Second Edition

Failure Case Studies in Civil Engineering

Structures, Foundations, and the Geoenvironment

Edited by
Paul A. Bosela, Ph.D., P.E.; Pamalee A. Brady, Ph.D., P.E.;
Norbert J. Delatte,

ASCE

This is a preview. Click here to purchase the full publication.

FAILURE CASE STUDIES IN CIVIL ENGINEERING

STRUCTURES, FOUNDATIONS, AND THE GEOENVIRONMENT

SECOND EDITION

EDITED BY

Paul A. Bosela, Ph.D., P.E.
Pamalee A. Brady, Ph.D., P.E.
Norbert J. Delatte, Ph.D., P.E.
M. Kevin Parfitt, P.E.

SPONSORED BY

Technical Council on Forensic Engineering
of the American Society of Civil Engineers

Published by the American Society of Civil Engineers

Cataloging-in-Publication Data on file with the Library of Congress.

Published by American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia, 20191-4400
www.asce.org/pubs

Any statements expressed in these materials are those of the individual authors and do not necessarily represent the views of ASCE, which takes no responsibility for any statement made herein. No reference made in this publication to any specific method, product, process, or service constitutes or implies an endorsement, recommendation, or warranty thereof by ASCE. The materials are for general information only and do not represent a standard of ASCE, nor are they intended as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document. ASCE makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefore. This information should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing this information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

ASCE and American Society of Civil Engineers—Registered in U.S. Patent and Trademark Office.

Photocopies and permissions. Permission to photocopy or reproduce material from ASCE publications can be obtained by sending an e-mail to permissions@asce.org or by locating a title in ASCE's online database (http://cedb.asce.org) and using the “Permission to Reuse” link.

Copyright © 2013 by the American Society of Civil Engineers.
All Rights Reserved.
ISBN 978-0-7844-1255-8 (paper)
ISBN 978-0-7844-7703-8 (PDF)
ISBN 978-0-7844-7748-9 (EPUB)
Manufactured in the United States of America.

Contents

Preface

This is a special publication of the Education Committee of the American Society of Civil Engineers' (ASCE) Technical Council on Forensic Engineering (TCFE). It was first published in 1995 as *Failures in Civil Engineering: Structural, Foundation and Geoenvironmental Case Studies* edited by Robin Shepherd and J. David Frost.

Forensic Engineering is the application of engineering principles to the investigation of failures or other performance problems. The investigations may involve testimony on the findings before a court of law or other judicial forum, when required. Failures include not only catastrophic events, such as bridge and building collapses, but also failures of facilities or components to perform as intended by the owner, design professional, or constructor. ASCE authorized TCFE in July 1985 following a number of dramatic collapses of engineered structures, such as the Hartford Coliseum, Kemper Arena, and the Hyatt Regency Walkways. The purpose of TCFE is to develop practices and procedures to reduce the number of such failures, to disseminate information on failures and their causes, to provide guidelines for conducting failure investigations, and to provide guidelines for ethical conduct in forensic engineering. It is the purpose of TCFE's Education Committee to promote the study of failure case histories in educational activities. Thus, the committee works to promote and advance the educational objectives of colleges and universities and act as a source of referral for educational material with forensic engineering emphasis.

Design and construction of civil engineering projects presents unique challenges. The design and construction "team" consists of owners, design professionals, and construction professionals in a temporary association for a specific project. The unpredictability of the exposure to natural and man-made hazards that the facility will experience during its life necessitates that the design be based on sound engineering judgment rather than certainty. In some industries, a series of prototypes can be designed and built to work out the problems before the final product is manufactured. Lessons learned from problems with the earlier prototypes are incorporated in the final product. By the nature of most civil engineering projects, that is not an option. Hence, it is critical that we learn from both the successes and failures of each individual project.

Failures can occur during construction, any time during the service life of the facility, and even during demolition. They occur for many reasons, such as inadequate consideration of the inherent instabilities of a structure, fragmentation of responsibilities that may occur during the construction process, not anticipating or designing for all modes of failure, and unusual or unanticipated loadings. Failures can often be traced to the beginning of a project's life; such errors include:

- Design errors and omissions
- Construction sequencing (means and methods)
- Construction phase process failures (e.g. shop drawings and submittals)
- Construction defects
- Materials defects
- System and component defects

Once a building or structure is in service, failure not directly attributable to design or construction is most often caused by one or more of the following:

- Deterioration
- Damage
- Catastrophic events
- Overload

Failures often result from a combination of factors, and it is instructive to study the underlying cause(s), triggering events, contributing factors, and mitigating factors. Sometimes, one failure results in a change in the standard of practice. Other times, it takes a series of repeated failures to influence change. Unfortunately, despite repeated failures, the lessons are not always learned. This second edition has been expanded with the inclusion of additional case studies such as the Alfred P. Murrah Building and Charles de Gaulle Airport Terminal as well as expanded descriptions of the case studies, and inclusion of additional references, photographs, and illustrations.

The objective of this publication is to provide resource material on typical failure case studies that can be used by engineering professors in their classrooms. It includes an outline of each case study, summary of the lessons learned, and a list of references for further study. It is anticipated that the discussion of failure case studies in the classroom will provide students with improved awareness that sound engineering requires an understanding of both the successes as well as the failures.

Acknowledgments

The Education Committee wishes to acknowledge the contributions of those involved in this publication. The original publication included short study descriptions contributed by the following individuals:

- Paul A. Bosela, Cleveland State University, Cleveland, OH
- Kenneth L. Carper, Washington State University, Pullman, WA
- Timothy J. Dickson, Construction Technology Laboratories, Inc., Skokie, IL
- J. David Frost, Georgia Institute of Technology, Atlanta, GA
- Narbey Khachaturian, University of Illinois, Champaign-Urbana, IL
- Oswald Rendon-Herrero, Mississippi State University, Starkville, MS
- Robin Shepherd, Forensic Expert Advisers, Inc., Santa Ana, CA

The following individuals contributed new case studies and other materials for the second edition:

- Paul A. Bosela, Cleveland State University, Cleveland, OH
- Pamalee A. Brady, California Polytechnic State University, San Luis Obispo, CA
- Kenneth L. Carper, Washington State University, Pullman, WA
- Norbert J. Delatte, Cleveland State University, Cleveland, OH
- M. Kevin Parfitt, Penn State University, University Park, PA
- Kevin Rens, The University of Colorado Denver, Denver CO
- Kevin Sutterer, Rose-Hulman Institute of Technology, Terre Haute, IN

The committee also wishes to acknowledge the contribution of Pennsylvania State University student Gaby Issa-El-Khoury, who contributed to the research on the Charles de Gaulle Airport Terminal 2E case history and provided summary translations of the original French investigation report and other articles. The Technical Council of Forensic Engineering Executive Committee provided review and support of this second edition. The Education Committee thanks Executive Committee members David B. Peraza (Chairman), Leonard J. Morse-Fortier (Past-Chair), Anthony M. Dolhon (Vice-Chairman), Michael P. Lester (Secretary), Michael J. Drerup, and Glenn G. Thater.

Paul A. Bosela
Pamalee A. Brady
Norbert J. Delatte
M. Kevin Parfitt
Editors

Chapter 1

Foundation Failures

TOWER OF PISA
(1173 & Ongoing)

The Tower of Pisa (Figure 1-1) in Italy is about 60 m (200 ft) tall from foundation to belfry, 20 m (66 ft) in diameter and weighs approximately 145 MN (14,500 tons). It was constructed in three phases. Four floors were built over a 5 year period from 1173 to 1178. Following an almost 100 year hiatus, in the second phase of construction, three additional floors were constructed between 1272 and 1278. The third construction phase occurred more than 80 years later between 1360 and 1370 when the bell tower was added. The tower's foundation is inclined at almost 5.5 degrees to the south; the tower overhangs the ground about 6 m (20 ft) out of plumb. The value corresponding to the eccentricity on the loads on the foundation is 2.3 m (7.5 ft).

Evidence indicates that the phased construction was mandated by the performance of the structure as it was being built. Further, records indicate that during construction the tower appeared to move sufficiently so that the builders used obliquely cut stones in an effort to maintain the floor of each successive story approximately horizontal. It is interesting to note that the obliquely cut stones were used by the Pisa Commission, entrusted with gathering and collating relevant data for an international competition organized to identify a method to stabilize the tower in 1972, to reconstruct the pattern of movements throughout the first two phases of the tower's construction. Their calculations showed that at the end of the first construction phase the tower had begun to lean towards the northwest. During the second and third phases, the angle of inclination increased and the principal direction of tilt shifted first to the northeast and then to the south.

By 1993 the tower's maximum horizontal tilt had progressed to 5.2 meters (17 ft). In June of that year an attempt was made to reduce the tower's tilt. Specially fabricated lead counterweights were placed on top of the north side of a tensioned concrete ring built around the base of the tower. The tilt was reduced by approximately 12 seconds of arc over a 6-week period, as about 1.3 MN (130 tons) of lead were placed. Over the course of the remediation, until January 1994, a total of 6.9 MN (690 tons) was applied and by July 1994 the tower had righted its position toward the north a full 52 arc seconds. The Pisa Commission decided to replace the lead counterweights with an anchored cable system. In 1995 they began freezing the ground with liquid nitrogen in preparation for installing the cables. As soon as the freezing stopped the tower began to once again lean southward at a rate of four arc seconds per day. The operation was halted. They continued a search for a permanent solution.

In March of 1996 engineers successfully completed a test of a soil-extraction method to reduce the tower's lean. In this method an inclined drill was used to create cavities that gently closed due to the pressure of the overlying soil. The method was fully employed three years later. In 1999, after the installation of temporary cables, which could be tensioned to steady the tower if detrimental movements occurred, engineers drilled a dozen boreholes over a width of approximately 5.5 m (18 ft). They slowly removed underlying soil at a rate of approximately 0.02 cubic meters