh rajonakh. Moscow. (russ.).


KLIMCHOUK A.B. and ROGOZHNlKOY V.YA. 1984. Relations of surface and underground
COLLAPSE DOLINES AND DEFLECTOR FAULTS AS INDICATORS OF KARST FLOW CORRIDORS

France ŠUŠTERŠIČ

ABSTRACT

The paper concerns collapse dolines, which appear to be one of the best-defined surface karst phenomena. Despite this appearance, one may find quite different views in the literature, and some of the aspects of their morphogenesis have been overlooked completely. Among these aspects the most obvious is the question of the ongoing development of the closed depression. Five of the most common collapse doline types found in Slovenia are considered in terms of general systems theory, leading to a conclusion that cave roof collapse remains the crucial event in a collapse doline’s development. However, the collapse event itself may be relatively subdued in terms of the volume of free fallen mass involved. Some types of collapse dolines appear along particular types of faults that function as a kind of screen; these faults are termed deflector faults. They are marked by collapsing within the caves, and by “active” collapse dolines on the surface. Existence of deflector faults is an indicator of flow corridors in the close neighbourhood.

KEYWORDS: collapse dolines, cave breakdown

1. Introduction

Larger scale karst subsidence phenomena that characteristically involve an element of catastrophic development are discussed. These were long ago added to the standard inventory of geomorphologic features, and are referred to generically as collapse dolines. The central ideas of karst science have remained essentially unchanged for more than a century (see Cramer, 1944, p.327), but field study has revealed a variety of evidence that makes the general understanding of the expression “collapse doline” much wider (Šušteršič, 2000a). This paper:
- describes and interprets the situations most commonly found in the Slovenian Classical Karst;
- demonstrates that the role of some types of feature changes over time;
- discusses practical uses of these findings in understanding the hydrogeology of the karst.

Aspects discussed in the paper are applicable to many karst areas, but most are based on field examples within the Classical Karst of Slovenia. More regional details are provided by Šušteršič (1996, 2000b).
2. Geomorphic processes

In this paper, collapse dolines are considered strictly as projections of underground negative masses at the surface. However, whether all collapse phenomena at the surface originated in this way, is arguable.

General understanding of basic karst processes is that development of collapse dolines is controlled by two sets of factors:

<table>
<thead>
<tr>
<th>Underground mass removal</th>
<th>→</th>
<th>generation of doline volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>(trans)formation of doline slopes</td>
<td>→</td>
<td>generation of doline shape</td>
</tr>
</tbody>
</table>

Intuitively, the basic geomorphic processes (generally, but not inevitably, starting at the top of the Table 1) involved appear to be:

**Table 1. Geomorphic processes involved in collapse doline development**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RM</td>
<td>Underground removal of fallen material</td>
</tr>
<tr>
<td>2</td>
<td>FC</td>
<td>Formation of large caverns</td>
</tr>
<tr>
<td>3</td>
<td>AP</td>
<td>Approach of the cavern to the surface / surface to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the cavern</td>
</tr>
<tr>
<td>4</td>
<td>CL</td>
<td>Collapse / opening of the cavern to the surface</td>
</tr>
<tr>
<td>5</td>
<td>SR</td>
<td>Slope retreat</td>
</tr>
<tr>
<td>6</td>
<td>DD</td>
<td>Gradual disintegration due to denudation</td>
</tr>
</tbody>
</table>

Detailed discussion of the processes can be found within the general literature (see citations in Šušteršič, 2000a) and more detail of the scheme presented above is provided by Šušteršič (o.c.).

At first glance there appears to be a corollary that the original cave chamber must inevitably be very large at the time of doline formation. However, many field measurements (Šušteršič, 1973, 1974, 1997) reveal that very large collapse dolines may evolve from cave chambers of relatively modest ground plan. This can be a consequence of:

- the existence of vertically oriented negative masses (voids) within the parent rock, or/and

- prolonged mass removal, extending well into the phase of doline shape transformation.

The first possibility is the case at Vranja jama, north of Planinsko polje in south-central Slovenia (Šušteršič, 1994), where collapse is related directly to a phreatic jump between two inception horizons (sensu Lowe and Gunn, 1997). Similar conditions are at least strongly suggested at several points within the Najdena jama system nearby, and it seems that such relationships may develop where relatively small cave channels are cut by sudden breakdown.

The second possibility is obvious in cases where extremely large dolines lie at the intersection of regional underground water flow and (in the studied cases) local strike-slip faults (Šušteršič, 1997; Šušteršič et al., 2001). In both possible situations
tectonic loosening of the parent rock has enhanced, if not dominated, the collapse process.

Mass removal by system drains is inevitable, but it is not the only influence upon doline volume and shape. In some cases, like Dolec (collapse doline) in the Najdena jama system (north of Planinsko Polje), a permanent draught of cold air into the cave from between collapsed boulders suggests that the potential role of condensation water in corroding fallen material cannot be ignored (Šuštersič, 2000a, p.218).

Though generally not mentioned explicitly, the final step in the logical chain is the gradual disintegration of the doline’s slopes and, consequently, the gradual loss of the doline’s identity within the surface. Surface denudation around and within the doline is constantly active but, being relatively slow, its effects can be neglected during the time that mass removal by an underground drain and/or condensation water and parallel slope retreat are active. Later, surface denudation becomes the only agent to operate upon the doline, slowly equalising vertical differences, perhaps making the doline shallower and wider (Habić, 1978). Eventually the now-subdued former collapse doline becomes just one among a variety of hollows on the land surface. Only outcrops of cave sediments (related to intersected caverns) within the slopes testify to the origin of the hollow. Such depressions are termed phantom collapse dolines (Šuštersič, o.c., p.218).

3. Common outcomes

A widely but tacitly accepted idea that, within a doline, the processes listed in Table 1 operate sequentially appears obvious (i.e. only one process can operate at a time). However, field evidence does not support this oversimplification. Instead, a number of combinations may occur, resulting in a variety of outcomes that may seem contradictory. Considering negative mass transport of breakdown material as the main process (i.e. non-denudational removal by the underground drain), collapse dolines may be either closed or open systems. Even so, it must be stressed that all collapse doline development sequences have a common end point (phantom dolines).

The following figures and text do not set out to examine development sequences in detail, but describe only the more interesting aspects.

Case Cl: totally closed system, stable cave roof (Fig.1, Cl)

The expression totally closed system indicates that mass removal by the underground drain ceases long before the big chamber establishes a stable roof. In such cases gradual ceiling breakdown and consequent accumulation of debris on the floor will initially insulate the void from the influence of any neighbouring cave channels. The process should stop as soon as a stable arch develops (Scheidegger, 1961).

Some (perhaps exceptional) field examples demonstrate that such stability is not achieved immediately. As the process advances, the ceiling adjusts to the geostatic stress field, gradually attaining mechanical equilibrium. A parabolic arch develops (Renault, 1967) and the chamber tends towards attaining a circular, or at least elliptical, ground plan (Šuštersič, 1974).
Case C2: totally closed system, unstable cave roof (Fig.1, C2).

In some cases the cave roof cannot achieve a stable arch morphology. Though the cavern’s ground plan may be at least equi-dimensional and tending towards elliptical or circular, the roof is highly irregular and free of flowstone cover, and collapsed debris on the floor looks fresh. The chamber is still developing, in the sense that collapse is ongoing. Such unstable cavern roofs will probably continue to decay until collapse eventually transforms the cave into a doline. Because the bulk volume of broken rock is greater than that of the solid source rock (Šušteršić, 1973), this process causes a reduction of the cave volume. However, if the rock above the original cavity is thick enough the chamber could eventually be filled completely (the void is consumed) due to the relative volume increase of the debris (Šušteršić, 1974). In such cases the breakdown process will stop before the collapse reaches the surface, and no doline will appear (Šušteršić, o.c., p.30, Fig.1b).
Cases C1 and C2 differ in the way that the arched cave roof arrives close to the land surface – that is, how the ceiling becomes too thin to support itself. In the second case cave roof block spalling and denudational surface lowering both operate. In the first case only the latter operates and the process might be much slower overall. Though no direct measurements of the rate of roof spalling in caves of this type exist, the process appears to act much more quickly than does simple denudation.

Variations on cases C1 and C2 may develop from initial phreatic jump situations (Šušteršič, 1996). Here the original cave chamber will be little wider than neighbouring “horizontal” passages. Volume will be distributed vertically, and the roof would not be expected to be unstable. After sufficient denudational surface lowering a relatively narrow but deep, vertical-walled, depression will appear, soon to transform into a more typical collapse doline of smaller dimensions. The entrance “shaft” of Gradišnica cave (Marussig & Velkovrh, 1959; Nagode, 1997) appears to be of this type.

Case C3: Hypothetical outcome: partly open system, closure at the time of collapse (Fig.1, C3).

This case is included because it appears to be accepted tacitly in some older literature. In 1963 Habič provided apparent support based on field observation of various collapse dolines in the area behind the Ljubljanica springs near Vrhnika. He noticed that their absolute floor levels fall within relatively few groupings, even though their rims are at various elevations. He concluded that this is the consequence of two facts:

- the caves beneath were formed at clearly defined levels, and
- removal of fallen mass lasted until the roof eventually collapsed.

For many years the validity of the former idea was, at best, uncertain, because only fragments of phreatic systems were known in the general area. Several caves have now been explored fully and the idea can be refuted. Reliable field evidence (Brenčič, 1992; Šušteršič, 1994) confirms that caves at discrete levels neither exist nor existed in this area, and there is no need to postulate them.

Case O1: totally open system, shallow underground stream (Fig.2, O1).

At some locations, where cave systems develop at relatively shallow depth, chamber ceilings will spall down progressively, until breaking through to the surface. Simultaneously, underground stream flow below is strong enough to remove collapse debris. Consequently, slope retreat within the newly formed dolines is unconstrained and they merge together. Eventually, a string of collapses will change into a canyon that will gradually be transformed into a karst valley. Denudation, however, cannot lower the floor of the depression below base level. Consequently, the valley will evolve into a wide depression with gentle slopes, which could be compared to a small karst polje. The Rakov Škocjan valley, with its natural bridges, is an excellent example.

In the case of Rakov Škocjan there is no necessity to invoke the involvement of significant tectonic structures. Relatively large cave chambers, later to be transformed into collapse dolines, develop mainly due to the direct influence of lithological contrasts. The underground stream retains its primary position because it can cope with removal of the total amount of collapsed material.
Fig. 2 - Collapse dolines explained in terms of open system conditions. Note that the last stages (phantom dolines) are omitted from this figure (cases O1 and O2). The scale is different in each example, and in the O2 case the volume of the doline might be as much as 100 times larger than that in the previous case (O1).

Case O2: totally open system, deep underground stream (Fig. 2, O2).

Present volumes of cave chambers such as Brezno pri Medvedovi konti (see Kortnik in this volume), which is $62 \times 10^4$ m$^3$ (Šuštersič, 1973), appear to be “enormous”. However, the doline that will evolve from such a chamber will not be spectacular, compared with the larger examples listed in Table 2. By reference to the example of the Rakovska kukava in the Classical Karst of south-central Slovenia, Šuštersič (1997) demonstrated that very large collapse dolines can evolve from relatively small cave chambers. However, a much more impressive example is provided by Laška kukava. This is nearly 100m deep and its volume surpasses 4Mm$^3$ (Table 2). There are two active foci of recent material removal in its floor (Šuštersič, 1974).

Not far away a clue to the formational mechanism of this type of collapse doline
is found in Riba jama. Here the whole of the accessible cave is a single, c.40m-deep cavern with an amoeba-like vertical section. Evidently this cavern formed by the simple settling down of tectonic crush within the shatter zone of a local strike-slip fault. The explanation is that underground water finds such zones difficult to break through. Consequently, once a route was opened, flow along it would persist, even if the passage was repeatedly obstructed by the ongoing periodic collapse of tectonic crush material. Such material being unstable, the process would continue until a Riba jama-like cave appeared at the surface. If the karst stream flow persisted long enough in the same position, the “cave” would eventually evolve into a doline, which would increase in volume until the stream flow ceased (start of closed system conditions), or until it appeared at the surface.

Evolution of Riba jama into a large collapse doline is, however, an extreme case. Provided that the underground stream is strong enough to cope with the debris production, achieving the necessary redistribution, all three cases presented as possible “closed system conditions” products can evolve further into an O2-type doline. Such cases may be even more common than the Riba jama case.

It must be stressed that the largest dolines of this type have volumes that surpass those of the largest cave chambers by a factor of about 20. Development of cave chambers of approximately similar volume is mechanically impossible (Šušteršič, 1973).

<table>
<thead>
<tr>
<th>Collapse dolines</th>
<th>Big chambers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laska kukava</td>
<td>Gradišnica / Błatna dvorana</td>
</tr>
<tr>
<td>Smrkovca</td>
<td>Najdena jama / Putickova dv.</td>
</tr>
<tr>
<td>Rakovska kukava</td>
<td>Najdena jama / Sulceva dv.</td>
</tr>
<tr>
<td>Dolga dolina</td>
<td>Logarček / Błatna dvorana</td>
</tr>
<tr>
<td>Gladovec</td>
<td>Jama za Bukovim vrhom</td>
</tr>
<tr>
<td>Ivanska kukava</td>
<td>Mačkovca / Velika dvorana</td>
</tr>
<tr>
<td>Cerkniška kukava</td>
<td>Logarček / Podorna dvorana</td>
</tr>
</tbody>
</table>

The “cases” examined above are not the only possibilities, and the options discussed here are those that appear to be supported by field observations. In other words, they are the options needed to explain, and allow understanding of, the collapse dolines of south-central Slovenia.

4. Deflector faults, collector channels and collapse dolines

Among the collapse dolines discussed above, those of O2 type are the least likely to be overlooked. Not only do they have the greatest volumes, they are also the most

<table>
<thead>
<tr>
<th>Volume</th>
<th>Cave Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.17 Mm³</td>
<td>Laska kukava</td>
</tr>
<tr>
<td>1.60 Mm³</td>
<td>Smrkovca</td>
</tr>
<tr>
<td>1.35 Mm³</td>
<td>Rakovska kukava</td>
</tr>
<tr>
<td>1.10 Mm³</td>
<td>Dolga dolina</td>
</tr>
<tr>
<td>0.92 Mm³</td>
<td>Gladovec</td>
</tr>
<tr>
<td>0.85 Mm³</td>
<td>Ivanska kukava</td>
</tr>
<tr>
<td>0.53 Mm³</td>
<td>Cerkniška kukava</td>
</tr>
</tbody>
</table>
easily recognizable, at least in the Dinaric Karst. Some of their characteristics need to be emphasized (Sustersič, 1997, p237, Fig.2; Šušteršič et al., 2001):

- most of them lie on well-expressed tectonic lines, perpendicular to the general underground flow direction;
- only a few of them achieved the “last” stage, during which the stream appears on the surface;
- predominantly they are ranged in lines along a master fault, and the dolines in the line are of different ages (reflecting the stages of slope decay).

This implies that they are related to the underground hydrology, and also that their role must change over time. This aspect was studied in detail at several field locations by Šušteršič et al. (2001), and a summary of the main ideas is given below. The study set out to investigate the idea that large (several kilometres long) collector channels exist parallel to the margins of some karst poljes in Slovenia (Gams, 1965, p.87).

The main drain of the Cerkniško polje (Classical Karst, south-central Slovenia) is a system of four interconnected caves, known generally as Karlovice (Fig.3). The

![Diagram](image)

Fig. 3 - Tectonic, speleological and doline pattern at the northwestern border of the Cerkniško polje.
total length of the presently known passages exceeds 8km. Due to the influence of deposits of Cerkniščica River dolomite gravel the general development of the cave was epiphreatic, but remnants of earlier phreatic shaping are still clearly recognizable.

Gams (1965) noticed that a string of channel segments, locally trending in various directions yet with a relatively consistent general alignment, extends parallel to, but about 100m to 200m away from, the polje margin. In view of their present function – collecting water from numerous streamlets sinking into small openings along the polje margin – Gams (o.c.) considered these segments to be parts of a collector channel. Gams stressed the parallelism of the collector channel with the polje margin. Its total length is nearly 2km and its SW-NE orientation is approximately perpendicular to the dominant regional (Dinaric) tectonic trend.

In the wider area around Karlovice the polje border is more or less vertical (with walls up to 40m high) and surprisingly straight for several kilometres. According to Čar & Gospodarič (1984) the polje border is tectonically guided. Thus, it might be expected that the parallelism of the collector channel is also somehow related to this guidance. However, the collector channel cannot run parallel to the polje border indefinitely. At some point the stream, endeavouring to flow away from the polje, must veer onto a direction perpendicular to the guiding structure. In other words, the fundamental condition for the formation of O2-type dolines must be fulfilled.

Within the cave Gospodarič (1970) identified several smaller faults on the same (perpendicular to Dinaric) trend, but limited access meant that no general conclusions could be drawn. Čar and Gospodarič (1984) recognized a regional fault on the same trend running a few hundred metres northwest of and parallel to the collector channel. This speleogenetically important fault was named Karlovški prelom (=Karlovice Fault) by Šuštersič et al. (2001).

The influence of the Karlovški prelom upon the cave system is obvious. On its southeast side (related to the part shown on Fig.3), the general trend of the collector channel is nearly straight. Active inlets deriving from the polje join it from the polje direction, whereas passages running away from the collector channel and away from the polje, towards the Karlovice Fault, are inactive and, as a rule, terminated by collapses.

Farther northeast the collector channel degenerates into a 3-D maze of scarcely accessible passages. Here also passages leading from the collector channel towards the Karlovice Fault are inactive, and choked by collapse. The main stream changes direction, becoming perpendicular to the Karlovice Fault trend. Gospodarič (1970) observed the fault zone at several points. Where the main stream crosses the fault zone ceiling collapse has modified the passage extensively. Surface mapping by Habič (1966) revealed several collapse dolines in different stages of decay at locations where currently unknown or inaccessible passages cross(ed) the fault.

Comparable relationships are repeated about a kilometre to the northwest, where the stream encounters a similar fault. It is evident that Karlovški prelom and the parallel fracture initially permitted water transmission perpendicular to their strike. However, as the passages continued to enlarge, the broken rock was too weak to maintain a stable arch. Subsequent roof collapse brought about formation of collapse dolines, whose floors continued to be undercut by the river until it had formed by-
pass channels nearby. It must be remembered that broken zones, though initially more transmissive than the solid rock, are much less able to support channel formation. When the water has enlarged the pores/voids between the rock fragments sufficiently, the whole mass will settle down and the situation will return to the beginning. On the other hand, the bedrock channel will grow continuously and finally attract most of the flow. The same relationship also holds good between completely loose collapse boulders and the partly re-cemented broken zones of inactive faults. Collapse of the cave roof at the points where the stream crossed the fault gradually forced the stream to concentrate into one collector channel, which runs parallel to the fault until reaching the point where water can (presently) cross it. Due to their "organizing" role such faults are termed deflector faults (Šušteršič et al., 2001, p.22), and all those so far studied are of early Tertiary age.

The collapse doline pattern evident on Fig. 3 indicates that the fault broken zone’s transverse transmissibility must be relatively uniform, whereas its mechanical strength, permitting the formation and survival of larger passages, is low. The collapse dolines have reached various stages of decay, indicating that they must have formed at different times. However, their dimensions are modest and local conditions could have influenced their appearance (apparent “age”) significantly. Also, their dimensions are still within the range of the largest cave chamber volumes, so that it is uncertain (though very likely) whether the subsequent enlargement characteristic of O2 type dolines took place.

This situation becomes obvious in the case of the Logarček cave (Fig.4), close to the northeastern border of Planinsko polje. Collapse dolines, some with volumes approaching 1 Mm$^3$, are clearly arranged along the early Tertiary Slavendolski prelom (= Slavendol Fault). The cave’s main passage appears to “bounce” along it towards the north. In this case the deflector fault is not aligned parallel to the polje border, yet its influence upon the formation of collapse dolines and the collector channel is obvious. Other faults on a similar trend that formed later in the Tertiary are not implicated in collapse doline formation, though they have guided development of some chambers in the cave.

It is evident that the Slavendolski prelom fracture zone and related collapse dolines deflected the underground stream northwards. However, farther north in this string there is one more collapse doline. It lies about half a kilometre beyond the northernmost doline marked on Figure 4. Its volume is “only” 0.62 Mm$^3$ (Šušteršič, 1974, p.36) and it appears to be quite “fresh”. Perhaps this is the location of the cave stream’s present breakthrough of the Slavendolski prelom broken zone (Šušteršič et al., 2001).

Conclusions

Even allowing for the restricting condition that, by definition, at least a small component of cave roof free fall (collapse) is crucial, several genetic sub-types of collapse doline can be recognized and defined.
The largest collapse dolines are those of type O2. These collapse dolines develop where cave streams cross a certain type of fault. Generally, several such dolines are aligned along a single master structure. The individual dolines are always of different ages (as best reflected by their degree of slope decay). Strings of type O2 collapse dolines do not reflect earlier cave directions; instead they indicate the locations of the main stream’s breakthrough of a structural barrier.

Collapse doline formation (and the effects of collapse in general) where the underground stream breaks through the master fault gradually deflect the stream onto a direction parallel to the master fault. Faults that have this effect are termed deflector faults.

Long-term cave system development under the guidance of deflector faults brings about the formation of collector channels. Development of a collector channel is a direct consequence of flow corridor rearrangement in response to the existence of a less transmissive and less stable geological structure, lying athwart the regional hydraulic gradient.
In combination with knowledge of the general hydrogeological conditions the mere existence of strings of type O2 collapse dolines on the surface offers information about the (likely) underground cave system organization.

Acknowledgement

Thanks to Dr. David J. Lowe for smoothing the English text, and for making many little suggestions that improved the contents.

REFERENCES


STABILITY APPRAISAL OF THE MEDVEDOVA KONTA POTHOLE

Jože KORTNIK

ABSTRACT
Until 1956 the underground details of areas around Pokljuka were practically unknown due to the area's non-karstic outward appearance. However, the presence of karst phenomena on this Alpine plain is undoubtedly indicated, primarily by the absence of a surface drainage network. A mathematical model was made of the Medvedova konta pothole, in which two different sets of material properties were used, corresponding to the Triassic limestone that forms the bedrock under the greater part of Pokljuka. The model simulates the gradual thinning of the ceiling of the underground hall, from the surface downwards, until its collapse.

The paper presents a stability appraisal of the Medvedova konta pothole in Pokljuka.

KEY WORDS: Medvedova konta pothole, stability appraisal.

1. Introduction – the Medvedova konta pothole

The history of research at the Medvedova konta pothole dates back to 1956, when a group of speleologists (J. Kunaver) first heard about this 200m-deep pothole from a Pokljuka forester. Until that year, underground features were practically unknown in the area around Pokljuka, primarily because this Alpine plain does not have a karstic appearance, as do, for example, the Jelovica, Mežakla or other plains surrounding the Slovene Alpine massifs. However, the presence of karst phenomena at Pokljuka is undoubtedly indicated, primarily by the absence of a surface drainage network in the central part, and by the presence of large sinkholes. The in the greater part of the Pokljuka area is Triassic limestone, on which a kind of covered or latent mountain karst has formed at the surface due to the presence of younger sediments and rock. In this case, surface karst phenomena are less numerous and less pronounced, and this is especially true of the youngest surface forms.

The entrance to the Medvedova konta pothole lies at an elevation of about 1390m, in the northwestern, upper part of Medvedova konta, between the peaks of Liparski vrh (1983m), Brdo (1844m), Okroglež (2009m) and Debele peč (2015m), where the Pokljuka plain begins to rise into the Pokljuka ridge.

The entrance void was formed along a major fault line, which runs NNW-SSE and is clearly visible at the surface. First, a deep and very steep sinkhole was formed along this fault line. On one side of the sinkhole is a vertical wall that continues into a pothole at its base, and then widens out into a hall at a depth of 45m. The dimen-
sions of the pothole, which has a rectangular profile along its entire length, are 6x3m at the top, expanding to 9x5m towards the transition into the hall. The pothole merges with the hall at its extreme southern end. The highest part of the hall ceiling is not at the point of the shaft’s entry, but is above the eastern part of the hall, and is estimated to be about 57m above the floor. The circumference of the hall is 433m, and the ground plan of the hall is an irregular circle, with a maximum width of 152m and a minimum width of 132m (Fig.1). The hall floor slopes towards the middle, from the southern and western parts to the north-western part. Approximately one third of the floor between the northern and the western parts of the hall is relatively level. In two places, the hall floor drops into potholes, both of which are of known depth. The first was formed in a similar manner to the entry pothole, near the fault line, right beside the hall wall. It is 20m deep, and at an elevation of 142m, its foot is the lowest point of the Medvedova konta pothole (Kunaver, J., 1960).

Fig. 1 - The Medvedova konta pothole.

2. Stability appraisal

A stability appraisal of the Medvedova konta pothole was made using the FLAC (Fast Lagrangian Analysis of Continua) numerical software package. The program is a two-dimensional explicit finite difference program for engineering mechanics computation. It offers a wide range of capabilities to solve complex problems in mechanics. Materials are represented by elements within a grid that is adjusted by the user to fit the shape of the object to be modelled. Each element behaves according to a prescribed linear or non-linear stress/strain law in response to applied forces or boundary restraints. The material can yield and flow, and the grid can deform and move with the material that is represented. The program is based on a Lagrangian
calculation scheme that is well suited for modelling large distortions and material collapse (Coetzee et al., 1993).

3. Primary stress state

The thickness of the ceiling of the hall in Medvedova konta is approx. 59m, which means that the roof of the main hall is located relatively close to the surface. In such cases, the ratio of horizontal to vertical stress varies considerably, but generally the horizontal stress $\sigma_H$ exceeds the vertical stress $\sigma_V$. Diagrams of coefficient $k$ versus depth were made on the basis of numerous measurements in different types of rock (Brady and Brown, 1985).

$$k = \frac{\sigma_H}{\sigma_V}$$

For a depth of 100m, the coefficient $k$ ranges between 1.3 and 3.5. In the model, the value of $k$ was assumed to be 1.

4. The model of the Medvedova konta pothole - profile C-D

One model was made, in which two different sets of material properties were used, each corresponding to possible properties of the Triassic limestone. The sets of material properties shown in the table below confirm the stability of the model before the beginning of the thinning of the ceiling.

![Figure 2 - Model of the Medvedova konta pothole - profile CD (Figure 1.)](image-url)
The model simulates the gradual thinning of the hall ceiling from the surface downwards, until its collapse. The grid size is 223x162 elements. The Mohr-Coulomb plasticity model was used.

**Table 1. Sets of rock properties used in the model**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Unit</th>
<th>Set 1</th>
<th>Set 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>(GPa)</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>ν</td>
<td>(GPa)</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>T</td>
<td>(MPa)</td>
<td>1.85</td>
<td>4</td>
</tr>
<tr>
<td>γ</td>
<td>(kg/m³)</td>
<td>2732</td>
<td>2732</td>
</tr>
<tr>
<td>C</td>
<td>(MPa)</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>ϕ</td>
<td>(°)</td>
<td>35</td>
<td>35</td>
</tr>
</tbody>
</table>

Three control points were chosen in the rock above the hall ceiling, where displacement development was monitored. The model was treated as stable if the displacement values at control points converged towards an end value. In the opposite case, the development of displacement values indicated the collapse of the hall ceiling.

**5. Results of modelling**

In the model, thinning of the hall ceiling was simulated by introducing gradual decreases of the cover thickness downwards from the surface side. This was performed in 10 steps, and the results are shown in Table 2.

**Table 2. Maximum displacements during the thinning modelled in the hall ceiling.**

<table>
<thead>
<tr>
<th>Step</th>
<th>Cover height (m)</th>
<th>Max. displacement Set 1 (mm)</th>
<th>Max. displacement Set 2 (mm)</th>
<th>Appendix</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>59</td>
<td>68.4</td>
<td>21.9</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>50</td>
<td>63.9</td>
<td>20.4</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>40</td>
<td>59.9</td>
<td>19.1</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>30</td>
<td>57.8</td>
<td>18.4</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>20</td>
<td>59.6</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>15</td>
<td>63.7</td>
<td>20.3</td>
<td>Figure 5, 6.</td>
</tr>
<tr>
<td>7.</td>
<td>10</td>
<td>83.3</td>
<td>26.7</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>8</td>
<td>107.7</td>
<td>34.6</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>6</td>
<td>154.0</td>
<td>49.4</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>&lt; 6</td>
<td>collapse</td>
<td>collapse</td>
<td></td>
</tr>
</tbody>
</table>

For both modelled sets of rock properties, the hall ceiling collapses when its thickness falls below 4m. Plastic areas appear in the rock near the ceiling and hall sides throughout the modelling. They are especially common in the area of the left and right hall sides, and, with the thinning of the ceiling, they migrate towards the hall ceiling and the surface. In places where the ceiling is thinner than 20m, there are gradual indications of the possibility of hall ceiling collapse. The maximum dis-
placements appear at the edges of the hall (Fig.3). Throughout the modelling, the maximum displacements appear in the hall ceiling and decrease towards both sides of the hall. The development of displacements at the control points of the model indicate a decrease in the maximum displacements with a decrease in ceiling thickness to 30m. With further modelling, displacements gradually increase with thinning of the hall ceiling, up until complete collapse (Fig.4).

**Fig. 3 - History of y-displacement at point 1 (110, 102).**

**Fig. 4 - Thinning of the Medvedova konta hall ceiling.**
Solid rock, such as the Triassic limestone, is characterised by brittle breakage. Since such rock can withstand only low percentage plastic strain, any appearance of plastic areas in the model represents a potential danger of hall ceiling collapse (Figs 5 and 6).

**Fig. 5** - Plasticity indicators in the surroundings of the hall area (ceiling thinner than 20m).

**Fig. 6** - Shear stresses in the surroundings of the hall area (ceiling thinner than 20m).
6. Conclusions

The model presented demonstrate that a hall ceiling collapse is an underground-rooted surface karst form. More precisely, it may be considered as a non-karstic projection of a karst void onto the karst surface (Sustersic, 2000).

The stability appraisal presented in this paper was used for study and research purposes at the Medvedova konta pothole. Modelling results of the type presented can contribute to an understanding of the mechanisms of sinkhole formation.

REFERENCES


COLLAPSE ABOVE THE WORLD’S LARGEST POTASH MINE (URAL, RUSSIA)

Vjacheslav ANDREJCHUK

ABSTRACT
This paper reports the results of the study of a huge collapse that occurred in June 1986 within the area of the 3rd Berezniki potash mine (the Verkhnekamsky potash deposit, Ural). Processes that took place between the first appearance of a water inflow through the mine roof and the eventual collapse are reconstructed in detail. The origin and development of a cavity that induced the collapse are revealed. Two factors played a major role in the formation of the collapse: the presence of a tectonic fold/rupture zone with in both the salt sequence and the overburden (the zone of crush and enhanced permeability), and the ductile pillars mining system.

KEYWORDS: collapse sinkhole, potash mine, Ural region, Russia

1. Introduction
The collapse that occurred within the area of the 3rd Berezniki potash mine (BPM-3) in July 1986 is one of the largest collapses ever to have occurred on salt deposits. It is unprecedented in terms of the depth of occurrence of the initiating cavity (>400m). The collapse occurred at a location where the depth and geological setting of mining were considered to provide the safest conditions of the whole deposit with respect to the potential collapse. This is the only collapse that occurred during the entire life of the mine. This collapse event and the preceding flooding of the world’s largest potash mine forced a revision of the development strategy for the deposit, especially the mining technology and the scope and aims of the accompanying scientific studies.

The collapse has raised an array of problems, the most important being the revealing of the causes of the mine flooding and the mechanisms of collapse formation. The author studied these issues for several years, in cooperation with the Geological Service of the “Uralkaliy” Enterprise. The paper presents a brief summary of the research, and a reconstruction of the geological and hydrogeological events and processes that led to the catastrophic collapse.

2. Geological structure of the collapse site
The Verkhnekamsky potash salt deposit is part of the Solikamsky potash-bearing
basin. The basin is located in the northern section of the fore-Ural, on the left side of the Kama River, between the Vishera (in the north) and Yayva (in the south) rivers (Fig. 1). The area of the basin is >6,500km² (Kopnin, 1995).

Saliferous sediments occur in the Irensky horizon of the Kungursky Series and in the Solikamsky horizon of the Ufimsky Series of Permian age. The salt body represents a giant salt lens that stretches 200km from north to south and is 50km wide (Fig. 2). The lens lies in the central part of the Solikamsky depression, the large (250x70km) structure within the fore-Ural deep. The salt deposit is complicated by dome-like dislocations resulting from halokinetic processes. The structures are asymmetrical, with their eastern flanks more gentle than the western, and their amplitude decreases eastwards from 150-300m to 30-50m.

The maximum thickness of the salt deposit is 500m. In its upper part potassium and potassium-magnesium minerals occur, forming the world-renowned Verkhnekamsky mineral salt deposit with enormous reserves of halite, potassium salts, potassium-magnesium salts and natural brines. The surveyed area of the spread of potassium salts is about 3,800km² (135 x 40-45km; Kopnin, 1995). Further prospecting is in progress on the deposit.

The total reserves of potassium-bearing minerals are estimated to comprise 56 billion tons of sylvinite (containing 9.8 billion tons of K₂O) and 76.5 billion tons of carnallite (Kopnin, 1996). The salts are mined by the room-and-pillar method. Two lithological zones are mined, each consisting of several productive beds: the lower 15 to 35m-thick sylvinite zone (beds A, Kr-I, Kr-II and Kr-III) and the upper sylvinite-carnallite zone containing nine potash beds (B, V, G, D, E, Zh, Z, I, and K) with eight intervening halite beds (B-V, G-D, and so on). The total thickness of the lower zone varies between 40 and 80m. Production is carried out by seven potash mines that belong to the “Uralkalij” and “Sylvinite” companies. The site where the catastrophic collapse occurred lies within the area of the 3rd Bereznikovsky mine, within the southern part of the deposit (Fig. 1B).
2.1. Lithology and hydrogeology

At the collapse site the underground mines lie at a depth of 235 to 425m below the surface (Fig. 3). Only the Kr-II bed of the sylvinite zone, with a thickness of 5 to 5.5m was mined here. In this area the total thickness of the sylvinite-carnallite litho-zone is reduced, at the expense of replacement of carnallite by halite and sylvinite.

Above the productive horizon is the 100 to 110m-thick salt complex (intercalated halite and carnallite beds)\(^1\). Its upper part (25m), near its contact with overlying terrigenous sediments, is called the transitional zone, within which halite beds intercalate with marls and gypsum (anhdrite). The salt complex belongs to the Irensky Formation of the Kungursky Series (P\(_1\)kgir\(_2\)). Immediately above the uppermost salt bed of the transitional zone, two beds (each 2m thick) of calcareous clays occur. Still higher (10 to 15m above the uppermost salt bed), there are 3 brine aquifers, respectively 2, 3 and 5m in thickness, with low specific yield. The brines are of Cl-Na composition (with minor amounts of MgSO\(_4\) and MgCl\(_2\)), with a total dissolved solids content of about 300 g/dm\(^3\).

Above the transitional zone lies the 50m-thick clay-marl sequence of the Solikamsky Formation (P\(_2\)sl\(_1\)). Its upper part hosts an aquifer in fissured marls, which contains brines of Cl-Na composition and TDS varying between 50-70 to >300 g/dm\(^3\). The groundwaters have considerable head (up to 150m or more). The lower part of the clay-marl sequence, which contains halite beds, together with the salt complex above the roof of the mines, comprise a lithological succession termed the waterproof complex (WPC). The waterproof characteristics of the succession are determined by its composition, which includes watertight salts, and by the presence of the brine aquifer, which protects the soluble salt rocks from the aggressive low-TDS waters of the overlying aquifers. Below the transitional complex the salt rocks do not contain brine horizons; such minor water shows as are observed are primary and related to sedimentation and diagenetic processes.

Above the clay-marl sequence, a 40m-thick limestone-marl sequence occurs, which is highly permeable and an aquifer, particularly in the culminations of brachyanticlinal structures. The aquifer is contained mainly in the upper part of the complex, where limestone predominates. Waters are HCO\(_3\)-Ca in composition, and

\(^1\) Names of divisions used in this paper are kept close to lithostratigraphic and mining nomenclature, and to terminology adopted by the local geological survey (Editors' note).
Fig. 3 – Geological conditions of potash mining in the Verkhnekamsky deposit (after Kopnin, 1995): 1 = Quaternary sediments, 2 = argillites, 3 = aleurolites and sandstones, 4 = dolomites, 5 = marls, 6 = clayey marls. Lithological divisions: 7 = variegated complex (Sheshminskaya Series), 8 = variegated complex (Solikamsky Series), 9 = terrigenous-carbonate complex, 10 = limestone-sandstone sequence, 11 = limestone-marl sequence, 12 = clay-marl sequence, 13 = salt complex (Bereznikovskaya Series). The water-proof complex: 14 = transitional zone, the lower part of the clay-marl sequence with two halite beds, 15 = salt-marl unit, 16 = salt unit, 17 = cover halite, 18 = halite-carnallite unit with potash beds Zh, Z, I and K, 19 = carnallite unit with potash beds V, G, D and E. Component content in rocks, %: 20 = clays and marls, 21 = halite, 22 = carnallite, 23 = carnallite and sylvinite, 24 = productive beds AB and Kr-II, 25 = sylvinite litho-zone, 26 = halite. Groundwaters: 27 = active circulation, 28 = sluggish circulation. Chemical types of groundwaters: 31 = HCO₃-Ca, 32 = SO₄-Ca, 33 = Cl-Na, 34 = TDS, g/dm³, 35 = directions of flow, 36 = fresh water / brine interface, 37 = salt karst level, 38 = movement of karst brines, 39 = dimensions of mining fields. Potash mines and their numbers: B – Bereznivovsky, C – Solikamsky.

The TDS is of the order of 0.2 to 0.5 g/dm³. The aquifer is recharged by infiltration of meteoric precipitation (where the beds crop out at the surface), and also by crossformational flow from aquifers located above and below (in the areas of fold plunge). At the collapse site the aquifer was confined, containing water under pressure.

The limestone-marl sequence grades upwards into sandstones, limestones and aleurolites which constitute the limestone-sandstone sequence (P₂s₁₂) of 50m in thickness. It contains a prolific aquifer (well yield is 10 l/s or more) with water of low TDS (0.2-0.5 g/dm³) and HCO₃-Ca composition. Recharge is from meteoric precipitation and the adjacent aquifers. At the collapse site the aquifer receives recharge from the aquifer above.

The limestone-marl sequence and the limestone-sandstone sequences together comprise the terrigenous-carbonate complex (TCC), and the underlying transitional zone and clay-marl sequences together are distinguished as the salt-marl complex.
(SMC). The Permian succession is capped by the multi-coloured (variegated) complex (PCC), composed of argillites, aleurolites and sandstones with a total thickness of about 100m ($P_{ss}$, the Sheshminskaya Series). Because of the lithological heterogeneity of the sequence, several small water-producing intervals located at various depths are relatively isolated, connected only adjacent to tectonic faults. The groundwaters are of HCO$_3$-Ca composition and low in TDS (0.2 to 0.3 g/dm$^3$). The aquifers are recharged from meteoric precipitation and they drain into erosional valleys and underlying horizons.

Quaternary deposits comprise a glacio-fluvial sandy-loam sequence about 20m in thickness. It contains HCO$_3$-Ca waters low in TDS (about 0.2 g/dm$^3$).

In a structural context, the collapse site lies in the lower part of the Durimansky synclinal structure. The mined section of the productive bed is located in the lowermost part of the tectonic depression and of the mining field (Fig.4).

On the basis of the thickness of the waterproof sequence (120 to 140m) the collapse site had been regarded as one of the safest areas, and favorable for mining. During 1984 and 1985 sylvinite had been using the room-and-pillar system with the following parameters. The width of the rooms was 5.3m, the height of rooms was 5.5m, and the width of pillars between the rooms was 3.8m. In due course the pillars crashed and the roofs sagged. This is why such a mining system is called the system of ductile pillars. It appears that this mining method played a substantial role in the failure of room ceilings and the flooding of the mine.

2.2. Fissuring of rocks

According to traditional views fissures do not develop in plastic salt sequences. Thus, such sequences are assumed to be water-tight and capable of providing a protective cover to mines. Micro-fissuring is commonly characteristic only of halopelitic beds, developing in the course of deformation of salt beds and halopelitic intercalations, due to their differing physical-mechanical properties.

Studies during the last 10 – to 15 years, especially those conducted in the Verkhnekamsky deposit, have led to a revision of traditional beliefs concerning fissuring in salts. Fissures were commonly observed by mine geologists during routine inspection of the productive sequences and in mine shafts. It was found that the "waterproof sequence" contains rupture deformations with zones of weakness developed along them. Various deformations develop as a result of both natural and anthropogenic factors (Andrejchuk, 1989). Rocks within the waterproof sequence also contain localized zones of fissuring, developed during halo-kinetic deformation of the beds (Filippov and Korochkina, 1990). Fissures and ruptures in the salts are commonly re-sealed (zones of replacement; Jarzhemsky and Tretjakov, 1989), but fresh ones (mining-related) can be open and penetrable by fluids.

Rupture deformations, especially anthropogenic fissures of displacement, foliation and unloading, present a considerable hazard as potential routes for brine rush into mines. In most cases anthropogenic ruptures develop inevitably along weakened zones, such as former deformations that have been sealed. Such zones are traced to considerable depths in the cover salt, evidencing past tectonic events (salt tectonics and also tectonic movements on a regional scale). They can contain brines in some sections. The threat of tectonically weakened zones is that they serve as tracks that link the cover salt sequence (above the mines), the brines in the overlying transitional zone and the lower parts of the clay-marl zone.
Fig. 4 – Simplified structural map of the salt deposit (after materials of the geological survey of the Bereznikovsky mine No. 3). 1 = elevation contours of the bottom of the salt deposit, 2 = contours of structures, 3 = flexures, 4 = brachyanticline structures, 5 = contours of the potash deposit, 6 = contours of mining fields. Main structures: I = Kamsko-Vishersky dome and its brachyanticline highs, II = Kamsky depression, III = Solikamsky anticline structure with brachyanticline highs, IV = Tveritinsky depression, V = Kharjushinskaja anticline structure with brachyanticline highs, VI = Osokinsky depression. Numbers in circles = main positive salt struc-
A complementary danger rising "from below" (from the mines) is presented by the fresh anthropogenic fissures that form above the mine rooms due to the sagging of their roofs. Studies have demonstrated that in the case of room-and-pillar mining, plastic deformation of roofs in rooms leads first to foliation of stratified sediments, and then to the development of fissured zones above the rooms, extending upwards for some tens of metres. Displacement fissures that form above rooms penetrate even higher into the cover salt sequence.

Most likely the interception of a weakened zone in the cover salt by an anthropogenic fissure caused activation of the former and the opening of flow paths along it. These paths allowed brines from above to penetrate into the mines. The existence of such a weakened zone is suggested by several geological observations. The most important one is a fold deformation in the overburden, observed in the wall of the collapse. This fold is marked by a high level of fissuring and high permeability (Fig.5).

**Fig.5 – Sketch of the northwestern side of the Berezniki Collapse (June, 1987). Arrows point to the fold deformation in the variegated complex.**
According to the general model of folded structures, rupture deformations are distributed differently on the uplifted and lowered parts of a structure (Fig. 4). The collapse is located on a syncline, where the culmination is characterised by low fissure frequency and by the presence of compressional microfolds. In the downward direction the density of ruptures increases, as does the width of the openings. It is reasonable to assume that the observed fold structure gives way downwards to a rupture structure, a vertical crush-zone, with enhanced fissuring and permeability, which penetrates into the upper part of the salt deposit. The presence of a large fault is also suggested by observations of piezometric levels and water circulation in the overburden.

It is apparent that this fold-rupture structure played a major role in the formation of the collapse. Firstly, the structure provided a path for inflow of fresh waters into the salt sequence and the mine. Secondly, the broken zone facilitated and guided failure of the roof of a cavity that formed in the salt, and supported its upward stoping. Because of the fragmentation of rocks in the fold zone the breakout dome could not reach equilibrium and a stable shape, so stoping continued. If the fold-rupture structure had not been there, a cavity at such a large depth would have formed a stable ceiling and survived for a significant length of time (from tens of years to a thousand years) without opening to the surface.

Below, a sequence of events that occurred in the collapse site is reconstructed, starting from the first appearance of water inflow into the room ceiling and continuing until formation of the collapse at the surface.

3. Formation of a cavity in the salt sequence above the mine

3.1. Appearance of leakage in the mine roof

The Bereznikovsky No.3 mine was one of the largest in the world. At the time of flooding the total volume of workings was estimated to be 15 million m$^3$ (Kotel’nikov and Minkevich, 1990).

The fourth western working, where the collapse occurred, lies in the northwestern section of the mining field. During the night of January 11 1986, brine inflow was recorded in the roof of room No.50. At 12:00 on January 11 inflows also appeared in the roof of room No.52. Two days later, on January 13, inflows were also found in rooms 48 and 54, and then in some other rooms (Fig. 6).

Brines that came from the mine roofs differed in composition from primary and condensation brines by having a diminished content of Br and CaCl$_2$ and elevated content of NaCl and CaSO$_4$. This indicated that they originated from the cover salt sequence, which is composed mainly of halite, containing gypsum and anhydrite interbeds in the upper part. Inflows occurred as streamlets entering under pressure.

Observations of the discharge and chemical composition of the inflows were started on January 11. They continued until March 8, and finished just before the disastrous situation that occurred due to increase of water inflow. On March 9 all people were evacuated from the mine, but all the mining equipment was left underground.

Observations made before March 8 allow tracking of the dynamics of water inflow and the solute load during a two-month period (Fig. 7). A conjugate analysis of the hydrograph and chemograph allows characteristic periods to be distinguished and inferences to be drawn about processes that took place in the salt sequence above
the mine during these periods. Three main periods with characteristic data curves can be discriminated:

1) January 11 to January 15: relatively steep growth of discharge (from 10 to 30 m$^3$/h), abrupt drop of TDS in brines (from 370 to 343 g/dm$^3$), rapid increase of the contents of NaCl (from 25 to 160 g/dm$^3$) and SO$_4$ (from 0.5 to 1.6 g/dm$^3$) and decrease of MgCl$_2$ (from 270 to 115 g/dm$^3$), CaCl$_2$ (from 30 to 13 g/dm$^3$) and Br (from 4.2 to 0.9 g/dm$^3$).

2) January 16 to February 20-23: relatively slow growth of discharge (from 30 to 100 m$^3$/h), decrease of TDS (from 345 to 323 g/dm$^3$) and the content of MgCl$_2$ (from 115 to 25 g/dm$^3$), CaCl$_2$ (from 13 to 2 g/dm$^3$), Br (from 0.9 to 0.3 g/dm$^3$) and increase of the content of NaCl (from 160 to 270 g/dm$^3$) and SO$_4$ (from 1.6 to 3.9 g/dm$^3$).

3) February 21-24 to March 8: abrupt growth of discharge (from 100 to >350 m$^3$/h), fluctuating TDS and chemical composition.

It is apparent from the graphs that the first and third periods were relatively short (5 and 13-14 days), and the second period was more prolonged (35-37 days). During the first and second periods, despite their different duration, correlation of discharge, TDS and the chemical composition of the brines is well expressed.

After anthropogenic activation of flow paths in the cover salt brines rejuvenated within the "waterproof zone". Before that the brines were of a different nature. The lower part of the zone contained bittern brines, and the upper part contained brines formed due to dissolution of gypsum, anhydrite and halite-slates. Various parts of the zone could contain primary brines related to diagenetic transformations of the rock (dissolution, re-crystallization and compaction). The anthropogenic opening of the zone provoked drainage of the different brines into the mine, accompanied by dissolution under pressure.

At a certain moment the zone became permeable across most or the whole of its thickness, and brines began moving down into the mine. At the beginning the bittern brines, the densest variety, were pressed out. This took place during the first period, evidenced by the prevalence of MgCl$_2$ in the brine composition. This component also

Fig.6 – Part of the mining field in which brine inflows in roofs of workings were recorded.
Fig. 7 - Dynamics of brine composition and discharge in the workings of block No. 8 in January-March 1986.

indicates that the brines came from the closest segment of the flow paths, i.e. from the potassium-magnesium section of the sequence, which includes the productive bed with mined tunnels.

After brines had been forced out of the nearest section, and after improvement of flow paths, movement of brines was activated in still higher (the middle and upper) parts of the zone. As the middle part is composed by halite, the second period demonstrates increase in NaCl content. Increase in SO₄ content indicates the connection of flow paths with the upper section of the zone, which contains gypsum and other sulphate minerals. Decreasing TDS indicates progressive improvement (dissolutional growth) of flow paths connecting the upper part of the zone with the mine.

As a result of the more than one month-long outflow of salts from the cover salt beds and the transitional zone, flow paths above the mine were activated and enlarged enough to drain brines from the upper part of the waterproof zone effectively and to involve low-mineralized waters from the upper aquifers. This began in the third period, when discharge increased abruptly and TDS and chemical composition began fluctuating. A period when the curves oscillated against the background of the growing discharge reflects the “critical state” of the flow paths, after which nothing could prevent a catastrophic inrush of aggressive waters and the flooding of the mine. The catastrophic stage began during March 8-9.
3.2. Volume of cavities formed

Before reconstructing further development of the processes that eventually led to the collapse, it is necessary to assess the transformations that occurred in the sequence during the monitored period. Beginning during the early days of the second period, brines that were formed due to dissolution of host rocks started arriving in the mines. The volume of primitive brines that had been pressed out of the waterproof zone was small. Dissolution was most intense in the upper part of the zone, where groundwater had a lower TDS content. Thus, a model of reversed “cone” can be taken as an approximation of the distribution of newly formed cavities.

Fig. 8 depicts the formation of cavities by dissolution of salts during the period between January 11 and March 8 1986, when regime observations on the water inflows to the mine were carried out. During the first period the volume of cavities formed was 336 m$^3$. During the second period a volume of about 10,000 m$^3$ was added. Approximately the same volume was added during the third period, when discharge of brines was growing abruptly. By March 9 cavities with a total volume of 20,500 m$^3$ had formed. Most likely, a single cavity continued downwards as a system of bifurcating vertical conduits. However, the shape of the cavity formed by this stage had no significant influence on subsequent events, as later the cavity enlarged by two orders of magnitude.

![Fig.8 - Dynamics of salt dissolution and cavities formation in the damage zone of mine No 3 between January 11 – March 8 1986. 1 = the volume of cavities formed above the mine by inflowing undersaturated brines (20,500 m$^3$), the volume of cavities formed at the mine level (4,221 m$^3$), 3 = saturation deficiency of brines arrived to the mine.](image)
3.3. Flooding of the mine and the formation of a huge cavity in the cover salt

From March 8-9 the water inflow into the mines became catastrophic, and a karstic cavity began to enlarge rapidly in the cover salt. All necessary conditions were present for fast dissolution: access of aggressive waters from the upper aquifers, the presence of well-developed conduits in the salt sequence and the large receptacle capacity of mine rooms (about 15 million m$^3$), in which the brines accumulated. Because of drainage of brines from the top of the waterproof zone and the lower part of the clay-marl sequence, a drawdown cone was formed in the aquifers above the cover salt (Fig. 10, the initial stage). Subsequent involvement of fresh waters from the overlying aquifers led to the formation of a general drawdown zone above the leakage area, traceable vertically for several hundred metres, including the aquifer of the (variegated) complex (Fig. 9). It was possible to trace the development of the depression zone thanks to the several observation wells that already existed and those urgently drilled above the mine.

The tectonic structure described above provided a path of high vertical permeability. Starting at the beginning of March, it guided rapid development of a cavity, which grew upwards from below. This cavity drained laterally-extending aquifers that it intercepted. Hydrodynamic development along this path continued until the collapse occurred. Because of the free-fall flow conditions in the vertical cavity and the high flow velocities, the water removed tiny solid particles from fissures and caused decompression and disintegration of rocks along the structure. Such weakening of the folded/disrupted zone favoured the subsequent gravitational breakdown of rocks.

The fresh waters coming into the salt sequence were highly aggressive. During the early stages the cavity probably had a reversed cone shape. It was widest at the level of the upper transitional zone, and narrowed downward. After establishment of free-fall flow conditions, aggressive waters quickly perforated the inclined salt walls at the base, and the shape of the cavity was eventually transformed to cylindrical. The cavity had merged with the mine. After formation of a cylindrical cavity the zone of intense dissolution moved to its base, to the level of the mine. Pillars and remaining barriers between the cavity and mine rooms were quickly removed by dissolution. Fast development of the cavity is suggested by the fact that inflow of aggressive waters was measured in tens and, eventually, hundreds of m$^3$ per day.

Fig. 10 is helpful in providing some quantitative estimates and relating events to time. The figure is a record of the main events that occurred at the site between the first appearance of the water inflow in the mine and the eventual collapse. The situation discussed above corresponds to the period from the beginning of March until about April 20. This month-and-a-half period was the main stage in the formation of the cavity in the salts. The end of April presents an important milestone, when intense failure of the cave roof began (the formation of a breakout dome) and the flooding of the mine was completed. After about April 20 the whole mine (about 15 million m$^3$) was inundated. This is evidenced by the behaviour of the piezometric level in the mine shafts.

For the most part the mine brines were supersaturated, and only near the damage area did undersaturated brines continue to dissolve the room walls. Knowing the volume of the mine and time of the inundation (March 8-9 to April 15-20), one can
Fig. 9 – Hydrodynamic situation in the area of mine flooding and subsequent collapse in May–June 1986. 1 = Quaternary sediments, 2 = variegated complex, 3 = terrigenous-carbonate complex, 4 = salt-marl sequence, 5 = rock salt, 6 = carnallite beds, 7 = clay, 8 = sylvinites beds, 9 = boreholes, 10 = mines, 11 = piezometric levels of the freshwater aquifers at the time of borehole drilling, 12 = level of the brine aquifer, 13 = water absorption by beds in L/s, 14 = water yield in L/s. Indexes of aquifers in: 15 = variegated complex, 16 = terrigenous-carbonate complex, 17 = salt-marl sequence, 18 = waterproof complex.
determine the average daily water inflow. This would be about 375,000 m³. In reality, the inflow rate was rising throughout. If we assume that the inflow increased uniformly from when the observations ceased (March 9) till mid April, we will obtain the rise from several thousand cubic metres per day (as for March 8-9) to about 750,000 m³/day (April 20). However, it seems to be more realistic that increase of water inflow was even more dramatic until a certain moment, and then it slowed down to a degree.

Using the volume of the inundated mine one can easily calculate the quantity of dissolved salts and hence estimate the approximate volume of the cavity that had formed in the salt sequence (including the level of the mine). Taking 365 g/dm³ as an equilibrium concentration (the average between solubilities of halite and sylvine under 10°C) one can find that during 40 days 5,475,000 tons of salt had been dissolved, which approximately corresponds to 2.6 million m³ of cave volume (assuming salt density of 2.1 t/m³). At least half of this volume (1.3 million m³) was dissolved at the mine level. However, because saturation was approached quickly, and because numerous rooms in the mine had large total contact surfaces, most of the dissolution occurred in the damage area.

Thus, by the final third of April the mine was completely flooded and a cavity of about 1.0 to 1.3 million m³ in volume had been formed in the salt sequence above the mine.
4. The formation of the collapse

4.1. Filling of the cavity by water

After the mine was flooded, groundwaters began to fill the karstic cavity formed above the mine. We can speculate about these processes from Fig.10. Because the flooded mine, the cavity and the mine shafts are connected hydrodynamically, the water level in the mine shafts corresponds to the level in the cavity. The behaviour of the levels in the shafts shows that filling of the cavity was rather slow. It began in the final third of April, and by the beginning of July the level had reached the first halite bed (the upper limit of the dissolution cavity). Such slow (about 80 days) filling of the cavity, with a volume of about 1.0 – 1.3 million m³, can be contrasted with the period of the mine flooding, which was half as long for a volume that was an order of magnitude larger. This can be explained by two causes: by further growth of the cavity volume and, more importantly, by a decrease of the inflow. Therefore, during May water inflow decreased considerably, becoming quite small by the beginning of June. Drilling results support this. Borehole No.10, drilled at the end of May, indicated that the lower part of the overburden had been entirely drained (Figs 9 and 10).

Thus, during the period of May (when the drainage of aquifers had ceased) through to the beginning of June the volume of the karst cavity remained almost the same as when it formed in the preceding period. It was revealed later that, above the water level, the dissolution cavity had been filled by a mixture of combustible gases, mainly methane, which accumulated during dissolution of salts.

4.2. The formation and stoping of the breakout dome

After the dissolution cavity had been formed, the main processes of its further development were gravitational failure of the roof and upward stoping of the cavity. There was a 300m-thick overburden separating the dissolution cavity from the surface.

Breakdown material had been gradually filling the original cavity in the salts. In the second half of May the stoping roof had been intercepted by the drilled borehole No.10 at a level of 100m above the upper salt bed (Fig.9). This means that even at the beginning of May the cavity had entered the gravitational stage of its development. By the end of June the roof had migrated to a level of 150m above the salt.

Starting from the beginning of May, when the cavity was connected to the surface by boreholes, it began to de-gas. Observations on the boreholes' gas regime showed that the gas exchange had an intermittent (inward-outward) character. Periodic release of gases from boreholes continued until the collapse at the end of July. This indicates that the formation of gases continued and suggests continuing dissolution of salts. However, during May and June gravitational processes predominated in the cavity that had formed dissolutionally during April and May. Therefore, active dissolution took place at the salt level in another place, which connected directly with the main gravitational cavity. This is supported by borehole No.9, drilled at the end of April, which intercepted a cavity in a different place, some 150m away from boreholes No.10 and No.6, which intercepted the main cavity (Fig.11). The roof of the second cavity was at some 50 to 70m above the salt top and therefore this cavity was
already at the gravitational stage. Most likely this was a branch of a single cavity connecting the main gravitational section with another dissolutional cavity in the salt (Fig.11). This is supported by the fact that there was no inflow to the mine at the location of borehole No.9, but an inflow was recorded near borehole No.8, where the neighbouring karstic cavity should be present. The presence of a cavity in that place is also indicated by the presence of a drawdown cone in the brine aquifer revealed by borehole No.8. It was the development of the second dissolution cavity that caused continued periodic gas release from the boreholes.

By the beginning of May there were two cavities present in the area of the subsequent collapse. They had merged by approximately the end of April - beginning of May. The merging of these cavities caused "the effect of the common roof", that is, the common roof was disequilibrated as compared to the roofs of the separate cavities that appeared to be in a more stable state. Besides this effect, the presence of the weakened fold/rupture zone had played a substantial role in the upward stoping of the breakout dome towards the surface.

By the middle of July the roof of the main cavity, stoping along the fold/rupture zone, had reached the bottom of the variegated complex (150 to 160m below the surface), and the slowly recovering piezometric level reached absolute elevations of 120 to 130m (Fig.10). From this point the intensity of the failure increased dramatically
due to the clastic and densely stratified nature of the sequence. This statement is supported by evidence of an abrupt raise of groundwater levels in mine shafts and boreholes, which is possible in this situation only due to the fast filling of the cavity by breakdown material that displaced the water. Breakdown of the variegated complex rocks and the roof stoping was particularly intense during the last 10 to 13 days before the collapse. This is illustrated by the fact that during this period the cavity had migrated through the whole thickness of the complex, that is 100 to 120m. During the last day before the collapse (between 18:30 and midnight, when the collapse occurred) workers in a borehole No.11 facility building clearly felt periodic underground shocks and heard a hum. It is apparent that the shocks were caused by failure of large blocks in the cavity.

4.3. The collapse

The collapse occurred at midnight of July 25-26. In contrast to the breakdown process in the variegated complex, the collapse of the 20m-thick Quaternary “bridge” was instantaneous. The size of the collapse at the ground surface was 40 x 80m. Collapsing was accompanied by an explosion with flashes of light. The shock wave was powerful enough to activate an alarm on windows of the mine office located some 1.5km distant from the collapse (Fig. 12a). The explosion had ejected sandstone and aleurolite clasts from a depth of 25 to 120m. A 20x15x5cm piece of a dark-grey limestone that occurs at a depth of 129 to 130m, was found at a distance of some 220m east

![Fig. 12 – The Bereznikovsky No3 mine, the part of the mining field and the location of the collapse. A: 1 = mines, 2 = surface facilities, 3 = mine shafts and their numbers, 4 = airways, 5 = boreholes and their numbers, 6 = embankment, 7 = profiles of ground settling measurements, 8 = collapse contour. B – Distribution of clasts ejected by the explosion: 1 = area of scatter, 2 = small clasts, 3 = large clasts, 4 = special boreholes.](image)
of the collapse. The radius of clasts scatter was several hundred metres (Fig. 12b). When striking the ground clasts created craters up to 2 m in diameter and 1 m in depth.

The explosion and light effects that accompanied the eventual collapse led some experts to speculations that the collapse was caused by the explosion. They offered the following picture:

- A large cavity was formed due to dissolution, then filled by combustible gases.
- The “gas cavity” migrated upward due to gravitational stoping.
- The explosion occurred when the cavity reached the bottom of the variegated complex, due to enormous gas pressure.
- The explosion had formed the collapse, a kind of a diatreme (Fig. 13).

Fig. 13 – View of the collapse from a helicopter, as on July 31, 1986.
The analysis of available data negates this eruptive hypothesis. Firstly, the pressure of gas in the gravitational cavity could not reach anomalous values, as the cavity had aerodynamic connection to the surface via boreholes. In addition, periodic inward suction of air was recorded in boreholes. Moreover, pressure could be released through fissured media and due to dissolution of gases in the water.

Secondly, explosions are effects that commonly accompany collapses, particularly in cases where a breakdown cavity was disconnected from original cavities located at the level of origin (cave systems or mines) by breakdown material. The mass of falling rocks acts as a piston that compresses the air in a closed volume. The compressed air causes a growing counteraction, and at some moment it “shoots” up. Even formation of small collapses commonly causes a loud noise resembling a gunshot (see the paper by Klimchouk and Andrejchuk in this volume).

In the case under study the cavity had been separated from the lower levels by breakdown material (Fig. 14). Collapsing of large masses of rocks caused strong compression of air in the cavity. This alone was sufficient for ejection of a large dust column and production of a loud noise. Moreover, the cavity was filled by combustible gases. Their ignition, probably caused by sparking from the falling drill string of borehole No.10, had added the lighting effects to the explosion and amplified the noise effect. Conditions for gas explosion were created by the piston effect. Ignition of compressed gases amplified the pneumatic explosion and added the chemical component. The resulting power of the explosion had proven to be sufficient for ejec-

![Fig. 14 - A sketch illustrating failure of isolated cavity and explosion ejection of rock clasts: 1 = fluvio-glacial sequence, 2 = variegated complex, 3 = breakdown deposits, 4 = gas-air mixture, 5 = compressed gas-air mixture](image-url)
tion of not only aleuritic and sandy particles but also of relatively large clasts. The action of the explosion was directed upwards, which is suggested by the fact that trees surrounding the collapse were neither thrown down nor burned. Therefore, the explosion was not the cause of the collapse but its consequence.

After the collapse occurred, a deep asymmetrical doline appeared, with steep slopes at the level of the fluvioglacial sequence and vertical walls at the level of the variegated complex (Fig.15). Its initial ground plan dimensions were about 80m along the long axis and 40m along the short axis (Fig.16). The long axis was oriented northwest-southeast, which coincided with the orientation of the fold and an associated ravine. For short period the doline assumed a cone shape in the upper part, at the level of the Quaternary sediments.

It was difficult to determine the depth of the collapse doline immediately after formation. The bottom could not be observed from a helicopter because of grey fog that filled the doline (Fig.13). Most likely, it was a mixture of water vapour, gases and dust. On August 8, half a month after collapsing, water appeared in the lower part, some 100m below the ground surface. It can be seen on Fig.10 that during the first ten days after the event the groundwater table in shafts and boreholes had been rising even more steeply than before. This was due to a continued massive fall-in of rocks into the doline. By the end of August the groundwater level had stabilised at a depth of 60 to 70m below the surface, and it continued to rise gradually after that. The water came from the variegated complex, Quaternary deposits and surface runoff. By the end of the 1980s the water level stabilised again at the depth of 36 to 40m below the surface. After that the doline began to fill up due to landslides and
erosion. While the initial depth (from the surface to the bottom of the lake) was about 150m as a minimum, by 1992-1993 it decreased to 80 to 100m. During this period the width of the upper part of the doline increased to 150 to 200m.

The Bereznikovsky Collapse is a spectacular example of anthropogenically-induced catastrophic collapse, caused by a mechanism that is characterised by all the signs of karst breakdowns.

REFERENCES


KOTEL’NIKOV A.N. and MINKEVICH I.I. 1990. Hydrogeological conditions of the formation of a collapse on the field of BKRU-3 mine. 49-50. In: Katastrofy i avari i na zakarsto...
vannykh territorijakh. Perm. (in russian)


KARSTOLOGY AND THE OPENING OF CAVES DURING MOTORWAY CONSTRUCTION IN THE KARST REGION OF SLOVENIA

Martin KNEZ and Tadej SLABE

ABSTRACT
The nature of karst makes constructing a roadway across karst areas a complex task, which is why karstologists take part in motorway construction across Slovenia’s karst. Working with planners, karstologists select the best route on the basis of preliminary research. Then they carry out regular karstological monitoring of the construction, to study newly discovered karst phenomena, mostly caves, and also help builders overcome the challenges of karst in a way that will preserve nature as much as possible. During the recent construction of a section of motorway, more than three hundred caves were encountered within a sixty-kilometre stretch of road. Varied tectonic and lithostratigraphical conditions make it even more difficult to predict the cave locations in advance. Various types of cave reflect the development of the aquifer due to the lowering of the groundwater level and of the karst surface. All caves are explored, and the sediments and flowstone in them studied, in an attempt to preserve the most important ones. Caves are an important part of Slovenia’s natural heritage, and research contributes new knowledge about the morphology and development of the karst region. Knowledge of unroofed caves and their traces on the karst surface provides a distinct advantage in planning new road sections. Expertise derived from recent experiences enables these features to be detected on the karst surface before the earth moving begins.

KEYWORDS: motorway construction in karst, karstological monitoring, unroofed caves

1. Introduction
One of larger projects currently underway in Slovenia is that of linking the country with a system of modern motorways. Practically half of Slovenia is karst, and more than half of its water supply comes from karst aquifers. The karst landscape is sensitive and is also an important part of the Slovenian natural and cultural heritage. A thorough knowledge and great effort are needed to preserve it.

For many years, karstologists have cooperated in planning and constructing motorways in karst regions. For this reason, knowledge of karstology is increasingly being applied during construction, since this knowledge provides comprehensive coverage of the characteristics of different types of karst and provides an understanding of the opening of caves and of karst groundwater flow. This knowledge also makes it possible to protect karst features and groundwater effectively. The wisdom of encouraging cooperation between karstologists and constructors has already been well demonstrated (Knez and Slabe, 2001).
In the selection of route corridors for motorway and railway construction, attention is given primarily to protecting the integrity of the karst landscape, and recommendations are made for avoiding the more important surface karst phenomena and previously known caves. The karstologists attempt to predict the likely degree of perforation of any individual part of the aquifer. Special attention is paid to the potential influence of construction and the eventual use of the motorways on karst waters. Motorways should therefore be impermeable, such that runoff water from the road is first gathered into oil collectors and cleaned before release onto the karst surface.

During motorway construction karstologists are involved in monitoring the route. Newly discovered karst phenomena, particularly caves, are studied, and advice on their preservation is offered if this is possible given the stage of the construction work. Knowledge from the new discoveries also assists the builders. Numerous new discoveries have been made, related to the formation and development of the karst surface, to the epikarst, and to aquifer perforation.

This article presents details of experiences gained from many years of studying karst phenomena during motorway construction. In the authors’ opinion, certain known karst phenomena have received too little attention in the past. Attention is focused on examples in Slovenia’s Kras region, the “Classical Karst”, which gave its name worldwide to landscapes formed from carbonate rock (Kranjc et al., 1997; 1999).

2. The Classical Karst

Kras is a region that rises above the northwesternmost part of the Adriatic Sea. It covers the area stretching from the Vipava Valley in the northeast and the Friuli-Venezia Giulia lowlands with the Soča River area in the northwest, to the Adriatic Sea in the southwest. To the southeast it is bordered by an extensive area of flysch, with altitudes greater than 600m, from which surface water flow creates typical and extensive contact karst at the junction with the carbonate rock.

Broadly speaking the 200 to 500m-high Kras plateau, with a total area of 440km², belongs to the Outer Dinarids, and is more specifically a part of the Trieste-Komen synclinorium. From the point of view of tectonic plate theory it lies on the deformed northern edge of the Adriatic plate and is a product of overlap tectonics. Only Cretaceous and Paleogene rocks are found here, including an outstanding variety of limestones that originated largely in shallow sediment basins with abundant flora and fauna.

The surveys discussed here found no evidence of the surface water flows that were used in the past to explain the development of the plateau. Whereas water initially flowed at shallow depth or just along the surface, and vertical percolation was minimal, the groundwater later dropped several hundred meters below the karst surface.

Today there are no surface waters in Kras. All the karst rivers disappear underground at the points where they run from flysch onto limestone bedrock. Underground water flows toward the sources of the Timava River in Italy. The largest stream is the Reka River, which sinks underground in the Škocjan Caves. Some 65% of the water, however, percolates through the surface in a dispersed and diffuse pattern. From the ecological point of view, Kras is one of the most vulnerable natural systems in Slovenia.
3. Planning

Wherever building is carried out in Kras, numerous karst phenomena are encountered, including dolines and filled or empty karst caves, as segments of old or recent drainage courses through the karst. High quality karstological studies are vital to the safe development of this largely unpredictable karst world. A thorough examination of the terrain where a new transportation route is planned makes choosing the best choice of a route corridor possible and, at the same time, is one of the fundamental starting points for planning construction in this unique and sensitive landscape. In planning motorways from the karstological viewpoint, karstologists therefore evaluate the karst surface, the karst underground and the hydrological features, and weigh the possibilities. Denudation has exposed numerous caves and these can be identified on the karst surface. Recently, special attention has been devoted to unroofed caves discovered during actual motorway construction.

Normally karstologists will initially gather information on karst phenomena with the help of published literature, archives and various collections. Later, the criteria for mapping the line of a selected route are determined with the help of a field survey. In the field, important rock sections are evaluated from the karstological viewpoint. The known entrances of karst caves are shown thematically on maps and augmented with the sites of possible new ones. A projection of subterranean cavities is made, based on surface maps and a genetic interpretation of the morphology and relief of visible denuded caves. If necessary, the possibilities for dumping excess material are also considered, on the basis of the surface maps.

Experience indicates that any route corridor crossing the karst will encounter caves and remnants of cave systems. To avoid potentially numerous unpleasant surprises, the degree of perforation of the karst is examined as thoroughly as possible before the work begins. The most common way to determine details of caves and their locations is by drilling, although drilling cannot provide for comprehensive information about caves. Along with normally measured parameters, drilling helps to determine the type of fill present, if any (e.g. flowstone, alluvium, etc). The shape, type, and frequency of caves in neighbouring areas can be partially predicted by interpolation of known surface and subterranean phenomena. Geo-electric methods have generally not provided satisfactory results in Slovenia, since this methodology normally detects only unroofed caves. Similar results have been recorded using georadar, since interpretation of subterranean cavities that have been crushed or filled with various sediments has been uncertain. The geomorphological approach of examining currently known phenomena has proven more productive.

In the field, the reliability of known data about caves is checked and augmented with new measurements and genetic interpretations. With better information, the karstologists can present a current picture of aquifer perforation and produce predictive subterranean maps.

Due to the specific properties of carbonate rock, the surface waters that percolate into the ground in the areas studied find direct routes to the underground karst aquifer without difficulty. Measurements have shown that water can percolate through a 100m-thick rock sequence in an hour. Although flysch rock — which in the Kras region lies in uninterrupted direct contact with carbonate rock — is commonly described as a totally impermeable stratum, it should be emphasized that flysch (in
some places not very thick) occurs merely as isolated lenses on permeable carbonate rocks. Furthermore, it is also recognized that, although they are less numerous, subterranean conduits also form in flysch rock and that rain falling on flysch flows into the karst. Hydrological mapping is therefore also done in the field, to demarcate and determine the basic features of hydrogeological units in the general area of the proposed route corridor, to list hydrological objects, and to determine the physical and chemical properties of springs. If necessary, tracing experiments are carried out during high and low water periods, primarily to determine the direction and speed of underground flow in the neighbourhood of the corridor. The karstologists draw hydrogeological charts and upgrade existing charts with the results of mapping and tracing experiments in the field, make an inventory of the state of the environment, and assess the potential influence of construction on karst waters.

The fundamental guidelines for planning transportation routes can be summarized in a few lines. A route corridor is selected on the basis of a comprehensive evaluation of the karst, with an emphasis on local characteristics. The final route selected will be designed to avoid unique individual karst phenomena, wherever possible. Since more than half of Slovenia’s drinking water comes from karst springs, one of the planning priorities is the preservation of karst aquifers.

4. Karstological monitoring of construction and the opening of caves

Construction in karst regions is greatly influenced by the degree of perforation of the karst. More than three hundred new caves were discovered along sixty kilometres of motorway constructed in Kras in recent years (Fig. 1). Removing soil and vegetation from the karst surface and, of course, major earthworks during digging cuttings and tunnels, exposed surface, epikarst, and subterranean karst phenomena. New discoveries are helping builders learn how to overcome obstacles to construction.

The area studied is dissected by dolines and unroofed caves. Some dolines are more and some less distinctly filled with soil that must be removed. Cracks and shafts are thus opened on their floors and slopes. The floors are reinforced with vaulted sloping rock since the mouths of shafts are commonly smaller than the caves below them, and the dolines are then filled with layers of rubble.

Epikarst is criss-crossed with cracks, which are particularly distinctive and large in Cretaceous limestone. Most are filled with soil, and their walls are dissected by subcutaneous rock forms. As a result of the lowering of the karst surface, a great number of shafts lie immediately below the surface.

Almost one third of newly discovered caves are unroofed caves (Fig. 2). These are old caves that became exposed due to the lowering of the karst surface and no longer have the upper part of their walls and ceiling. They are an increasingly recognizable phenomenon on the surface. The shape of an unroofed cave is a consequence of the type and shape of the original cave and the development of the karst aquifer and its surface in various geological, geomorphological, climate, and hydrological conditions. However, how distinctly the surface form of an unroofed cave appears to be dictated by the speed at which the alluvium was washed out of the cave compared with the lowering of the surrounding surface. If the speed was low, soil and vegetation, or areas of alluvium and flowstone, are visible on the surface; where it was
faster, unroofed caves on the karst surface resemble dolines, strings of dolines or oblong depressions.

Doline-like forms occur when the lowering surface cuts an old tunnel in a cross-section that is filled with alluvial deposits and flowstone, when reaches it at a single point, or when dolines develop in the cave alluvium that fills a larger uncovered passage. Strings of such shapes commonly reveal the shape and size of the remodelled cave. Oblong depressions develop from larger unroofed tunnels running parallel to the surface. Many of them represent an interweaving of various old forms, that is, caves and current karst formations, surface karst and epikarst. Fine-grained fill, which in this case is largely ancient cave alluvium, must also be removed from unroofed caves, and the caves must then be refilled with rocks and rubble. Otherwise, water could gradually wash away the alluvium, and silt would appear on the surface. Parts of these caves, or younger cavities that developed through them and are only exposed as the fill is excavated, can be also be sediment free and open (Fig. 3a: a doline with caves).

Relative to the aquifer development, caves can be divided into old caves through which waters percolated when the karst aquifer was enclosed, higher and covered with flysch, and shafts through which water percolates vertically from the permeable karst surface toward the underground water. The deepest shaft found so far measures 110m in depth (Figs.3b, c). The old caves may be empty or filled with alluvium, and filled caves represent almost two thirds of those found. Many of the caves are opened during the digging of road cuttings and tunnels, and they include shafts or parts of old caves. They open under roads or in the road banks during construction. Cave
roofs commonly collapse due to blasting or other construction work nearby.

All of the caves are studied, plans are drawn and their form and rock relief are determined. Samples of alluvium are collected for palaeomagnetic and palynological research, and flowstone samples are collected for mineralogical research and dating. Additionally, attempts are made to discover the locations of inaccessible parts of the caves. The approach to preservation and treatment of caves depends on the individual caves and the conditions surrounding them, particularly the deformation of the rock. Thorough surveys, which always require extreme caution due to the possibility of rockfalls, have proven indispensable to the builders. Individual survey programmes are dictated by the forms of the caves themselves, which have been hollowed out in various ways beneath and beside the route corridors. Commonly only small entrances are open, and below them are caves that expand in width. Many cave roofs are thin and there is a danger of collapse during further construction or the later use of the roads (Figs. 3d, e). As a rule, the builders reinforce the surface above such caves with concrete slabs. This, of course, is not possible with caves whose walls and ceilings have been fractured by blasting and where thicker roofs have collapsed (Fig. 3f).

Cave roofs may also collapse during the use of large vibrating rollers for final compacting of ballast on a roadbed (Fig. 3g). A relatively large number of caves are also opened in the course of building embankments (Figs 3h, i). This shows that caves can quickly be concealed during blasting, as they either collapse or their entrances are covered with rock and rubble. However, such features can be preserved with slower manual digging.
Fig.3 - Cross-section of newly discovered caves
5. The preservation of caves and new knowledge about the development of karst gained during past motorway construction

As many caves as possible were preserved. Shafts were the easiest type to preserve, since their relatively smaller entrances can simply be closed with concrete slabs. In similar fashion it was possible to preserve old caves whose walls and ceilings were solid. However, caves that were opened by blasting and which were in perforated rock had to be reblasted and filled in. Caves split by road cuttings, whose entrances were in the cutting sides were sealed off with rock walls. The cave walls and ceilings were highly fractured and therefore they were unsafe for further visiting. Furthermore, water could carry clay from alluvium-filled caves and deposit it on the road. One well-preserved cave was left unsealed, for viewing by visitors crossing the border with Italy. The most interesting and well-preserved caves were protected completely, even though they are now under the motorway. These are accessible through concrete pipes closed with locked grids beside the road.

The consequences of various types of blasting in caves have also been studied, and the information gained will help in future construction and the preservation of karst phenomena.

Unroofed caves are a distinctive and common karst form. Today, these significant karst surface features represent a familiar phenomenon, but they had not been studied thoroughly before the construction of the motorway across Kras. Subsequently great attention has been devoted to unroofed caves, since the incidence of this phenomenon turned out to be far higher than previously expected. A number of articles on unroofed caves and the construction of new motorways are now available (Knez and Šebela, 1994; Šebela and Mihevc, 1995; Slabe, 1996, 1997a, 1997b, 1998; Mihevc and Zupan Hajna, 1996; Mihevc, 1996; Kogovšek, Slabe and Šebela, 1997; Mihevc, Slabe and Šebela, 1998; Šebela, Mihevc and Slabe, 1999; Knez and Slabe, 1999). Unroofed caves are also an important part of the epikarst and provide an outstanding indication of the development history of the karst aquifer.

Many of the caves were filled with alluvial sediments. In most cases, these represented inundations of fine-grained flysch alluvium with intervening layers of gravel. Samples of alluvial deposits were taken from caves at Kozina and Divača for palaeomagnetic analysis, which confirmed that they pre-dated the end of the Olduvai chron. The conclusion is that the caves were formed before the Messinian phase. To a large extent they were filled with alluvial sediment after the refilling of the Mediterranean basin with water approximately 5.2 million years ago (Bosak et al., 2000), when the groundwater level in aquifers around the Mediterranean Sea rose to a high level relatively rapidly. The study examined evidence of the oldest preserved periods of karstification in Kras – not counting palaeokarst, of course – and established that the oldest caves in Kras are much older than karstologists previously supposed. In pockets of palaeokarst confirmed as dating from the Early and Late Cretaceous periods, the remains of dinosaurs and numerous other animals have been found.

The karst surface and epikarst that developed over the traces of older periods of karst development are typically formed on different bedrock. On Cretaceous limestone, karren commonly occur with distinct subterranean fissures below them. On Paleogene limestone, however, the surface is more smoothly rounded and in some places covered with rubble that originated due to surface disintegration during the
Pleistocene Epoch, and the rock, although most commonly more densely fractured, is criss-crossed with fewer distinct fissures. Some of these caves are also rubble-filled.

6. Conclusions

The involvement of karstologists with all stages of motorway construction in karst regions, that is, during the entire process of encroaching on the sensitive karst landscape, is very useful. In this way the natural heritage can be preserved and basic knowledge about the origin and development of the karst, and about road building in such regions, is broadened. There are many different types of karst, and each demands a unique approach. Therefore, there must be regular cooperation with road builders in every case. In Slovenia during the past ten years this requirement has been very much recognized, and the level of cooperation between planners, road builders and karstologists now serves as a model for the planning and execution of various construction projects in karst regions.

In Slovenia’s karst, which along with its many and diverse landforms is also characterized by active tectonics and lithostratigraphical diversity, caves are difficult to locate in advance. As a general rule, areas of contact between flysch and limestone are more heavily pierced by cavities. On the other hand, unroofed caves are a distinctive and increasingly readable feature of the karst surface. The degree of perforation is therefore determined primarily on the basis of a thorough knowledge of the karst, along with meticulous work during road planning and construction. The results gained are also useful in planning other construction projects in karst regions.

REFERENCES


SUBSIDENCE HAZARDS AS A CONSEQUENCE OF DAM, RESERVOIR AND TUNNEL CONSTRUCTION

Petar MILANOVIC

ABSTRACT
Considering all man-made structures in karst areas, dams, reservoirs and tunnels are the most vulnerable in relation to induced subsidence and caverns. Reservoirs that are located entirely or partially on karstified rocks covered with unconsolidated sediments are especially subsidence-prone. As a consequence of induced subsidence a number of reservoirs in karst areas failed and were never fully filled. Such subsidence formation is very damaging because the development is unpredictable and practically instantaneous. Reservoirs in karst areas may fail to fill despite an extensive site investigation programs and sealing treatment. Every problem is unique and past experiences are never repeated.

This review focuses on the meaning and consequences of selected prominent examples, but the conclusions reached are valid for subsidence problems related to man-made structures in general.

KEY WORDS: karst, karst subsidence hazard

1. Introduction

The centuries-old problem of dewatering karst poljes and other depressions has forced the inhabitants of karst regions to maintain constant swallowing conditions in subsidence ponors. At numerous sites in the Dinaride, Helendic and Tauride regions, remains of constructions intended to prevent material being washed into and filling the entrance sections of ponors are visible. To prevent erosion of agricultural soils, great attempts have been made to plug subsidence ponors and estavelles, using natural materials such as stone, wood and clay (Fig. 1).

Overburden thickness in subsidence-prone areas varies from a few meters to more than 70 m. Subsidence in reservoir floors and banks occurs under the influence of water (groundwater, flood water and pore water), as erosion and piping action break down the support of poorly consolidated sediments. In some cases, water under pressure (water hammer) or water pressurizing air in the aeration zone (air hammer), has triggered blow-outs through overlying sediments.

In some cases subsidences that originated within the alluvial floors of reservoirs are connected with long, wide and very deep cracks.

During dam construction the presence of caverns poses unique problems. In
Fig. 1 - Ancient subsidence protection solutions. 1 = Karst channel; 2 = Wooden structure with stone loading; 3 = Alluvial deposits; 4 = Soil cover and 5 = Walled-in subsidence.

extreme cases, caverns may be large and extensive enough to defy geotechnical solution. The most common technical difficulties are water leakage at dam sites and from reservoirs, and as a consequence, subsidence development (origin) within the reservoir.

Defects that propagate during underground excavation, especially tunneling, in karst can cause undesirable effects at the surface, especially in situations with thin overburden. Defects that develop during tunnel operation are also very common in karst environments.

Subsidence along river beds and beneath dikes and embankments can give rise to considerable damage during hydrotechnical construction operations.

2. Subsidesces in reservoirs

Subsidence development is a very common process, which endangers the safety and integrity of reservoirs. Subsidence induced by filling or due to extensive water level fluctuation in man-made situations has resulted in significant leakage from certain reservoirs (Hutovo Reservoir - Popovo Polje, Herzegovina, 3 m³/s; Vrtac - Niksicko Polje, Yugoslavia, 25 m³/s; Keban - Turkey, 26 m³/s; Mavrovo Reservoir – Macedonia, 7 m³/s; Perdika Reservoir – Greece; and many others).

The paleorelief beneath unconsolidated sediments deposited in karst depressions and river valleys has typical karst morphology, including sinkhole and swallowhole (ponor) features. During sedimentation these features were covered with deposits of clay, terra-rossa, gravel, cobbles and boulders. All karst features, including the openings of swallowholes (ponors), were partly or completely plugged. In this way connection with the underlying karst aquifer is partially or totally prevented.

Man-made reservoirs change the regime of underground and surface water, provoking many different destructive processes, including suffosion, erosion, air hammer and water hammer effects.

Suffosion (mechanical suffosion) may be activated from the surface by flood water or from below by underground water. After an initial channel has formed as a consequence of flood water, suffosion and erosion processes occur. Large volumes of
eroded material are transported through the karst channels. Subsides in the form of funnel-like shafts, originating at the surface (reservoir floor or banks), are the locations of concentrated water leakage.

In places where the karst channel is covered with unconsolidated sediments, strong upward flow can provoke fluidization and the piping process. The final result is the same as in the previous case, i.e., the collapse of the overlying alluvial layers is of subsidence origin.

Karst poljes are very sensitive from the subsidence point of view, and the subsidence prone zones can occur anywhere. During the dry period of the year, the water table is deep below the polje bottom, but during the wet seasons, the water table rises abruptly and a considerable part of the reservoir floor is under the influence of strong uplift. Subsidence and huge open cracks in the reservoir bottom appear as a result. Good examples are provided by reservoirs in karst poljes in the Dinaric karst.

The Hutovo reservoir, located at the lowest part of the large Popovo Polje karst depression (Herzegovina), is a good example of induced subsidence occurrence. The reservoir floor is covered with alluvial deposits, which increase in thickness from the flanks, reaching about 30 m towards the middle part of the polje. The Cretaceous limestone bedrock topography is typical for karst.

The reservoir area was losing water under natural conditions through 75 recorded ponors, represented by different sized subsidence. The largest was formed above the fossilized ponor of the river Trebisnjica (Fig. 2).

By applying different investigation methods (geological mapping, geophysical investigations, and close spacing drilling), the fossilized opening of a ponor was detected at depth of 50 m beneath the floor level. Fig. 3 shows contour lines of paleo karst relief (a) and a cross-section (b) through the infilled karstic sinkhole with fossilized ponor at the very bottom. Presently, the swallowing capacity of the ponor is drastically limited.

Before the reservoir was filled, the ponor was only active from time to time. During the reservoir operation, despite surface treatment, a number of large subsidences occurred. 38 new subsidence developed after the first impounding, followed by 44 in the next year and 36 during the third year of operation.

The subsidence zone was rendered impermeable by grouting the karstified paleo-relief. Pressure grouting with a cement mixture was introduced from the surface. After grouting of the bedrock, the channels in the alluvial parts of the ponors were filled in with grout mix. A grouting mix with the approximate characteristics of the surrounding material (the proportion of clay was increased with respect to cement) was used.

In this area pressurized air plays an important role in subsidence formation. During dry periods, the water table is very deep (100 or more meters below the surface). Short periods of heavy precipitation lead to flash flooding of the reservoir floor and an extremely rapid rise of the water table (50–80 m within 24 hours).

As a consequence, large volumes of air become trapped in some caverns, as shown in Fig. 4a. This air does not have time to escape, because the surface layer of soil is rapidly saturated with water. Therefore, air becomes entrapped and pressurized (Fig. 4b). When the pressure exceeds the strength of the overlying alluvial layers, air
eruption destroys this zone. At the surface this has been observed as fountain-like eruptions. After water table depression beneath the area of destroyed sediments, water sinks through newly created ponors (c).

In some cases reinforced shotcrete is not sufficiently resistant against strong uplift pressures (Fig. 5).

A need was foreseen to introduce aeration pipes through the alluvial cover and down to the karst channel in the bedrock, to allow timely evacuation of confined air. The tops of these pipes were set above the maximum expected levels of water in the reservoir (Fig. 6).

After rendering the reservoir floor impermeable by compaction, two-dimensional defects developed, in the form of wide and long fissures in alluvium. Fissure widths ranged between 1 and 30 cm, and lengths from a few meters to a hundred meters. Such features were found even under the protective plastic membrane. New subsidences also originated along some of the fissures, especially at points of fissure inter-
Fig. 3 - Main subsidence – temporarily active ponor (Hutovo Reservoir): (a) = Contour lines of paleorelief and locations of investigation boreholes. Arrows indicate trace of fossil river bed toward the main ponor; (b) = Cross-section: 1 = Karstified limestone, 2 = Alluvial deposits; 3 = Degraded zone in alluvial deposits; 4 = Karst channel; 5 = Direction of underground flow; 6 = Subsidence; 7 = Investigation boreholes; 8 = Zone treated by compaction, and 9 = Zone treated by grouting.

Fig. 4 - Subsidence created by air-hammer effects

section. In some cases subsidences developed between two parallel cracks (Fig. 7). Both features appeared after reservoir filling and a short time in operation. The fissures were already visible when the reservoir floor was covered with water.

After a sudden rise of water table in the karst aquifer beneath the polje, it was found that air circulated even through piezometers installed in the reservoir area. Due to the abrupt water level rise the air current from the piezometric pipes and aeration
Fig. 5 - Subsidence created in a shotcrete protective layer by strong groundwater uplift.

Fig. 6 - Aeration pipe.

Fig. 7 - Subsidence developed between two parallel cracks.
pipes reached a velocity of 15 m/s. It was also found that this circulation was pul­
satory, expelling and sucking in air with a periodicity of 17 to 35 minutes. This pul­
sation was recorded only when the water table was rising, never when it was falling.

A particular problem is presented in the case of estavelles in the storage reservoirs. Because of its double hydrogeological function every estavellle is a potential subsi­
dence site. In order to improve the water-tightness of Vrtac reservoir in Niksic Polje, Yugoslavia, several sealing methods were applied (cylindrical dams, plugging of ponors, non-return valves and concrete blankets). Unfortunately, all these measures were unsuccessful. After the first reservoir filling and a strong water table rise during the wet season, the groundwater could not discharge through the natural estavelle openings. As a consequence more than 100 new subsidences were formed in the reservoir floor (Fig. 8).

Successfully rendering reservoir floor subsidences impermeable does not ensure that the process of new subsidence development will definitely came to an end. The case of Mavrovo Reservoir, Macedonia, is a good example. At the time of first fill­
ing (1960) two large and several small subsidence ponors developed in the alluvial cover overlying the karstified marble limestone, and about 9 – 12 m³/s of water escaped from the reservoir. The subsidence ponors were filled with crushed stone and covered with a protective impervious blanket, 70 m wide and 430 m long. During its next 25 years of operation (until 1986) the reservoir was never filled to the designed operational level. Permanent reservoir fluctuation led to the washing out of the cave

![Fig. 8 - Niksic Polje. Subsidence induced by reservoir operation.](image)
fill sediments, finally creating erosion channels in the alluvial cover. During the very rainy year of 1986, abrupt water level increase served as a trigger to development of subsidences (Fig. 9).

Some of the subsidences were formed within the blanket zone, but more of them developed in the natural deluvial cover overlying the marbleized limestone. These subsidences provoked considerable environmental impact in the form of heavy damage to local roads and surrounding houses. A wide range of geological and geophysical investigations have been carried out to determine the actual conditions, to ensure selection of an appropriate impermeability treatment. Finally, the subsidence (ponor) zone was isolated from the reservoir by construction of an earth filled dyke.

The floor of the May Reservoir in Turkey comprises a 15 – 20 m-thick alluvial layer, overlying karstified limestone, conglomerate and marl. During the first filling of the reservoir many subsidence ponors opened in the floor of the downstream part of the reservoir, as well as along the right bank close to the rock fill dam. The reservoir leakage led to a severe reduction in the usage of the stored water.

The Keban Dam, in Turkey, is situated in a deeply karstified ridge of metamorphic marble and limestone, including beds of dolomite and calcareous schist of Paleozoic age. During the first filling of the reservoir a large vortex was observed on the left abutment, 150 m upstream of the dam crest. A large subsidence, connected with a huge cav-

Fig. 9 - Mavrovo Reservoir. Subsidence induced by reservoir operation.
ern, was created in the thin alluvial cover. Water losses from the reservoir increased to 26 m$^3$/s. In an attempt to minimize water losses, about 600,000 m$^3$/s of limestone blocks, gravel, sand and clay were dumped into the cave through an excavated shaft 2.5 m in diameter, and through 13 boreholes of 14 to 17 inches in diameter.

The Perdika Reservoir, in Greece, is situated in karstified Upper Cretaceous limestone. Plio-Pleistocene sediments (clayey silts, silty sand, coarse sand and gravel) on the reservoir floor vary in thickness from zero to more than 90 m (Pantzartzis et al, 1993).

During its first filling, numerous ponors, cracks and subsidences occurred inside the reservoir. There was no relation between the development of subsidences and the thickness of the overburden. Groundwater level was about 70 m below the reservoir floor. Rehabilitation measures were not successful.

In some cases subsidence development is not a consequence of groundwater filtration out of a reservoir. It occurs as a consequence of frequent and high amplitude fluctuation in deep reservoirs, particularly if the amplitudes are more than 50 m. Intensive, but local, suffosion processes between the upper and lower parts of the same bank of the Bileca reservoir (Herzegovina) provoked a few subsidences in the upper section (Fig. 10).

![Fig. 10 - Bileca Reservoir. Subsidence created by local water filtration.](image-url)
3. Problems with caverns and subsidences in underground excavation

Defects encountered during underground excavations and tunnelling operation in karst can provoke undesirable effects at the surface. Any fault or cavernous zone that connects a tunnel section with the surface holds potential for subsidence, especially in the case of thin overburden (Fig. 11). The collapse prone areas are particularly susceptible in the case of hydrotechnical tunnels, especially derivation high-pressure tunnels.

Subsidences created during tunnelling operations are illustrated by the following example. Water leakage from a headrace tunnel tube eroded and washed away unconsolidated cave deposits in the section where the tunnel intersected a large filled cavern (Fig. 12).

Percolation through the tunnel lining caused intensive erosion and transport of great volumes of sandy-clay cave deposits toward deeper channel sections over time. This resulted in the development of an empty space around the tunnel tube, and formation of subsidence at the surface. Particularly dangerous was the washed-out part of the cavern situated below the lining, with a length of 16 m, a width of about 7 m and a depth of 8 to 15 m. The loss of support seriously endangered the stability of the tunnel tube.

Complex investigation work has been carried out, including drilling, water level monitoring, measurements of leakage, geological analysis, speleological investigations, TV logging and tracing tests by dye and smoke tracers (Fig. 13). Speleological investigations, including detailed mapping of surface subsidence and underground collapse, were very successful.
Fig. 12: Headrace tunnel for HPP Capljina. Subsidence as a consequence of tunnelling operations: 1 = Tunnel lining; 2 = Part of lining additionally reinforced; 3 = Collapse; 4 = Cave origin as a consequence of collapse; 5 = Empty cavernous space below tunnel tube; 6 = Cave deposits (clay, sand, and limestone blocks); 7 = Limestone; 8 = Borehole; 9 = Fault.
Fig. 13 - Headrace tunnel for HPP Capljina. Cavern contours.

1 = Tunnel; 2 = Subsidence; 3 = Cavern, originated as a consequence of subsidence; 4 = Shaft cut through the lined invert; 5 = Limestone; 6 = Cavern contour line below the tunnel lining; 7 = Cavern contour line above the tunnel tube; and 8 = Connection established by smoke tracer.

REFERENCES


KARST SUBSIDENCE IN SOUTH-CENTRAL APULIA, SOUTHERN ITALY

Marco DELLE ROSE and Mario PARISE

ABSTRACT
Subsidence in the karst of Apulia (Southern Italy), one of the classical karst areas of Italy, is described in this paper. The carbonate rocks that make up the geological structure of the Apulia region are affected by subsidence, which is of different type and intensity depending upon geological, topographical, and hydrogeological conditions. In particular, we discriminate between inland subsidence and coastal subsidence. Inland subsidence is generally restricted to the presence of individual cavities, either empty or partly or totally filled with deposits produced by dissolution of soluble rocks underground. Locally, such subsidence can cause severe effects on anthropogenic structures above.
The coastal plains of Apulia, particularly the southernmost part (Salento Peninsula), show interesting karst subsidence. Here the main feature is the development of compound sinks extending for several thousands of square metres, or the formation of individual, mostly circular, dolines along the coastline. Occurrence of one or the other of the above features seems to depend upon topographical conditions, and also upon their relationship with sea level oscillations.

KEYWORDS: karst, subsidence, sinkholes, subsidence hazard, Southern Italy

1. Introduction
Subsidence is a geological hazard that affects many areas of the world. It can be related to several different processes, both natural and induced by Man. According to a widely accepted general definition, subsidence is: "... the sudden sinking or gradual downward setting of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved. Subsidence may be caused by natural geological processes, such as solution, thawing, compaction, slow crustal warping, or withdrawal of fluid lava from beneath a solid crust; or by man's activity, such as subsurface mining or the pumping of oil or ground water." (Bates and Jackson, 1987, p. 658).
The occurrence of subsidence events in various geological settings is an increasing hazard, as recently demonstrated by several papers dealing with this topic in different environments (e.g. Amin and Bankner, 1997; Carminati and Martinelli, 2002; Hu et al., 2002).
The complexity of subsidence phenomena is still greater in karst areas, which are characterized by very peculiar geological, morphological and hydrogeological fea-
tures (Cvijic, 1918; Nicod, 1972; White, 1988; Palmer, 1990). The latter features, and particularly the presence of underground cavities produced by dissolution of soluble rocks, make karst a highly fragile and delicate environment, prone to subsidence caused by a variety of natural and anthropogenic processes (White, 1990; Tharp, 1999; Lamont-Black et al., 2002).

In some cases identification of landforms related to subsidence can be very difficult, since these may have been removed or had their effects partly cancelled out by past erosion, and remodelled or obscured by human activity.

The most common landforms produced as a consequence of subsidence in karst areas are sinkholes, whose dimensions (width, depth) depend upon local geological characteristics and also upon the rate of development and intensity of karst processes. In many cases, the sinkhole development may be preceded by the appearance of cracks in buildings and structures above, which might thus be considered as precur-sory features of a likely collapse.

Dolines are among the most widespread surficial landforms in karst environments, and not all of them are produced by subsidence. Thus, there can be a problem discriminating between dolines produced by karst subsidence and those related to other processes (e.g. simple dissolution of soluble rocks). Making this distinction can be particularly difficult in some cases because of the similarity of the morphologies produced. In an attempt to distinguish between different types of sinkhole, White and White (1987, p. 85), for example, define subsidence sinks as “...those caused by upward stoping of a collapsing solution cavity through substantial thicknesses of bedrock, some of which may be non-carbonate”.

On the other hand, karst subsidence may also relate to the presence of heterogeneous fillings in subterranean cavities or in dolines. Settlement of these deposits, caused by the movement of water through them, with consequent physical erosion and chemical dissolution, may result in gradual downward settling of the ground above, with formation of a depression at the ground surface.

Sinkholes produced by karst subsidence can be isolated and localized, or may be more complex and ramify over a more or less wide area. In the latter case the morphologies produced have been described as compound sinks by White (1988). Their main characteristics are the development of many individual sinkholes that, with time and the evolution of karst processes, grow and coalesce to form large closed depressions. These are generally shallow, but may occupy areas of several square kilometres.

In the present paper, after a brief summary of past studies dealing with subsidence in karst areas, we describe some cases of karst subsidence in Apulia (Southern Italy), attempting to differentiate types of subsidence occurring within the different topographical, geological and morphological settings of the region, one of the classical karst areas of Italy.

2. Subsidence events and their effects on the natural and human environment

Dissolution and erosion in subterranean cavities may result in collapse and eventual breakthrough of the cavities to the ground surface, forming sinkholes. Whether natural or anthropogenically-induced, this process affects carbonate formations that are subject to karstification in many areas of the world (Jennings et al., 1965;
Calembert, 1975; Stringfield and Rapp, 1976; Cotecchia, 1980; Soriano and Simon, 2002). Such effects are commonly encountered during road construction or other engineering works in karstic areas (Pewe, 1990; Cavounidis et al., 1996; Roje-Bonacci, 1997; see also papers of Knez and Slabe, and Milanovic in this volume).

The karstic and engineering-geological literature offer details of many studies dealing, directly or indirectly, with such phenomena. They can be differentiated, according to the origin of the subsidence phenomena, as either natural or induced by human activities.

Considering the first category, it is worth quoting the case of East Tennessee, where, in a seven-year period, more than 250 karst subsidence incidents were registered, according to an inventory gathered by interviewing personnel of federal, state, and county agencies (Ketelle and Newton, 1987). Most of the sinkholes were twenty feet or less in maximum surface dimension.

Another example of a collapse feature formed by upward migration of an underground dissolution cavity by successive roof failures until it breached the land surface is the Wink Sink, in Texas. Here, natural dissolution of salt was in some way influenced by petroleum-production activity in the immediate area (Johnson, 1987).

Also in Texas, Kasting (1987) identifies two main forms of evidence for subsidence and collapse in carbonate rocks: 1) slumped units of stratigraphically younger Paleozoic beds within depressions formed in earlier carbonate rocks, and 2) “filled sinks” (i.e. dolines filled with horizontally deposited younger beds).

Piping extending from the limestone to the surface can be a further process leading to subsidence phenomena and sinkhole formation (Benson and Yuhr, 1987).

Alongside natural processes, several anthropogenic activities may induce sinkhole development and subsidence in karst environments. Among these, groundwater abstraction is one of the most common causes. For example, in 1977, when a spell of freezing weather was experienced in Florida State, strawberry growers in the Dover area applied large quantities of groundwater withdrawn from the Floridan aquifer to their crops (Hall and Metcalfe, 1984). This triggered development of at least 22 sinkholes, some of which resulted in property damage. Similarly, pumping of water from industrial wells in parts of Tennessee and Georgia has initiated active subsidence at several locations (Wilson, 1984).

3. The Apulia region

Apulia represented the geological foreland during the building up of the Southern Apennines of Italy. Most of the region is made of thick sequences of limestone and dolomite (Fig.1) formed within carbonate platforms during the Cretaceous (Richetti et al., 1988). Later on, these materials, having been faulted, deformed, and affected repeatedly by karst processes, were partly covered by recent deposits, mostly represented by calcarenites.

The landscape is generally flat, characterized essentially by landforms of karst origin, whose best morphological expressions are identifiable on the Murge Plateau of inland Apulia (Neboit, 1974; Sauro, 1991). There have been many active karst phases, producing an extensive network of underground cavities and conduits. Today the Apulia regional caves inventory, managed by the Apulian Speleological Federation,
lists more than 2000 caves (Giuliani, 2000), including famous show caves such as the Grotte di Castellana and the Grotta Zinzulusa, as well as caves of great archaeological or palaeontological interest (e.g. Grotta Paglicci, Grotta dei Cervi at Porto Badisco and Grotta di Lamalunga).

Features characteristic of landscapes where karst is the main geomorphic agent, can be identified in Apulia, including the absence (or very limited presence) of surface runoff, outcrops of residual deposits from karst processes (the so-called terra rossa), and hydrological connectivity between surface and underground systems. The role of human activity must also be stressed, since the landscape has everywhere been modified markedly by anthropogenic intervention.

Most of this description will concentrate on the Salento Peninsula, which is the southernmost part of the Apulia region (Fig.1). It is formed of Jurassic to Cretaceous limestone and dolostone covered by Tertiary and Quaternary clastic carbonates and subordinate clays. Structurally, Salento is a wide horst, dissected into uplifted and lowered blocks by high-angle faults, striking NW–SE, (Doglioni et al., 1994), which locally show evidence of reactivation (Delle Rose, 2001). Reflecting the predominance of calcareous rocks, surface and underground landforms are characterized by karst features.

The present form of the Salento Peninsula began to develop during the Early Pleistocene, when tectonic uplift was accompanied by a relative lowering of the sea
to its present level. Emergence took place discontinuously, leading to the formation of coastal plains on both the Adriatic (north-east) and Ionian (south-west) sides during the Late Pleistocene (Dai Pra, 1982; Palmentola, 1987). The elevation of the coastal plains is at most a few metres above sea level, and the partially swamp-covered plains extend inland for several kilometres.

4. Subsidence in the Apulian karst

This section considers only cases of subsidence produced by natural processes, not those caused directly by human activity. Nevertheless, some effects of subsidence on the anthropogenic environment also discussed. Subsidence in inland areas and that along the coastal plains are considered separately.

4.1. Inland subsidence

Subsidence in inland Apulia is generally related to the presence of individual underground cavities, whose upward stoping towards the ground surface may cause settlement and collapse of anthropogenic structures, where present. Such features, though numerous and widespread do not generally evolve to produce compound sinkholes (White, 1988), but instead they remain localized. Their presence is directly dependent upon the distribution and dimensions of subterranean cavities, and upon the local hydrogeological setting.

In the past several towns in Apulia have been affected by these phenomena, and in recent years many problems have had to be faced at some sites. The case at Castellana-Grotte (discussed below) is an example of such a situation.

Castellana-Grotte

The town of Castellana-Grotte lies some tens of kilometres south-east of Bari (Fig. 1). It is famous worldwide due to its remarkable caves, first explored in 1938 and more than 3km long and 120m deep, which have become one of the most visited show caves in Europe.

The oldest part of Castellana-Grotte lies at the bottom of a karst basin, whose main morphological feature are flat valley floors filled with alluvial deposits, detritus and terra rossa. These valleys and drainage routes (locally called lame) are the remnants of the original hydrographic network (Parise, 1999). Most are directed toward the northern boundary of the Castellana catchment basin, where both its lowest-lying sector and the town itself are located. Largo Porta Grande, a broad square within the lowest part of the town, has repeatedly been the scene of flood events in the past. The origin of these floods must be sought within a combination of peculiarities of the karst environment and mismanaged human activity (Sgobba, 1896; Orofino, 1990; Pace and Savino, 1995; Parise, 2002).

Precisely the same site is also marked by subsidence phenomena related to the presence of underground cavities that are partly filled with colluvial deposits and terra rossa. In fact, on September 15 1968, a building on the west side of the square suffered serious damage due to differential settlement. It was evacuated temporarily, and some geological investigations were performed.

Local stratigraphy, as illustrated by boreholes drilled at the site, consists of a complex succession of detrital deposits and terra rossa, which fills a depression with a
maximum depth of 55m. The bedrock is limestone, but large blocks of carbonate breccia were also encountered before the top of the carbonate rock mass was reached (Zezza, 1976). Eventually, to complicate the local geological situation further, a thin and laterally discontinuous layer of "pozzolane" (a deposit of volcanoclastic origin) was also recognized above the limestone at some locations. The origin of the latter deposits was not investigated fully; likewise, authors studying the site in the past did not explain the origin of the carbonate breccia. The blocks of breccia were probably related to repeated collapse from the original ceiling and from the walls of the cavity, and to successive re-cementation of the rocky debris.

In any case, the greater part of the ancient underground cavity was filled with terra rossa. Above that, a maximum thickness of 7m of detrital deposits was present; the latter deposits, originating from anthropogenic activity, were material used in historical times to level the old topography and allow construction at the site.

Following the 1968 event, other settlements occurred in 1969 (four months after the first one), and again in 1972, until the building had finally to be evacuated and abandoned (Fig.2). Only recently, the Municipality of Castellana-Grotte decided to recover the site, clearing away the debris and creating a garden area across the site previously occupied by the building.

Situations like that described at Castellana-Grotte, generally localized at a single site or distributed across an area of few tens of square metres, have been recorded during the last few centuries in many other towns of the Apulian karst, especially in the Murge Plateau.

Spedicaturo area

A second site of inland subsidence lies in the Salento Peninsula (Fig.1). The Spedicaturo area is part of an inland plateau delimited to the west and east by the low

Fig.2 - The site of Largo Porta Grande, at Castellana-Grotte, affected by repeated subsidence events since 1968 (photo taken in 2000).
relief areas of the Serre Salentine. It presents surface karst morphologies, including several dolines, partly or totally filled with residual deposits, as well as karren fields and many other micro-forms of karstic origin. Man has, over time, created a network of artificial channels across the area to control the flow of meteoric water, and to facilitate its infiltration into the underground karst system (Beccarisi et al., 1999).

Subsidence phenomena active in the area interfere with Man's activities and cause damage to structures and buildings. In March 1996, for example, collapse of the ceiling of a karst cavity resulted in the formation of a sinkhole in the vicinity of an important communication route that had to be closed temporarily (Carrozzo et al., 1996).

The local geological situation at Spedicaturo is characterised by the presence of Early Pleistocene calcarenites (the Salento Calcarenite Formation) that overlie Late Miocene marls, limestones and calcarenites (the Andrano Calcarenite). All of the stratigraphical sequence is sub-horizontally bedded. It is affected by SE-NW sub-vertical faults and several fracture systems, which appear to guide the development of subterranean karst landforms.

The difference in permeability between the two formations (very high in the Salento Calcarenites and low in the Andrano Calcarenites) determines the presence of a shallow aquifer in the Salento Calcarenites. Shallow phreatic speleogenesis operates close to the water table level, with formation of karst conduits and protocaves (sensu Ford, 1988), whose evolution occurs through successive ceiling collapse, formation of wide caverns and sinkhole development at the surface.

This mechanism can be identified readily in many more of the Salento caves, where the subsidence events, and the successive evolution of the forms so produced may result in the formation of compound sinks aligned along the main tectonic trends.

4.2. Coastal subsidence
In recent years the coastal plains of Salento have been affected by repeated episodes of land subsidence, some of which have damaged or destroyed roads and buildings. Consequently, understanding of these events and the processes causing them, and of their likely evolution in the future, is extremely important in helping to evaluate their incidence across large areas of southern Apulia, and to determining the most adequate measures for controlling and mitigating the related environmental hazards.

Sinkhole-like landforms in the coastal areas of Apulia have recently attracted great interest from researchers because of their possible archaeological significance, as evidenced for example at the archaeological site of Gnathia. A new interpretation has been proposed for the so-called "Amphitheatre", an elliptical depression within the ancient town of Gnathia, which was one of the most important harbours on the Adriatic coast during Roman times (Delle Rose et al., 2002).

Even though subsidence processes and the landforms they produce are present on both the Ionian and Adriatic side of Salento, the following section deals mainly with the situation on the Adriatic side. In addition, some details about the less well-developed karst subsidence on the Ionian side are provided.

Cesine area
For the purposes of this study, the Cesine area (Fig.3), with an extension of about 8km² along the Adriatic coastal plain of Salento, has been analysed. Several events affecting the village of Casalabate during recent years illustrate ongoing karst subsi-
dence processes within this coastal stretch. During the last decade there has been frequent development of sinkholes, which appear to be aligned along the main tectonic fractures (Delle Rose and Federico, 2002). In particular, formation of a sinkhole in 1993 caused collapse or severe damage of buildings (Fig.4). On that occasion, brackish water was found inside the dolines. This water comes from a coastal near-surface aquifer that contains salt water encroaching from the sea at lower level.

Fig.3 - Geological and morphological sketch of Cesine (see Fig. 1 for location). Explanation: a) reclamation channel; b) fractures of tectonic origin; c) doline; d) swamp; e) paludal deposits; f) Early Pleistocene calcarenites. Numbers indicate elevation above sea level (expressed in metres). The vertical scale is exaggerated in the section. The inset refers to the sector for which the evolution model of Fig.9 is discussed in the text.

Fig.4 - Damage to buildings in the village of Casalabate, due to subsidence events that occurred in 1993 (photo taken in 1994).
Other events must be cited to emphasise the importance and frequency of subsidence phenomena in this area. Among these, during 2000, limited subsidence was observed on the beach at Casalabate, where elliptical dolines with a diameter of a few metres and depth in the order of 70-80cm, were produced (Fig.5). These dolines disappeared within two or three days due to the low resistance of the materials to erosion, and the small dimensions of the landforms.

More than one km² of the Cesine area is occupied by water, and swamp environments are present (Fig.6). Furthermore, marshland deposits, generally not greater than a metre thick, spread across an area of some 3km². Cesine lies some 15km east of Lecce (Fig.1), and is elevated a few metres above sea level. Inland, the area becomes a slightly inclined plateau. The local bedrock comprises Early Pleistocene calcarenites, several tens of metres thick, lying with stratigraphical discontinuity over Pliocene calcarenites and calcilutites. The strata are affected by sub-vertical fracture systems. At the turn of the 20th century, reclamation works were performed in the area, and several reclamation channels were dug, of which the largest was 4m wide and 3m deep. This excavation exposed calcarenites cropping out in its floor and in its sides (Figs 3 and 7).

The shoreline is composed of beaches, bordered by sand dunes, alternating with small promontories of calcarenite rock. Inland, the calcarenites are covered by recent and active paludal deposits (clays and silts), and by residual (terra rossa) deposits that have been partially affected by pedogenesis. The shape and orientation of landforms such as shorelines, edges of escarpments and watershed divides depend largely upon the spatial arrangement of the tectonic fractures.
Fig. 6 - Overall view of the Cesine area.

Fig. 8 - Swamp areas in the Cesine. Note, in the foreground, the recent development of a sub-circular doline.
Swamps and marshland developed by evolution from initial individual dolines, as described below. Sub-circular dolines are very common at Cesine (Fig.8). Their maximum area is some hundreds of square metres, with a maximum depth of several metres. Nowadays recognition of individual dolines in the marshlands is difficult. Moving inland, the dolines are generally covered by thin layers of terra rossa. However, in the latter case, the dolines can be still recognized by way of aerial photo interpretation. Even inland, most of the dolines appear to be aligned along the main tectonic lineations of the area (Fig.3).

The rate of evolution of karst features in this area can be appreciated even within the timescale of human life. Periodic surveying carried out in the last twenty years has shown, for example, the development of several dolines that were generally masked rapidly by fill deposits and vegetation cover. Enlargement of individual dolines due to rock falls around the perimeter, and a tendency for adjacent dolines to coalesce, with an overall widening of the area affected by karst subsidence, is common.

Underground water circulation is influenced in part by the tectonic fracture systems and is marked by submarine springs that lie along fractures running transverse to the coast. Underwater investigations, carried out after the sinking of part of submerged beach at Casalabate in 1997, revealed a spring with tubular conduits draining the aquifer and running parallel to one of the main fracture systems.

The swamp areas are flooded by brackish water produced by the mixing of salt water encroaching from the sea and fresh groundwater from the aquifers (Cotecchia et al., 1975; Tadolini et al., 1971; Delle Rose et al., 2000). Salinity of the brackish water, which is of the order of a few metres deep, increases towards the bottom.

The chemical and physical characteristics of the brackish water lead to enhanced dissolution of the carbonate rock, a phenomenon described as "hyperkarst" in the scientific literature (Cigna and Forti, 1986). Local speleogenesis can thus be traced to dissolution of carbonate deposits by brackish water. The brackish groundwater surface, the elevations of which relate to the average level of the sea, represents the karstic base level in the studied area.

The aggressiveness of the water tends to decrease with the increase in the degree of saturation. However, maintenance of hyperkarstic conditions is guaranteed by the continual "rejuvenation" of the brackish water. This phenomenon is caused both by salts contained in the encroaching sea water spreading into the groundwater (Tadolini and Tulipano, 1981), and by mixing of the water masses occurring as a result of tidal oscillations.

Chemical and biological karstic action at the surface, may also contribute to the collapse of cavity ceilings. Epigean features such as solution pans, in fact, make a significant contribution to the thinning (from above) of the ceilings, due to the frequent salinity variations in the solutions that produce hyperkarstic conditions.

The areas around the swamps, and in particular the many topographic depressions, host a paludal fauna and flora, whereas solution pans, grooves and wells are filled in part with soils and vegetation. In turn this leads to three different types of erosional action on the substrate: secretions of chemical substances, physical disintegration and chemical processes caused by the decay of organic matter (Schneider, 1977).

This type of phenomenon has also been observed in other karst areas. Norris and
Back (1990), for example, describe the geomorphic consequences of the groundwater mixing zones along the coast of Yucatan in Mexico. The formation of lagoons occurs through the development of subsurface dissolution channels, coalescing into cave systems (strongly guided by fracture patterns), collapse of the cave roof, formation of a lagoon, further erosion by biological activity, and final evolution through erosion by wave action.

Sinking occurs frequently at Cesine due to the limited thickness of the rock (from a few decimetres to a few metres at most), i.e. the cavity ceiling, between the surface of the brackish groundwater and the topographical surface.

The tectonic fracture systems affecting the carbonate units represent an important guiding factor in the geomorphological karst evolution of the coastal plains (Lin Hua, 1986). They have an effect not only on shorelines and watersheds, but also on shape and orientation of the areas subject to collapse, in a way similar to that relating to uvala development in the karsts of Slovenia and Triest (White, 1988).

In the Cesine area it was observed that sinkhole development normally takes place parallel to the shoreline, and tends to generate wide compound forms separated from the sea by narrow barriers of rocky substrate.

Even though marshland, commonly consisting of saturated peat or organic matter supported by weak soil, are subject to land subsidence when drained and used for anthropogenic purposes (Bozosuk and Penner, 1971), the case at Cesine is quite different. In fact, in the authors' opinion, the development of marsh and swamp areas is related directly to karst processes.

On the basis of field survey and geological, morphological and hydrogeological studies, the model of evolution shown in Fig.9 is proposed for the swamp area of Cesine. For the sake of simplicity, the model takes no account of variations of sea level and, consequently, of the karstic base level.

The model originates with the presence of individual dolines, whose distribution follows the main tectonic lines in the area (Fig.9a). Rock falls and spalling at the doline boundaries, guided by the main discontinuity systems in the rock mass, determine enlargement of the individual dolines (Fig.9b). Thus, the dolines acquire an elliptical plan, whereas an overall outline in the form of a broken line can be recognized.

The dolines tend to widen and coalesce along tectonic alignments, producing compound sinks extending for a few thousand square metres (Fig.9c). The compound sinks are separated from the sea by "barriers" of highly karstified and unstable rocky substrate (Fig.9d), the collapsing of which might lead to the formation of coastal channels.

The progress of these processes is relatively rapid, in geological terms. Considering the age of formation of the coastal plains (Late Pleistocene), and excluding from this very qualitative account the time during which sea level was much lower than today (due to the last episodes of glaciation), a maximum estimate in the order of several tens of thousands of years is obtained. The rapidity of the process is further evidenced, within human timescales, by repeated, though generally small-scale, events (local collapses, doline development, etc.) in the last few tens of years. This poses a problem in terms of assessing the geological hazards relating to this type of subsidence within the anthropogenic environment in Apulia.
**Ionian Coastal Plain**

Between Torre Castiglione and Serra Cicora, on the Ionian side, the coastal plain joins inland with the low hills of an escarpment formed by a NW- to SE-striking fault. Toward the sea it is delimited by a low, jagged, rocky coast, with numerous inlets, mostly oriented sub-parallel or perpendicular to the coastline, and, less frequently, N–S or E–W.

Along the coast, Late Pleistocene calcarenites and fossiliferous limestones crop out (Dai Pra, 1982), with an overall thickness of several metres. The strata are characterised by several sub-vertical fracture systems with average directions approximately coincident with the main coastline directions. The Pleistocene deposits lie unconformably over Cretaceous limestones and dolostones, which in turn show sub-vertical fracture systems with varying orientations. Clays and marsh silts, dune and shore sands and residual deposits (*terra rossa*), partially affected by pedogenic processes, form the recent superficial cover.

The area is characterized by various karst morphologies, including numerous collapse dolines, known locally as “*spunnulate*”, a dialect term that can be translated literally as “sunken”. Other epigean karst features, filled in part with soil and vegetation, are also widespread. The dolines and compound sinks are easily

---

*Fig. 9 - Model of evolution in the Cesine area: a) development of individual dolines; b) widening of dolines; c) coalescing of the individual dolines, with formation of compound sinks; d) present situation. For more details, see the text.*
Table 1. Summary of different situations of karst subsidence in central-southern Apulia, and their main features

<table>
<thead>
<tr>
<th>Location</th>
<th>Local bedrock</th>
<th>Phase of evolution of hypogean karst systems</th>
<th>Karst dissolution</th>
<th>Sinkhole development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murgie, Serre Salentine</td>
<td>Limestones and dolomitic limestones (Cretaceous)</td>
<td>Old age of karst systems; the active karst level is present at greater depth</td>
<td>Absent, or limited to condensation from moist draughts</td>
<td>Related to the presence of individual cavities</td>
</tr>
<tr>
<td>Inland plateaux</td>
<td>Calcarenites (Tertiary and Quaternary)</td>
<td>Active speleogenesis (shallow phreatic type)</td>
<td>Present along karst conduits</td>
<td>Localized along the main tectonic lines, with formation of aligned compound sinks</td>
</tr>
<tr>
<td>Coastal plains</td>
<td>Calcarenites (Quaternary)</td>
<td>Active speleogenesis, with formation of caves at the water table</td>
<td>Hyperkarstic conditions within brackish water of the coastal aquifer</td>
<td>Widespread over the coastal plain, with formation of wide compound sinks. The recognition of their alignment along the main tectonic lines is more difficult</td>
</tr>
</tbody>
</table>

observed where fill deposits are thin or lacking and near the shoreline, where a bare lithic substrate is present because of the erosional action of the waves. Inland, the dolines are filled either naturally or by farmers, who tend to use them for agricultural purposes.

As observed on the Adriatic side, some dolines are separated from the coast by narrow barriers of highly karstified and unstable rocky substrate, the collapsing of which may lead to formation of coastal inlets (Delle Rose and Federico, 2002).

5. Discussion and conclusion

Subsidence phenomena in the karst of Apulia, described in this paper, can be considered as a relatively widespread hazard, as is also the case in many other karst areas. Geohazards such as flooding and subsidence are, for example, present in the Mediterranean karst. This is the case at many sites in Spain, where subsidence phenomena occurring in the evaporite rocks create serious damage to buildings in urban areas (Gutierrez and Cooper, 2002; Soriano and Simon, 2002).

The hazards related to these types of phenomena can be very difficult to evaluate, and this poses a serious problem in the management of those parts of karst areas that are selected for constructional activities. In such geological conditions it is very important to perform detailed studies aimed at the identification of possible underground cavities and their secondary fill deposits.

Analysis and mapping of geological hazards related to karst require an interdisciplinary approach devoted to examination of the specific problems presented in the karst environment (Forth et al., 1999). The peculiarities of karst make it a unique setting from many different points of view (geological, morphological, hydrogeological, not to mention its high vulnerability in terms of land degradation, pollution and human impact). Again it must be stressed that study of areas affected by karst subsidence cannot be restricted to examination of their geological characteristics. As evidenced by Cooley (2002), to understand the hazard related to subsidence phenomena fully in areas where carbonate rocks are overlain by clay materials, it is fundamental to study the geotechnical characteristics of the clay mantle. These relate
closely to the occurrence of collapse features, and are in turn tied directly to the underlying water flow routes and their development through time. Also, in areas where only carbonate rocks crop out, the contributions of experts in speleology, karst morphology, geotechnics, hydraulics, etc., may be crucial.

Karst exerts a very strong influence on the general geological environment and specifically on the engineering-geological one, in relation to land-use activities and regional planning (Liszkowski, 1975). The specific character of karst environments puts several restraints on many types of human activity and land-use. Subsidence events, extremely difficult to forecast because they are commonly related to site-specific conditions and still more to local stratigraphy, may result in serious economic and social damage to the anthropogenic environment.

On the other hand, the interest of studying the characteristics and evolution of areas such as Cesine, with a high natural environment value, should not be overlooked. Besides helping to reach a better understanding of the processes causing land subsidence and the development of sinkholes in karst areas, such study can help support correct management of the territory, and for its sensible exploitation for nature- and landscape-oriented tourism. In this context it would be interesting to establish karst management guidelines, following the good examples already available from some land management authorities, such as the Tasmania Forestry Practices Code (Forestry Commission, 1987).

The great importance of karst environments and aquifers is further evidenced by the estimate that water supplies for one-quarter of the world’s population are gained from karst, either from discrete springs or from karst groundwater (Gillieson, 1986). As a direct consequence, there is an urgent need to maintain high water quality in karst. This is not an easy task, due to the high to very high vulnerability of karst environments and groundwater. Nevertheless, protection of karst catchment areas, including non-karst areas that contribute drainage to the karst, represents the first priority of appropriate karst management.

The Apulian karst case studies illustrated in this paper provide a preliminary description of the various type of subsidence phenomena that can be observed in the area. A tentative classification of the phenomena described is shown in Table I, where the subsidence cases are described in terms of local geological conditions, karst processes and resultant morphological landforms. This scheme needs to be more fully validated, through its extension and application in other areas. Nevertheless, in the authors’ opinion, it represents, a good starting point for analysis of the cases of karst subsidence in the Apulia region.

The Salento Peninsula is of particular interest for the analysis of such phenomena, since it appears to present two different phases of karst subsidence evolution. On the Adriatic side, the development of wide and distributed subsidence is observed. The Cesine represents the best example, with swamps and lagoons of brackish water, enclosing remnants of the old calcarenite topography within the flooded areas. Moving inland, similar landforms (sinkholes, depressions) can be recognized, but with greater difficulty, due to the presence of vegetation and, in some cases, to the effects of anthropogenic activity that have strongly modified, if not obliterated, the original landforms. To date the farthest inland that the emergent water table has been identified in a sinkhole is more than 2km from the coast.
On the Ionian side, on the other hand, the slightly different topography (plains at higher elevation, adjoining the sea at a rocky cliff line a few metres high) evidences a younger stage of evolution of the same type of phenomena. In this case, the dolines are individual rather than ramifying over wide areas as compound sinks. This distribution strongly favours continuous evolution of the dolines through perimeter rock falls and spalling that cause their enlargement and widening. Recognition of compound sinks derived from the coalescing of two or more individual dolines is very rare along the Ionian coastline.

Taking into account conditions encouraging hyperkarst collapse the relative risk for buildings, infrastructures and, above all, the safety of people, the length of the coastal plains exposed to karst subsidence hazard in the Salento Peninsula is estimated to be several dozen kilometres. Subsidence phenomena have already made a significant contribution to the development of large swamp areas along other stretches of the Salento coastline, such as at Idume, and have caused considerable shoreline recession, with formation of large inlets, such as east of Torre Castiglione, on the Ionian side.

REFERENCES


KARST SUBSIDENCE IN SOUTH-CENTRAL APULIA, SOUTHERN ITALY


NOTICE TO CONTRIBUTORS

1. Papers should be submitted on 3.5" diskette plus two copies of the complete text of each article. Any word processor commonly used for Macintosh and PC is admitted. For long tables Excel should preferably be used. Submission of a paper will be taken to imply that it is unpublished and is not considered for publication elsewhere.

2. Papers should be written preferably in English. Other allowed languages are French, German, Italian and Spanish. Authors using a language not their own are urgently requested to have their manuscripts checked for linguistic correctness before submission. SI system should be used. Dates should be in the form “5 February 1975”.

3. Papers should be headed by a title, the name(s) in full of author(s) and an exact description of the post held and business address of the author(s). If more than one author, please underline the name of the person to whom correspondence and proofs should be sent. All papers should contain at least an English summary giving a synopsis of the paper with sufficient detailed information. The English translation of the title must always be reported.

4. Each paper will be subject to editorial review by one or more referees. The Editor reserved the right to refuse any manuscript submitted, whether on invitation or otherwise, and to make suggestions and modifications before publication. Submitted papers should be in a final form ready for publication. Correction to proofs should be restricted to printer’s and editorial errors only. Other than these, very substantial alterations may be charged to the author.

5. Bibliographical references should be listed in alphabetical order at the end of the paper. References should be in the following forms:

- **Article:** GOURBAULT N. 1976. Recent karyological research on cave Planarians. Int. J. Speleol. 8: 69-74.


6. References should be cited in the text in parentheses, e.g. “(Jones, 1961)” except when the author’s name is part of the sentence, e.g. “Jones (1961) has shown that…” When reference is made more than once to the same author and year, a, b, c etc. should be added to date in text and reference list.

7. Each table should be reported on a separate sheet. Tables should be numbered in Arabic numerals e.g. “Table 1”, etc. Should a table not be an original, the exact reference should be quoted. Tables should be supplied with headings and kept as simple as possible.

8. Figures and photographs should be kept to a minimum and generally should not duplicate information in tables. Figures should be numbered in Arabic numerals, e.g. “Fig. 1”, etc. Graphs and diagrams should be suitable for a reduction to the journal format. Authors will be asked to contribute to the cost of excessive illustrations and elaborate tables. Coloured plates and insets with cave maps are charged to the authors.

9. Letters to the Editor present a single piece of information, comments on editorial policy or content of the International Journal of Speleology, or respond to criticism or comments in another Letter.

10. Articles accepted by the Editor will become property of the Publisher and may not be reprinted or translated without the written permission of the Publisher.

11. The Editor and the Publisher of the International Journal of Speleology are not responsible for the scientific content and statement of the authors of accepted papers.
CONTENTS

PREFACE: Alexander Klimchouk and David Lowe ....................................................... 1

SUBSIDENCE HAZARD IN DIFFERENT TYPES OF KARST: EVOLUTIONARY AND SPELEOGENETIC APPROACH: Alexander Klimchouk .......................................................... 5

THE ENGINEERING CLASSIFICATION OF KARST WITH RESPECT TO THE ROLE AND INFLUENCE OF CAVES: Tony Waltham ................................................................. 19

CAVE BREAKDOWN BY VADOSE WEATHERING: R.A.L. Osborne ........................................ 37

KARST BREAKDOWN MECHANISMS FROM OBSERVATIONS IN THE GYPSUM CAVES OF THE WESTERN UKRAINE: IMPLICATIONS FOR SUBSIDENCE HAZARD ASSESSMENT: Alexander Klimchouk and Vjacheslav.Andrejchuk ............................................................ 55

MECHANISMS OF KARST BREAKDOWN FORMATION IN THE GYPSUM KARST OF THE FORE-URAL REGION, RUSSIA (FROM OBSERVATIONS IN THE KUNGURSKAJA CAVE): Vjacheslav.Andrejchuk and Alexander Klimchouk ............................................................ 89

COLLAPSE DOLINES AND DEFLECTOR FAULTS AS INDICATORS OF KARST FLOW CORRIDORS: France Sustersić ............................................................................. 115

STABILITY APPRAISAL OF THE MEDVEDOVA KONTA POTHOLE: Joše Kortnik ................................................ 129

PRE-REQUISITES AND MECHANISMS OF A HUGE COLLAPSE ABOVE THE WORLD LARGEST POTASH MINE, URAL, RUSSIA: Vjacheslav Andrejchuk ............................................................ 137

KARSTOLOGY AND THE OPENING OF CAVES DURING MOTORWAY CONSTRUCTION IN THE KARST REGION OF SLOVENIA: Martin Knez and Tadej Slabe .......................................................... 159

SUBSIDENCE HAZARDS AS A CONSEQUENCE OF DAM, RESERVOIR AND TUNNEL CONSTRUCTION: Peter Milanovic .......................................................... 169

KARST SUBSIDENCE IN SOUTH-CENTRAL APULIA, SOUTHERN ITALY: Marco Delle Rose and Mario Parise .......................................................... 181