Sinkholes and Subsidence

Karst and Cavernous Rocks in Engineering and Construction

Tony Waltham
Fred Bell and
Martin Culshaw

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Springer

Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

Dr Tony Waltham
Lecturer in engineering geology
Civil Engineering Division
Nottingham Trent University
Nottingham
UK

Professor Fred. G. Bell
Visiting Research Associate
British Geological Survey
Keyworth
Nottinghamshire
UK

Martin G. Culshaw
Manager of the Urban Geoscience and
Geological Hazards Programme
British Geological Survey
Keyworth
Nottinghamshire
UK

SPRINGER–PRAXIS BOOKS IN GEOPHYSICAL SCIENCES
SUBJECT *ADVISORY EDITOR*: Dr Philippe Blondel, C.Geol., F.G.S., Ph.D., M.Sc., Senior Scientist, Department of Physics, University of Bath, Bath, UK

ISBN 3-540-20725-2 Springer-Verlag Berlin Heidelberg New York

Springer is part of Springer-Science + Business Media (springeronline.com)

Bibliographic information published by Die Deutsche Bibliothek

Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available from the Internet at http://dnb.ddb.de

Library of Congress Control Number: 2004112901

Printed in Germany

Cover design: Jim Wilkie
Project Management: Originator Publishing Services, Gt Yarmouth, Norfolk, UK

Printed on acid-free paper

Contents

Preface

It is the authors' and publisher's intention that this book provides an accessible information source for civil engineers who encounter one of the most serious types of difficult ground conditions – on cavernous karst. Essentially it is written by geologists for engineers. It aims to explain and improve the understanding of ground cavities, subsurface processes, sinkhole collapses and ground subsidence that together constitute a significant geohazard on terrains of limestone and certain other rocks. It is the authors' belief that, once the processes of karst terrains are fully appreciated, the modern generation of construction engineers will be well able to design structures and buildings that will stand safely on this difficult ground. Sadly there is a welter of misunderstanding and misconception about "holes in the ground" that needs to be rectified, and hopefully this book does just that.

The main chapters first review ground conditions and processes, and then move on to the thorny problems of assessment, before reviewing appropriate engineering practices. They were written with extensive cooperation between the three authors. The case studies are all by invited specialists who have contributed material from their own experiences on karst. Each contributor is credited in his own case study heading, and the authors are delighted to be able to thank all of them for their welcome efforts that have created a most valuable section of the book.

Illustrations in the text are all credited to their appropriate sources, except that the photographs from Tony Waltham's Geophotos picture library are credited as TW for purposes of repetitive brevity. The authors are grateful to the colleagues and companies who have permitted their own photographs to be used in these pages. Copyright is retained by all the photographers, except Martin Culshaw and Anthony Cooper whose images are copyrighted by the British Geological Survey (NERC). The book is published with the permission of the Executive Director of the British Geological Survey (NERC).

The authors are grateful to their many friends who contributed to the preparation of this book, especially Lu Zhengxin (Nottingham University) who investigated cave roof stability through his numerical modelling, Cath Poulton (British Geological Survey) for assistance in literature search and Hilary Lambert for providing the small, central cover photograph. We also thank Trevor Ford (Leicester University), Ian Jefferson (Birmingham University), Dave Reddish (Nottingham University) and Dave McCann (British Geological Survey) for their valuable comments during peer review of various chapters. Finally, we thank Clive Horwood at Praxis Publishing and Neil Shuttlewood at Originator for seeing the book successfully into print.

Tony Waltham, Fred Bell and Martin Culshaw
Nottingham, 2004

Postscript

Just as this text had been completed, its significance was demonstrated by an event in Tampa, Florida. In April 2004, an elevated section of an extension to the Lee Roy Selmon Expressway collapsed while under construction. A single massive column, that supported the entire 3-lane width of the road between spans of 30 m, dropped abruptly by 5 m. The column extended down into a caisson 1.8 m in diameter, which was founded in apparently strong limestone 19 m below the surface; rockhead was 11 m deep. The column carried a dead load of 11 MN, increased at the time of failure by 3 MN from a massive temporary truss used in the construction process. The caisson appears to have punched through the roof of a cave just below its base. Prior to construction, each column had been proven by a borehole that reached just 3 m below the caisson base. This was simply inadequate for such heavily loaded columns in limestone that is well known for its mature karst features. Repairs are now budgeted for $11M, whereas prior probing to 5 m or even to 7 m beneath every caisson toe would have added only a few thousand dollars to the total project cost. This failure was avoidable.

Press comments that "A sinkhole as deep as this is undetectable", "It was just a bizarre event", "A small problem with the soil, something 1–6 m across, is easy to miss; if you try to find every one, you could not afford the project", and "It was an act of God" showed a complete lack of understanding of the karst. The authors hope that this book will improve understanding in the future.

Contributors

Fred G. Bell, Consultant geologist, Nottinghamshire, U.K.
fred.g.bell@btinternet.com

Martin G. Culshaw, British Geological Survey, U.K.
mgc@bgs.ac.uk

Tony (A.C.) Waltham, Nottingham Trent University, U.K.
tony@geophotos.co.uk

Roger Brucker, Consultant geomorphologist, Ohio, U.S.A.
brucker@graphtronics.net

David Buttrick, VGI Consult, South Africa
intrac@mweb.co.za

Fred Calitz, Africa Geo-Environmental Services, South Africa
fcalitz@ages-group.com

C. Warren Campbell, Western Kentucky University, Alabama, U.S.A.
warren.campbell@wku.edu

Anthony H. Cooper, British Geological Survey, U.K.
ahc@bgs.ac.uk

John Deceuster, Faculté Polytechnique de Mons, Belgium
john.deceuster@fpms.ac.be

Percy H. Dougherty, Kutztown University, Pennsylvania, U.S.A.
dougherty@kutztown.edu

Clive Edmonds, Peter Brett Associates, U.K.
cedmonds@pba.co.uk

Kenneth S. Johnson, Oklahoma Geological Survey, U.S.A.
ksjohnson@ou.edu

Patricia Kambesis, Western Kentucky University, U.S.A.
pnkambesis@juno.com

Olivier Kaufmann, Faculté Polytechnique de Mons, Belgium
olivier.kaufamann@fpms.ac.be

Martin Knez, Karst Research Institute, Slovenia
knez@zrc-sazu.si

Mingtang Lei, Institute of Karst Geology, China
sinkhole@mail.karst.ac.cn

Junlin Liang, Institute of Karst Geology, China
sinkhole@mail.karst.ac.cn

Peter McDowell, Portsmouth University, U.K.
pmcdowell@waitrose.com

James T. Neal, Sharlot Hall Museum, Arizona, U.S.A.
hjneal@commspeed.net

Hyeong-Dong Park, Seoul National University, Korea
hpark@snu.ac.kr

Bernardas Paukštys, Public Establishment Water House, Lithuania
bernardas@iti.lt

Tadej Slabe, Karst Research Institute, Slovenia
slabe@zrc-sazu.si

Peter Styles, Keele University, U.K.
p.styles@esci.keele.ac.uk

Figures

Cover photographs

Front main	Polygonal karst on the Sinkhole Plain, Kentucky
Front central	Collapse sinkhole at Dishman Lane, Bowling Green, Kentucky
Front right	Re-activated collapse sinkhole over gypsum at Ripon, U.K.
Back left	Large collapse sinkhole containing lake (Modro Jezero), Croatia
Back right	New subsidence sinkhole in Sivas gypsum karst, Turkey

Tables

Boxes

Glossary of sinkhole terminology

Blue hole	Deep water-filled sinkhole in a coastal karst or the floor of a shallow sea.
Breakdown	Blocks of rock fallen from the walls or roof of a cave.
Breccia pipe	Column of breakdown debris above a collapsed cave chamber.
Buried sinkhole or **doline**	Sinkhole filled with loose sediment beneath a soil cover.
Caprock sinkhole or **doline**	Sinkhole in insoluble rock formed by collapse into underlying cavernous rock.
Cave	Natural hole in the ground, large enough for human entry.
Cavern	Cave or cave chamber usually of large dimensions.
Cenote	Steep-sided collapse sinkhole floored by a lake whose surface is at the regional water table.
Closed depression	Karst hollow with internal drainage, including sinkhole, doline, uvala, polje and cockpit.
Cockpit	Large stellate doline between the conical hills of cone karst.
Collapse chamber	Cave chamber modified by wall and roof collapse.
Collapse sinkhole or **doline**	Sinkhole formed by collapse of rock into a cave passage or chamber.

Cutter	Soil-filled fissure in rockhead of a soluble rock (*used in U.S.A.*)
Daya or **daia**	Wide and shallow, flat-floored depression in a desert limestone plateau.
Dissolution sinkhole or **doline**	Same as solution sinkhole or doline.
Doline	Closed depression in karst, often known as a sinkhole.
Doline karst	Karst terrain where the dominant landforms are solution dolines.
Dropout sinkhole or **doline**	Subsidence sinkhole that forms rapidly in a soil cover.
Filled sinkhole	Same as buried sinkhole.
Fissure	Cavity opened by dissolution along a rock discontinuity, but smaller than a cave passage.
Grike or **gryke**	Dissolution fissure within the bare rock of a limestone pavement (*used in Great Britain*).
Karren	Small dissolutional runnels etched into bare limestone surfaces.
Karst	Landscape created on soluble rock with efficient underground drainage.
Pinnacled rockhead	Extremely irregular rockhead with soil-filled fissures and buried sinkholes between remnant rock pinnacles.
Pipe	Cylindrical or conical mass of clay and sand that fills a solution sinkhole, shaft or cave.
Polje	Closed depression with wide alluviated floor, much larger than a doline.
Polygonal karst	Terrain composed entirely of internally drained dolines or sinkholes between a polygonal net of low ridges.
Ponor	Sink, normally into an open cave passage in the floor of a polje (*mainly used in eastern Europe*).
Pothole	Solutional shaft or mainly vertical cave system.
Pseudokarst	Terrain with caves and/or karst landforms not formed by dissolution of rock.

Ravelling	Breakdown and disassociation of soil that falls away from the roof and walls of a ground cavity.
Regolith	Soil cover that overlies bedrock (*mainly used in U.S.A.*).
Rockhead	Buried interface between the underlying bedrock and its soil cover.
Shaft	Vertical or steeply inclined cave passage.
Shakehole	Small suffosion sinkhole in till overlying limestone (*mainly used in England's Pennines*).
Sink	Point where a stream or river disappears underground.
Sinkhole	Small closed depression in karst, also known as a doline.
Solution sinkhole or **doline**	Sinkhole formed by dissolutional lowering of the rock surface in and around zones of drainage into a cavernous rock.
Stoping	Progressive collapse of roof rock that causes a cavern to migrate upwards.
Subsidence sinkhole or **doline**	Sinkhole created where soil is washed down into underlying cavernous rock.
Suffosion	Removal of fines by down-washing through unconsolidated sediment.
Suffosion sinkhole or **doline**	Subsidence sinkhole that develops slowly in a soil cover.
Swallet	Same as sink (*mainly used in southern England*).
Swallow hole	Same as sink.
Tiankeng	Extremely large collapse sinkhole.
Tumour sinkhole	Collapse sinkhole formed by undermining, where no large chamber ever existed.
Turlough	Karst depression that is seasonally flooded, larger than a sinkhole.
Uvala	Closed depression with multiple sink points (*now little used*).

1

Rocks, dissolution and karst

Karst refers to a distinctive terrain that evolves through dissolution of the bedrock and development of efficient underground drainage. It is therefore associated primarily with limestone, but also forms on other carbonates and other soluble rocks. The special landforms of karst include sinkholes, dry valleys, pavements, cave systems and associated springs. Karst terrain possesses not only topographic features peculiar to itself but also unique hydrogeological characteristics. The landforms of karst vary enormously in character, shape and size, and combine to create a terrain that may represent extremely difficult ground conditions for construction and engineering. Collapse of rock over caves formed by dissolution is fundamental to the evolution of karst terrains, but is the least important of karst hazards in civil engineering (Chapter 3).

Karstic rock masses may be overlain by allogenic sediments or by residual soils that represent the insoluble material left after dissolution. Residual soils are mainly sandy silty clays, and their wide range of plasticity reflects their clay content; chert fragments are a common component. Dissolutional weathering imparts a loose packing to residual soil, which may or may not be consolidated or indurated subsequently. In addition, the rockhead beneath the soil cover is typically abrupt rather than gradational, and may be highly irregular with pinnacles of rock protruding upwards into the soil. Although these soils may possess their own engineering problems, the most widespread hazard in karst terrains occurs where soil is washed into underlying bedrock openings so that a void migrates upwards by progressive collapse to form a subsidence or dropout sinkhole (Figure 1.1). Though these sinkholes form entirely within the soil cover, they are a major component of most karst terrains (Chapter 4). They also constitute the greatest hazard for construction engineers, especially as their development is so frequently induced by engineering activity (Chapter 8).

Cavities, collapse and ground subsidence may also develop as pseudokarst in insoluble rocks. Tubes and caves in some basaltic lava flows, along with

Figure 1.1. A new subsidence sinkhole in the garden of a house in Kentucky.
Photo: Art Palmer.

piping failures in clastic soils, are the most widespread forms of pseudokarst (Chapter 6).

Limestone is one of the world's most widespread sedimentary rocks, and karst is developed to some degree in almost every country of the world. Areas of limestone outcrop have potential for the development of karst and therefore the development of sinkholes (Figure 1.2). Available data varies greatly in quality, so the figured map varies in its detail, with high quality in Europe, Iran, U.S.A. and some other countries, but very generalised in Russia and Saudi Arabia for example. Furthermore, large areas marked on this map, including much of northern Canada, Siberia, Kazakhstan, Egypt and northern Australia have few sinkholes, because the karst is either buried or is poorly developed in desert or arctic environments. The potential impact on engineering is represented by the fact that in the U.S.A. 40% of land east of the Mississippi is underlain by some form of karstic rock – where hazardous bedrock cavities and surface sinkholes can therefore occur. The other most notable regions where large areas of karst lie beneath densely populated land are in southern China and the countries that once constituted Yugoslavia.

1.1 LIMESTONE LITHOLOGIES

Carbonate rocks are defined as those containing more than 50% by weight of carbonate minerals, although the proportion commonly exceeds 90%. The two

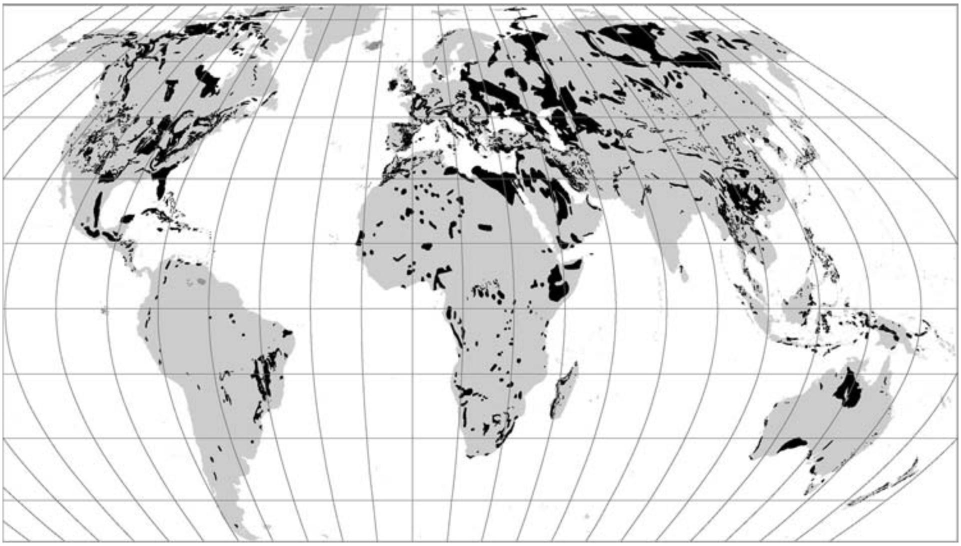

Figure 1.2. The worldwide distribution of karst, on an equal-area projection. The black areas are the main areas of limestone outcrop with potential development of karst with sinkholes. Major areas of pseudokarst on basalt and quartzite are also marked in dark grey, as in Iceland and Venezuela respectively, but small areas are barely distinguishable at this scale.
From Ford and Williams (2005).

major carbonate minerals are calcite ($CaCO_3$) and dolomite ($MgCa(CO_3)_2$), while aragonite (also $CaCO_3$), siderite ($FeCO_3$) and magnesite ($MgCO_3$) are rare in sedimentary rocks. Any non-carbonate fraction in these rocks is generally any of the clay minerals or cryptocrystalline silica (as chert or flint), which is left to form the residual soils during dissolutional weathering. The rocks known as dolomites contain high proportions of dolomite mineral, but are very similar to limestones with respect to their karst and their sinkhole hazards (Section 1.5).

The mechanical properties of old, well-lithified limestones cover a range of unconfined compressive strengths (UCS) of 30–100 MPa for the intact rock (Waltham and Fookes, 2003). Most caves, sinkholes and karst form in the stronger rocks with UCS > 60 MPa, unit weight 2.6 kN/m^3 and primary porosity $< 2\%$. Groundwater flow and dissolutional development are focused on fractures to create discrete conduits. These properties are largely dictated by tectonic history, but age of the limestone is irrelevant; major karst terrains lie on limestones that are Proterozoic in Brazil, Ordovician in Pennsylvania, Carboniferous in Great Britain, Permian in China, Mesozoic in Europe and Tertiary in Malaysia. Limestones of moderate strength, with UCS around 30 MPa, unit weight around 2.3 kN/m^3 and primary porosity $> 10\%$, have a larger proportion of diffuse groundwater flow, so their fissures are not so rapidly enlarged by dissolution. These include the Jurassic limestones of England's Cotswold Hills, where the extensive karst is significantly less cavernous and with fewer sinkholes than in the neighbouring Carboniferous limestone. Chalk and some other weaker varieties of limestone also support sinkhole karst, but have very distinctive engineering properties (Section 1.6). Marbles are metamorphosed limestones, generally strong and also prone to erosion into cavernous karst.

Limestones are polygenetic. Some are of mechanical origin representing carbonate detritus that has been transported and deposited or has accumulated *in situ*; these include the chalks. Others represent chemical or biochemical precipitates, or organic deposits such as coral limestone that have formed in place. Biological or biochemical processes dominate in the production of carbonate detritus, that mostly originates as shell debris. Allochthonous or transported limestone may have a fabric similar to that of sandstone and may display current bedding structures. Autochthonous limestones, that have formed *in situ*, possess only poor stratification. Some autochthonous limestones show growth bedding, the most striking of which is stromatolitic bedding, as in some algal and reef limestones.

Most limestones were formed as shallow-water marine deposits in environments that include tidal and supratidal flats, shelf and bank areas, marginal reefs and back-reef lagoons. They largely consist of varying proportions of complex derived grains (allochems), coarsely crystalline calcite (sparite) that may constitute a cement binder and microcrystalline calcium carbonate (micrite) that commonly forms the matrix (Folk, 1962). They may be described as calcilutites (carbonate mudstones) or calcarenites (of sand grain size), or by other terms based on their texture (Dunham, 1962). Ooliths are roughly spherical grains, 0.2–2.0 mm in diameter with concentric or radial structure, that formed by accretion on lagoon floors and may constitute the majority of the rock in oolitic limestones (also known as oolites). Most other carbonates are minor as rock units. Pelagic oozes and turbidites of deep-water marine basins leave little geological record. Those from evaporitic basins can be more extensive, but are mostly dolomitic (Section 1.5). Caliche is a carbonate duricrust that may be widespread in arid regions. Tufa is a soft porous carbonate precipitated by algal and bacterial action in springs and streams in limestone terrains. Travertine is a dense, banded deposit, similar to tufa in that it is deposited in flowing streams, but generally in response to changes in water chemistry or downstream of hydrothermal sources (the terms travertine, tufa and sinter are almost synonymous in different parts of the world). Stalagmite is the variety of travertine deposited in caves. Wind-blown carbonate sand may form on beaches and as dunes on coral islands, and is commonly capped by a partially cemented duricrust.

The mechanical behaviour of all carbonate sediments is influenced by grain size and those post-depositional changes that bring about induration, and thereby increase density and strength. Induration of limestones commonly starts during the early stages of deposition, by cementation that occurs where individual grains are in contact. Consequently, cementation is not solely dependent on consolidation due to increasing overburden pressure. Because induration can take place at the same time as deposition, carbonate sediments can sustain high overburden pressures, and can therefore retain high porosities at considerable depths. A bed of cemented grains may overlie one that is poorly cemented. Eventually, high