

EARTH BUILDING

History, science and conservation

Paul Jaquin and Charles Augarde



bre press

EARTH BUILDING

History, science and conservation



bre press



Zhenchen Lou. Hakka Tolou, Fujian Province,
China. Constructed 1912

EARTH BUILDING

History, science and conservation

Paul Jaquin and Charles Augarde



bre press

Published by IHS BRE Press

IHS BRE Press publications are available from
www.brebookshop.com

or

IHS BRE Press
Willoughby Road
Bracknell RG12 8FB
Tel: 01344 328038
Fax: 01344 328005
Email: brepress@ihs.com

Printed on paper sourced from responsibly managed
forests

Requests to copy any part of this publication should
be made to the publisher:

IHS BRE Press
Garston, Watford WD25 9XX
Tel: 01923 664761
Email: brepress@ihs.com

The authors and publisher accept no responsibility,
nor liability, in any manner whatsoever for any
error or omission, nor any loss, damage, injury, or
adverse outcome of any kind incurred as a result
of the use of the information contained in this
book or reliance upon it. Readers are advised to
seek specific professional advice relating to their
particular construction project and circumstances
before embarking on any building work.

Reasonable care has been taken to ensure the
accuracy of the information in the book at the
time of printing. Drawings and technical details are
indicative and typical only and final detailing for any
project remains the responsibility of the designer.

The publisher accepts no responsibility for the
persistence or accuracy of URLs referred to in
this publication, and does not guarantee that any
content on such websites is, or will remain, accurate
or appropriate.

Front cover images:

Left, Rammed earth, Kasbah Caid Ali, Asslim,
Morocco

Top right, Adobe bricks drying, Aït Ben Haddou,
Morocco

Middle right, Cob toilet block, Melon car park,
Eden Project, Cornwall, UK. Courtesy of Jackie Abey
and Jill Smallcombe, Abey Smallcombe cob builders

Bottom right, Rammed earth barn, Villafeliche,
Spain

Back cover image:

Lime-rendered cob house, Devon, UK

Index compiled by Paul Nash

EP 101

© Copyright Paul Jaquin and Charles Augarde 2012

First published 2012

ISBN 978-1-84806-192-7

PREFACE

This book is the result of research carried out at Durham University, and subsequent work at historic earthen sites around the world. Paul Jaquin undertook a PhD supervised by Dr Charles Augarde, and the research shed light on the important mechanisms behind the mechanical behaviour of earthen construction. We believe this research is the first to view earth buildings in the framework of unsaturated soil mechanics, and we show that, by doing this, many aspects of the behaviour of earth buildings can be explained better. By appreciating the unsaturated nature of earth buildings, it is possible to understand the changes in behaviour of earth buildings and the causes of damage, and therefore to develop successful restoration strategies.

We have focused specifically on the conservation of historic earth buildings, but the principles outlined are equally applicable to modern earthen construction. We have included a section on the history of earth building to allow readers to place buildings within a historical and geographical context.

Although much of the research focused on the conservation of historic rammed earth, the underlying principles are common to all types of earth building, and while the damage and conservation techniques are also inclined towards rammed earth, many of the damage and repair

strategies are independent of the type of earthen construction.

This book is written for engineers, conservation professionals, and those interested in earth buildings. As earth is such a varied material, and many aspects of earth building are based on experience, the book does not generally provide specific values (for example for strength or stiffness), or rules of thumb for earthen construction and restoration.

There is still a great deal of work to be undertaken before understanding of earth building reaches the levels of more conventional building materials such as steel and concrete. Further research is required into earth buildings at all scales, from investigation of the interparticle contacts to the development of codes of practice and standards. Of particular interest are the behaviour of earth buildings in earthquakes (which is not covered in this book), the exposition of archaeological sites, and the thermal behaviour of earthen buildings. Earth is becoming increasingly popular as a sustainable construction material, and it is hoped that this book will lead to improved scientific and engineering understanding of earth as a construction material.

Paul Jaquin
Charles Augarde
November 2011

ACKNOWLEDGEMENTS

Thanks must go first to Professor Chris Gerrard of the Department of Archaeology at Durham University, who first wondered whether the large cracks in a building he was studying in Spain were a problem, and who really set this line of research going. Thanks also to Professor David Toll of the School of Engineering and Computing Sciences at Durham University, who on viewing an early experimental rammed earth wall in the civil engineering laboratory, noted that it ‘looks like suction’. We also thank Nick Clarke, Publisher at IHS BRE Press, whose vision for the publication of this material has finally come to fruition.

Many students at Durham University have been involved in earth-building research, and have helped us understand these materials through their work, specifically Chris Beckett, Cynthia Hendy, Tom Horncastle, Tom Howard, Steven Perkins, Jenny Durie, Lucie Le Grand and Jacinto Canivell. Thanks to those with whom we worked on developing this field at Durham, namely Dr Sergio Lourenço (now at Cardiff University) in the field of unsaturated soil mechanics and Dr Cathy Clarke (now at Stellenbosch University) for help with the chemistry.

Paul was privileged to undertake a Research Associate role at the University of Bath during the summer of 2008, and thanks go to Professor Peter Walker, Dr Andrew Heath and Dr Enrico Fodde at University of Bath for their discussions and support during this period of research. Thanks also go to Manfred Fahnert, organiser of the Lehm Express in Morocco, who taught Paul to clay plaster.

Parts of the research overseas have been undertaken with the aid of travel grants from the Institution of Structural Engineers and Engineers without Borders for visits to India and Bhutan.

Thanks go to members of the ICOMOS International Committee on the Conservation of Earthen Architecture for their expertise and support, and to Paul’s colleagues both in the UK and in Sweden, for their support and interest in this non-conventional building material. Thanks also go to those who have supplied photographs which has enabled us to show a much wider range of earth building.

Finally, for help, support and enthusiasm, and for being dragged on earth-building-related ‘holidays’ for many years, thanks go to Paul’s girlfriend, Eleanor Trueman.

CONTENTS

PREFACE	v	3.13 Current research	35
ACKNOWLEDGEMENTS	vi	3.14 Conclusions	36
NOMENCLATURE	viii	4 DAMAGE TO EARTH BUILDINGS	37
INTRODUCTION	1	4.1 Introduction	37
1 TYPES OF EARTHEN CONSTRUCTION	3	4.2 Structural	37
1.1 Introduction	3	4.3 Water	43
1.2 Earthen construction principles	3	4.4 Render	48
1.3 Monolithic earth walls	5	4.5 Organic matter	50
1.4 Unit construction	9	4.6 Abrasion	51
1.5 Conclusions	12	4.7 Concluding remarks	52
2 HISTORY OF EARTH BUILDING	13	5 CONSERVATION STRATEGIES	53
2.1 Introduction	13	5.1 Introduction	53
2.2 Eastern Asia	14	5.2 Conservation principles	53
2.3 Central Asia and the Indus valley	15	5.3 Earth-building analysis and repair strategy	54
2.4 Asia	16	5.4 Foundation issues	56
2.5 Africa	17	5.5 Cracks	57
2.6 Europe	20	5.6 Wall lean	60
2.7 North America	21	5.7 Water	64
2.8 South America	23	5.8 Face repair	69
2.9 Australasia	25	5.9 Repair to the wall using fallen or similar material	71
2.10 Conclusions	26	5.10 Whole building reconstruction	75
3 FUNDAMENTAL BEHAVIOUR OF EARTHEN CONSTRUCTION MATERIALS	27	6 CONCLUDING REMARKS	77
3.1 Introduction	27	REFERENCES	78
3.2 Soil mechanics	27	BIBLIOGRAPHY	81
3.3 Soil strength	28	INDEX	83
3.4 Effective stress	28		
3.5 Unsaturated soil mechanics	29		
3.6 Fundamentals	29		
3.7 Relative humidity	30		
3.8 The soil water retention curve	31		
3.9 Compaction	32		
3.10 The role of clay	33		
3.11 The role of stabilisers	34		
3.12 The effect of water content on the mechanical behaviour of earth structures	34		

NOMENCLATURE

CEB	Compressed earth blocks	s	Suction
CSH	Calcium silicon hydrate	T	Temperature
OWC	Optimum water content	T_s	Surface tension
RH	Relative humidity	u	Pressure, pore water pressure
SWRC	Soil water retention curve	u_a	Air pressure
c	Apparent cohesion	u_w	Water pressure
F	Force	v_w	Molar volume of water
F_{tension}	Attractive force due to surface tension	θ	Contact angle
F_{pressure}	Attractive force due to pressure difference	μ	Coefficient of friction
g	Acceleration due to gravity	ρ_d	Dry density
h	Relative humidity, height	σ	Stress, total stress
N	Normal force	σ'	Effective stress
p_0	Pressure of saturated water vapour	τ	Shear strength
p_v	Pressure of water vapour	ϕ	Macroscopic friction angle
R	Universal gas constant	ϕ'	Effective macroscopic friction angle
r	Radius		
r_{neck}	Radius of the neck of a liquid bridge		
r_x, r_y	Radius of curvature of meniscus		
S_r	Degree of saturation		

INTRODUCTION

Earth buildings are perceived by many as simple ‘mud huts’, liable to damage, and earth as at the bottom of the list of desirable construction materials. While earth buildings are more liable to damage by water than those constructed from other construction materials, earth is one of the simplest and most sustainable construction materials, and many of the oldest structures in the world are constructed from this material. Around 30% of the UNESCO World Heritage Sites are constructed from earth.

In common with buildings made from all other types of construction materials, historic earth buildings are liable to damage, through lack of maintenance to protect against the weather, changes to the local environment, or damage caused by external factors. This book aims to present the reasons for the occurrence of such damage, and to provide strategies that may be useful in the conservation of historic earth structures. We do this by providing a scientific rationale for the behaviour of earth buildings. By viewing earth buildings in the framework of unsaturated soil mechanics, we are able to better understand their behaviour, and thus the damage that earth buildings may suffer.

The book begins with an introduction into the different types of earth building, and we argue that although the construction techniques are markedly different, there are definite common themes that apply to every type of construction material. In Chapter 2 we briefly describe the history of earth building, using some of the main archaeological and architectural sites worldwide. This serves to allow the reader to place any structure under investigation into an international and chronological context. The principles of general and unsaturated soil mechanics are outlined in Chapter 3. Relatively recent research

findings allow for an improved understanding of the mechanical behaviour of earth buildings, and in Chapter 4 we show how this relates to observed damage mechanisms in earth buildings. Finally, in Chapter 5 we present mitigation and repair solutions that may prove useful in the conservation of historic earthen sites.

This book is not a practical guide on earthen construction, nor is it an engineering textbook. Techniques for different types of earthen construction can be learned from numerous sources, both through practical courses and through guides. A history of earth building is provided that focuses on some main sites, although many are not included for brevity, and the history of specific earthen sites is not explored. The principles of unsaturated soil mechanics are explained, but there are many logical steps that are not included, and reference should be made to our journal papers and to other engineering textbooks. As earthen construction is so varied, and as there is a much smaller pool of test data than for other, more conventional construction techniques, specific values for soil testing and mechanical properties are not given. We do not provide information on field or laboratory techniques for the testing of earthen materials. Engineering analysis methods for structures are not explained, and the advice of a competent engineer should always be sought when considering the conservation of historic earth buildings.

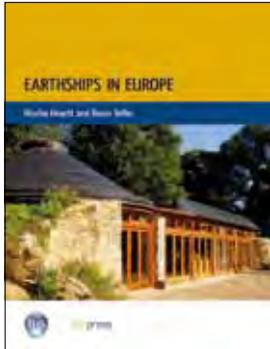
Finally, the behaviour of earthen buildings in earthquakes is not specifically discussed. This behaviour is complex, and although the damage mechanisms are similar to those described in this book, we do not deal with these, or with the retrofitting or reconstruction of earth buildings after seismic events.

OTHER TITLES FROM IHS BRE PRESS

EARTHSHIPS IN EUROPE

Evaluate the building of the first earthships in Europe by investigating energy and water conservation, building with waste, and construction methods. The new edition of this successful book, which includes case studies and post-construction monitoring, gives design recommendations to make earthships more effective in different climatic conditions.

Ref: EP 102, 2nd edition



HEMP LIME CONSTRUCTION

A guide to building with hemp lime composites

The first complete guide to building with hemp lime, this fully illustrated book gives you numerous examples and design details to enable practical construction with this novel, sustainable material.

Ref: EP 85

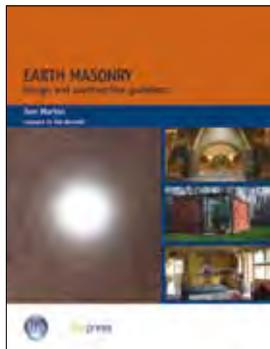


EARTH MASONRY

Design and construction guidelines

Improve your understanding of one of the oldest and most widespread building materials. This extensively illustrated guide to earth masonry provides guidance on using earth brick to produce durable buildings that fit their climate and are suited to a wide range of uses.

Ref: EP 80

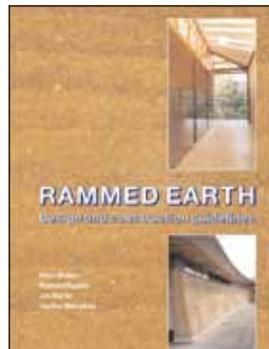


RAMMED EARTH

Design and construction guidelines

Get authoritative, state-of-the-art, practical guidance on rammed earth wall construction. Containing construction details and numerous photos of rammed earth buildings in the UK, Europe, USA, Africa and Australia, this book gives advice on all aspects of rammed earth for housing and other low- and medium-rise buildings.

Ref: EP 62



All titles are available in print and pdf format.

Order now @ www.brebookshop.com or phone the IHS Sales Team on +44 (0) 1344 328038.

EARTH BUILDING

History, science and conservation

This book covers various types of earth construction including adobe, cob and rammed earth. It presents a wide-ranging review of the history of earth building, tracing the development of earthen construction techniques from antiquity to the present day, and showing the development of the techniques over time and in different locations around the world. The behaviour of earth building materials is explained using, for the first time, principles from soil mechanics. There is a detailed discussion of strategies for the analysis and conservation of earth buildings to enable engineers, conservation professionals and architects to understand and preserve earth buildings better in the future. Richly illustrated with photographs and diagrams, this book provides an invaluable tool for the conservation of earth buildings.



ABOUT THE AUTHORS

Paul Jaquin is a civil and structural engineer. After completing an engineering degree at Durham University, he undertook a PhD supervised by Charles Augarde entitled 'Analysis of historic rammed earth'. This research established the link between earth buildings and unsaturated soils and much of the research is included in this book. He has acted as a consultant on sustainable construction projects in the UK and on conservation and development projects in the US, Canada, Australia, UAE, China and Bhutan.

Charles Augarde is Reader in Civil Engineering at the School of Engineering and Computing Sciences, Durham University, and a Chartered Civil Engineer. His research interests are in two principal areas: sustainable earthen construction materials and computational geomechanics. He has published over 70 articles in peer-reviewed journals and conferences since 1998, is currently on the Editorial Board for the international journal *Computers and Geotechnics* and is a former member of the *Géotechnique* Advisory Panel.



bre press

IHS BRE Press, Willoughby Road
Bracknell, Berkshire RG12 8FB
www.brebookshop.com
EP 101

ISBN 978-1-84806-192-7

