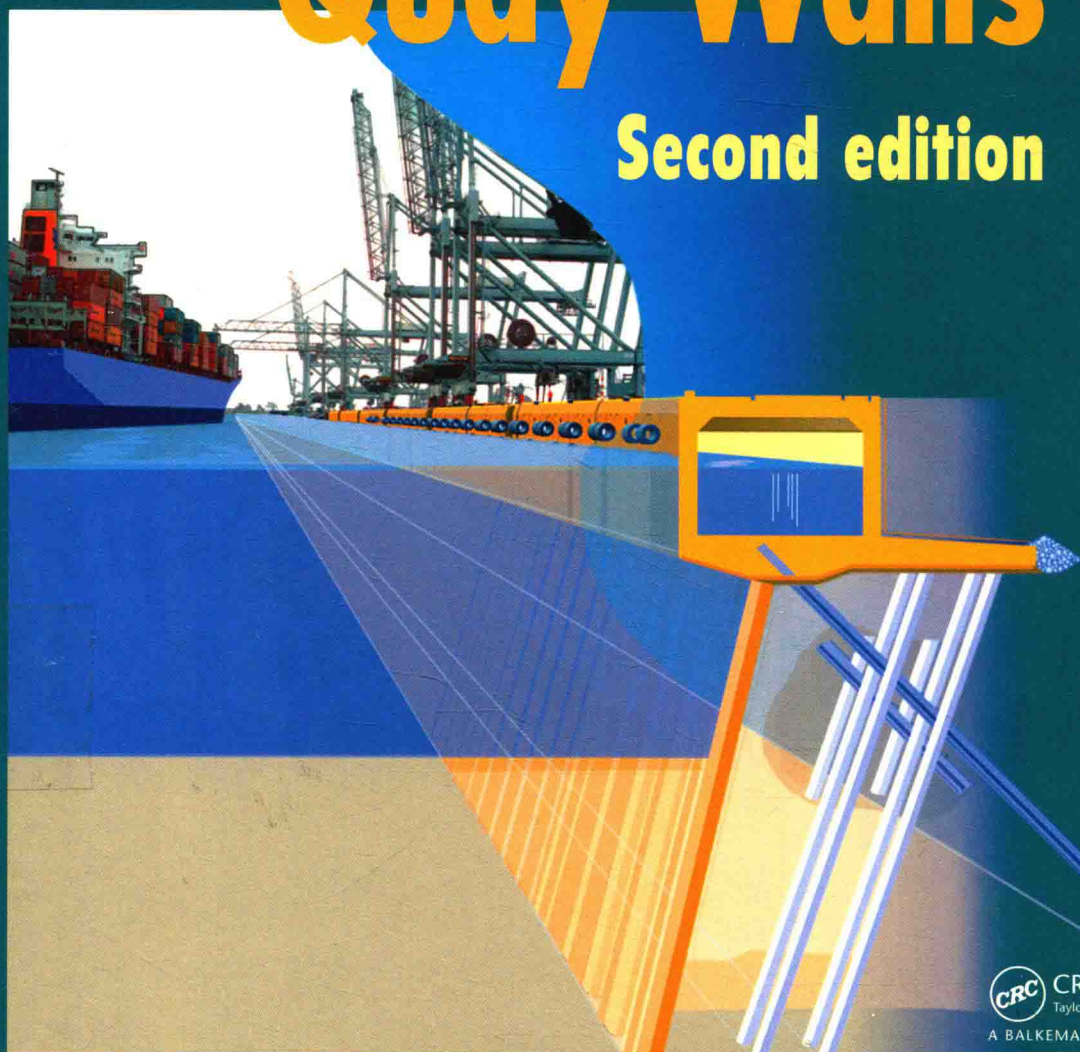


**Editors: J.G. de Gijt & M.L. Broeken**

# Quay Walls

**Second edition**



SBRCURnet Publication 211E

# Quay Walls

Second edition

*SBRCURnet*  
*Municipality Rotterdam*  
*Port of Rotterdam*



**CRC Press**

Taylor & Francis Group

Boca Raton London New York Leiden

---

CRC Press is an imprint of the  
Taylor & Francis Group, an **informa** business

A BALKEMA BOOK

*Published by CRC Press/Balkema, an imprint of the Taylor & Francis Group,  
an informa business*

© 2014 SBRCURnet, Rotterdam, The Netherlands

Typeset by MPS Limited, Chennai, India

Printed and bound in the Netherlands by PrintSupport4U, Meppel.

### **Copyright**

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording and/or otherwise, without the prior written permission of SBRCURnet.

It is allowed, in accordance with article 15a Netherlands Copyright Act 1912, to quote data from this publication in order to be used in articles, essays and books, provided that the source of the quotation, and, insofar as this has been published, the name of the author, are clearly mentioned. “© SBRCURnet Publication 211E ‘Quay Walls, Second Edition’, 2014. SBRCURnet, Rotterdam, The Netherlands.”

### **Liability**

SBRCURnet and all contributors to this publication have taken every possible care by the preparation of this publication. However, it can not be guaranteed that this publication is complete and/or free of faults. The use of this publication and data from this publication is entirely for the user's own risk and SBRCURnet hereby excludes any and all liability for any and all damage which may result from the use of this publication or data from this publication, except insofar as this damage is a result of intentional fault or gross negligence of SBRCURnet and/or the contributors.

All rights reserved. No part of this publication or the information contained herein may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, by photocopying, recording or otherwise, without written prior permission from the publishers.

Although all care is taken to ensure integrity and the quality of this publication and the information herein, no responsibility is assumed by the publishers nor the author for any damage to the property or persons as a result of operation or use of this publication and/or the information contained herein.

*Library of Congress Cataloging-in-Publication Data*

Applied for

Published by: CRC Press/Balkema  
P.O. Box 11320, 2301 EH, Leiden, The Netherlands  
e-mail: Pub.NL@taylorandfrancis.com  
www.crcpress.com – www.taylorandfrancis.com

ISBN: 978-1-138-00023-0 (Hardback)

ISBN: 978-1-315-77831-0 (eBook PDF)

## FOREWORD

Since the publication of the Dutch edition in 2003 and the English version in 2005 considerable new experience has been obtained by many practitioners using the book, leading to the need to update this handbook. The introduction of the Eurocodes in 2012 was also an important reason for a new version of this handbook, resulting in a complete revision of the Design chapter, in order to comply with the Eurocodes. Additional recommendations for using FEM-analysis with quay wall design have been incorporated.

Within the industry, discussions are going on about buckling criteria for steel pipe piles. Therefore in the framework of this CUR project a thorough research project was carried out on steel pipe piles filled with sand and piles without sand. The results of this research programme have been incorporated in this new version.

Finally, the section about corrosion has also been updated to the latest knowledge and attention has also been given to the latest global developments in quay wall engineering.

The review of this handbook was done under the supervision of CUR Committee C183 "Quay Walls". This committee consists of the following members:

|                                                |                                                                 |
|------------------------------------------------|-----------------------------------------------------------------|
| Dr. J.G. de Gijt,<br>chairman, Editor          | Stadsontwikkeling, Ingenieursbureau Gemeente Rotterdam/TU Delft |
| M.L. Broeken, Editor                           | Stadsontwikkeling, Ingenieursbureau Gemeente Rotterdam          |
| A.A. Roubos, Secretary                         | Port of Rotterdam Authority                                     |
| S. Azzouzi                                     | ARCADIS Nederland                                               |
| Dr. K.J. Bakker                                | WAD43/TU Delft                                                  |
| Prof. Ch. Bauduin                              | N.V. BESIX S.A./KU Leuven                                       |
| H.E. Brassinga                                 | Municipality Rotterdam                                          |
| E.J. Broos                                     | Port of Rotterdam Authority                                     |
| E. Dupont                                      | Fundex NV/SA                                                    |
| R.A. van der Eijk                              | VolkerInfraDesign                                               |
| A.J. van der Geest                             | BAM Speciale Technieken                                         |
| A. Groeneweg                                   | Ballast Nedam Funderingstechnieken                              |
| H.L. Jansen                                    | Fugro GeoServices                                               |
| D.J. Jaspers Focks                             | Witteveen+Bos Raadgevende Ingenieurs                            |
| J.P. Klootwijk                                 | GEKA BOUW B.V.                                                  |
| P.A. Kraaijeveld                               | Volker Staal en Funderingen                                     |
| A.P. Louwen                                    | Port of Rotterdam                                               |
| P. Mulders                                     | ArcelorMittal Projects Europe                                   |
| D.J. Peters                                    | Royal HaskoningDHV                                              |
| P.J. Plooy                                     | Raadgevend Ingenieursbureau Lieveense                           |
| C.N. van Schaik                                | VolkerInfraDesign                                               |
| H.J. Wolters                                   | IV-Infra                                                        |
| Dr. R.B.J. Brinkgreve,<br>corresponding member | Plaxis                                                          |
| A. Jonker, Coordinator                         | SBRCURnet                                                       |

Scientific contributions were given by Prof. A.F. van Tol, Prof. A.C.W.M. Vrouwenfelder and Prof. J.K. Vrijling.

## **SPONSORS**

SBRCURnet would like to thank the organizations and companies listed below whose support made the publication of this handbook possible:

Aannemingsbedrijf De Klerk BV  
ARCADIS Nederland BV  
ArcelorMittal Projects Europe  
Ballast Nedam Funderingstechnieken  
BAM Civiel bv  
BAUER Funderingstechniek B.V.  
BESIX  
FCO GWW 2011/2012  
Funderingstechnieken Verstraeten B.V.  
FUNDEX N.V.  
Gebr. De Koning B.V.  
GEKA BOUW B.V.  
Hakkers b.v.  
N. Kraaijeveld B.V.  
Groningen Seaports  
Port of Rotterdam Authority  
Raadgevend Ingenieursbureau Lieveense  
Royal HaskoningDHV  
Stadsontwikkeling, Ingenieursbureau Gemeente Rotterdam  
Stere Midden Nederland B.V./Stere Heiwerken B.V.  
Van der Straaten Aannemingsmaatschappij B.V.  
Van Oord Dredging & Marine Contractors bv  
Volker Staal en Funderingen bv  
Voorbij Funderingstechniek B.V.  
Witteveen + Bos Raadgevende Ingenieurs  
Zeeland Seaports

## **ACKNOWLEDGEMENTS**

The SBRCURnet wishes to thank the CUR committee and all other persons who gave their contribution in the publication of this handbook by generously contributing the fruits of their expertise in the form of information and comments.

November 2013

The Board of SBRCURnet

## SAMENVATTING

Bij het ontwerpen van kademuren is het de kunst om de interactie tussen de verschillende constructieonderdelen en de grond op een goede manier te schematiseren. Dit handboek geeft een overzicht van de beschikbare kennis en ervaring op het gebied van het ontwerp, de uitvoering en het beheer van kademuren.

In de inleidende hoofdstukken wordt de functie van kademuren in de loop van de geschiedenis behandeld en wordt een overzicht gegeven van de hoofdvormen. Aan de hand van voorbeelden uit binnen- en buitenland wordt een toelichting gegeven op de diverse constructiemogelijkheden.

De daaropvolgende hoofdstukken volgen het ontwerpproces op de voet. Omdat betrouwbare gegevens van wezenlijk belang zijn, wordt er ingegaan op het verzamelen en bewerken van basisgegevens en het opstellen van het programma van eisen. De ontwerpfilosofie is toegespitst op kades met een ontlastconstructie en dragende damwand. Voor het ontwerp van andere constructieve vormen, gewichtsconstructies en steigerachtige constructies, wordt verwezen naar de aangegeven literatuur. Veel aandacht is geschonken aan de semi probabilistische ontwerpmethode in relatie tot de Eurocode.

Een belangrijk punt is het ontwerp van de elementen waaruit een kade is opgebouwd. Deze bepalen immers in hoge mate de uiteindelijke functionaliteit van de kade. Vanuit deze filosofie wordt de nodige aandacht besteed aan het ontwerp van de kade-elementen. Vele voorbeelden, details en praktische raadgevingen zijn opgenomen. Het gebruik van de verschillende materialen wordt behandeld vanuit een materiaaltechnologisch gezichtspunt. Aandacht wordt besteed aan de maatregelen die genomen moeten worden om aantasting of schade te voorkomen.

Hoewel het handboek in de eerste plaats gericht is op de ontwerppraktijk hebben ook de uitvoering, de kosten en het beheer een plaats gekregen. Hier is de uitdaging vooral toegespitst op optimalisatie en praktische benaderingen. De realisatie van een kademuur is immers zeer kapitaalintensief en complex, of dit nu in den natte of in den droge gebeurt. Naast kostencalculatie krijgen werkvoorbereiding, realisatie, kwaliteitszorg en oplevering de nodige aandacht. In het hoofdstuk dat gewijd is aan het beheer en onderhoud van de kademuur wordt een pleidooi gehouden voor een pro-actief beheer dat vooraf een aantal kwaliteitsdoelen stelt. Daarbij worden de kademuren gemodelleerd en wordt geanalyseerd wat de bedreigingen van deze doelen zouden kunnen zijn in de vorm van veroudering en overbelasting.

Een apart hoofdstuk is gewijd aan ervaringen en de lessen die geleerd werden bij het verleggen van grenzen of bij het bouwen van nieuwe concepten. Het bevat een veelheid aan

ervaringsgegevens, zowel ontwerptechnische en uitvoeringstechnische zaken, als aanwijzingen voor een verantwoord gebruik van de kade. De vastgelegde ervaringen beogen niet alleen de lezer te behoeden voor missers, maar willen tevens een stimulans zijn om creatief te zoeken naar oplossingen voor de problemen die zich in de eigen situatie voordoen. Iedere situatie is immers uniek en levert nieuwe uitdagingen waarvoor echte standaardoplossingen moeilijk te vinden zijn.

Het boek zou niet compleet zijn zonder de behandeling van toekomstige ontwikkelingen die ontwerp, realisatie en beheer van de kade kunnen beïnvloeden. Tenslotte zijn een verklarende woordenlijst opgenomen met de gebruikte termen en afkortingen om de leesbaarheid te bevorderen, en een index om de terugvindbaarheid van de verschillende begrippen en onderwerpen te vergemakkelijken.

## SUMMARY

The handbook on Quay Walls provides information about planning, design, execution and maintenance of quay walls. Since the introduction in Dutch in 2003 and the English version in 2005 much experience has been obtained by many practitioners using the book. This experience gained by the users has led to the need to update this handbook. Another reason for this new version of the handbook was the introduction of the Eurocodes in 2012. Therefore the Design chapter has been completely revised to comply with the Eurocodes. Additional recommendations have been incorporated for using FEM-analysis with quay wall design.

Within the industry discussions are going on about buckling criteria for steel pipe piles.

Therefore a thorough research project was carried out on steel pipe piles filled with sand and piles without sand. The results of this research programme have been incorporated in this revised version.

The section about corrosion has also been updated to the latest knowledge.

Some attention has also been given to the latest global developments in quay wall engineering.

This revision was made possible by contributions of experts from the Netherlands and Belgium.

Editors: Associate Professor dr. J.G. de Gijt and M.L. Broeken, BSc.

## CONTENTS

|           |                                                            |     |
|-----------|------------------------------------------------------------|-----|
|           | FOREWORD .....                                             | V   |
|           | SAMENVATTING .....                                         | VII |
|           | SUMMARY .....                                              | IX  |
| Chapter 1 | INTRODUCTION .....                                         | 1   |
| 1.1       | Function of quay walls .....                               | 5   |
| 1.2       | Objective of this book .....                               | 6   |
| 1.3       | Composition of the book .....                              | 7   |
|           | References .....                                           | 8   |
| Chapter 2 | OVERVIEW OF QUAY WALL CONSTRUCTION .....                   | 9   |
| 2.1       | Ports as a source of prosperity .....                      | 13  |
| 2.2       | Ports and quays past and present .....                     | 13  |
| 2.3       | History of quay wall construction in Rotterdam .....       | 25  |
|           | References .....                                           | 41  |
| Chapter 3 | MAIN TYPES OF QUAY WALLS .....                             | 43  |
| 3.1       | Functions and main types of quay walls .....               | 47  |
| 3.2       | Gravity walls .....                                        | 48  |
| 3.3       | Sheet pile walls .....                                     | 52  |
| 3.4       | Sheet pile walls with relieving platforms .....            | 60  |
| 3.5       | Open berth quay .....                                      | 62  |
| 3.6       | Examples of gravity walls .....                            | 63  |
| 3.7       | Examples of sheet pile walls .....                         | 68  |
| 3.8       | Examples of walls with relieving platform .....            | 71  |
| 3.9       | Examples of open berth quays .....                         | 74  |
| 3.10      | Examples of repair or deepening of quay walls .....        | 76  |
|           | References .....                                           | 84  |
| Chapter 4 | INVESTIGATION .....                                        | 87  |
| 4.1       | Importance of investigation .....                          | 91  |
| 4.2       | Survey and monitoring plan .....                           | 91  |
| 4.3       | Topographical and hydrographic investigations .....        | 92  |
| 4.4       | Hydraulic investigations: water levels .....               | 94  |
| 4.5       | Hydraulic investigations: waves .....                      | 101 |
| 4.6       | Hydraulic investigation: other wave phenomena .....        | 103 |
| 4.7       | Hydraulic investigations: points of special interest ..... | 103 |
| 4.8       | Hydraulic investigation: currents .....                    | 104 |
| 4.9       | Investigation into ice loads .....                         | 106 |

|           |                                                                                                                          |     |
|-----------|--------------------------------------------------------------------------------------------------------------------------|-----|
| 4.10      | Investigation into meteorological conditions .....                                                                       | 108 |
| 4.11      | Investigations into morphological conditions.....                                                                        | 108 |
| 4.12      | Investigation into nautical boundary conditions .....                                                                    | 108 |
| 4.13      | Investigation into seismic impacts .....                                                                                 | 109 |
| 4.14      | Geotechnical and geohydrological investigation: soil<br>investigation plan .....                                         | 109 |
| 4.15      | Geotechnical and geohydrological investigations: desktop study,<br>geological maps, groundwater maps .....               | 113 |
| 4.16      | Geotechnical and geohydrological investigations: site visits,<br>geophysical investigations and site investigations..... | 114 |
| 4.17      | Geotechnical and geohydrological investigations:<br>laboratory tests .....                                               | 126 |
| 4.18      | Geotechnical and geohydrological investigation:<br>determination of parameters .....                                     | 129 |
| 4.19      | Geotechnical and geohydrological investigation:<br>presentation of the results .....                                     | 141 |
| 4.20      | Environmental investigation.....                                                                                         | 142 |
|           | References .....                                                                                                         | 145 |
| Chapter 5 | TERMS OF REFERENCE .....                                                                                                 | 147 |
| 5.1       | Terms of reference for design and construction.....                                                                      | 151 |
| 5.2       | Functional terms of reference .....                                                                                      | 156 |
| 5.3       | Technical terms of reference .....                                                                                       | 159 |
| 5.4       | Detailed explanation .....                                                                                               | 161 |
|           | References .....                                                                                                         | 191 |
| Chapter 6 | DESIGN OF QUAY WALLS .....                                                                                               | 193 |
| 6.1       | Introduction .....                                                                                                       | 197 |
| 6.2       | Functional design aspects .....                                                                                          | 200 |
| 6.3       | Structural design aspects .....                                                                                          | 201 |
| 6.4       | Design philosophy .....                                                                                                  | 218 |
| 6.5       | Features of the structural design .....                                                                                  | 237 |
| 6.6       | Design models and calculation methods of retaining walls .....                                                           | 241 |
| 6.7       | Sequence of design calculation .....                                                                                     | 282 |
|           | References .....                                                                                                         | 310 |
| Chapter 7 | QUAY-ELEMENTS.....                                                                                                       | 313 |
| 7.1       | Introduction .....                                                                                                       | 317 |
| 7.2       | Pile foundations .....                                                                                                   | 317 |
| 7.3       | Sheet pile wall systems .....                                                                                            | 322 |
| 7.4       | Anchorage .....                                                                                                          | 327 |
| 7.5       | Superstructures .....                                                                                                    | 334 |
| 7.6       | Transitional structures .....                                                                                            | 342 |
| 7.7       | Berthing equipment .....                                                                                                 | 343 |
| 7.8       | Other berth details .....                                                                                                | 347 |

|            |                                                                    |     |
|------------|--------------------------------------------------------------------|-----|
| 7.9        | Drainage systems .....                                             | 352 |
| 7.10       | Crane tracks and rail structures .....                             | 353 |
| 7.11       | Bottom protection .....                                            | 357 |
| 7.12       | Instrumentation for data collection .....                          | 361 |
|            | References .....                                                   | 364 |
| Chapter 8  | MATERIALS .....                                                    | 367 |
| 8.1        | Concrete and concrete technological aspects .....                  | 371 |
| 8.2        | Steel .....                                                        | 381 |
| 8.3        | Corrosion .....                                                    | 385 |
|            | References .....                                                   | 401 |
| Chapter 9  | CONSTRUCTION .....                                                 | 405 |
| 9.1        | Introduction .....                                                 | 409 |
| 9.2        | Design .....                                                       | 409 |
| 9.3        | Construction methods .....                                         | 410 |
| 9.4        | Layout of the construction site .....                              | 412 |
| 9.5        | Surveying of the construction site .....                           | 413 |
| 9.6        | Environmental boundary conditions .....                            | 413 |
| 9.7        | Foundation and substructure .....                                  | 414 |
| 9.8        | Superstructure .....                                               | 421 |
| 9.9        | Monitoring .....                                                   | 432 |
| 9.10       | Fill behind the quay wall .....                                    | 433 |
| 9.11       | Dredging .....                                                     | 437 |
| 9.12       | Scour protection .....                                             | 437 |
| 9.13       | Auxiliary structures .....                                         | 440 |
| 9.14       | Quality control and quality assurance .....                        | 445 |
| 9.15       | Completion and acceptance of the works .....                       | 450 |
|            | References .....                                                   | 452 |
| Chapter 10 | COSTS .....                                                        | 453 |
| 10.1       | Introduction .....                                                 | 457 |
| 10.2       | Cost estimate system according to CROW .....                       | 457 |
| 10.3       | Estimation of the construction costs on the basis of indices ..... | 459 |
| 10.4       | Estimation of the engineering costs .....                          | 461 |
| 10.5       | Risk analysis .....                                                | 462 |
|            | References .....                                                   | 465 |
| Chapter 11 | MANAGEMENT AND MAINTENANCE OF QUAY WALLS .....                     | 467 |
| 11.1       | From reactive to active management .....                           | 471 |
| 11.2       | The quay wall as a system .....                                    | 476 |
| 11.3       | Objectives .....                                                   | 477 |
| 11.4       | Modelling .....                                                    | 482 |
| 11.5       | Information .....                                                  | 486 |
| 11.6       | Assessments .....                                                  | 487 |

|            |                                                        |     |
|------------|--------------------------------------------------------|-----|
| 11.7       | Measures .....                                         | 490 |
| 11.8       | Implementation .....                                   | 494 |
| 11.9       | Contribution, conveyance and feedback .....            | 495 |
|            | References .....                                       | 496 |
| Chapter 12 | LESSONS FROM EXPERIENCE .....                          | 497 |
| 12.1       | You can't make an omelette without breaking eggs ..... | 503 |
| 12.2       | Soil investigations .....                              | 504 |
| 12.3       | Combined walls .....                                   | 509 |
| 12.4       | Pile foundations .....                                 | 520 |
| 12.5       | Relieving platform .....                               | 525 |
| 12.6       | Anchorage .....                                        | 527 |
| 12.7       | Superstructure .....                                   | 531 |
| 12.8       | Berthing equipment .....                               | 535 |
| 12.9       | Bottom protection .....                                | 536 |
| 12.10      | Drainage and dewatering .....                          | 538 |
| 12.11      | Deformations of quay structures .....                  | 540 |
| 12.12      | Back fill and dredging .....                           | 543 |
| 12.13      | Earthquake zones .....                                 | 545 |
| 12.14      | Working in an aggressive tropical environment .....    | 546 |
| 12.15      | Quality assurance .....                                | 548 |
| 12.16      | Wise use of the quay .....                             | 549 |
|            | References .....                                       | 551 |
| Chapter 13 | FUTURE DEVELOPMENTS .....                              | 553 |
| 13.1       | Introduction .....                                     | 557 |
| 13.2       | Port developments .....                                | 557 |
| 13.3       | Shipping developments .....                            | 558 |
| 13.4       | Development of logistic concepts .....                 | 560 |
| 13.5       | Development of new quay concepts .....                 | 560 |
|            | References .....                                       | 575 |
| Chapter 14 | BIBLIOGRAPHY AND STANDARDS .....                       | 577 |
| 14.1       | Bibliography .....                                     | 581 |
| 14.2       | Standards .....                                        | 584 |
| Annex A    | GLOSSARY OF TERMS AND ABBREVIATIONS USED .....         | 587 |
|            | NOTATION .....                                         | 621 |
|            | INDEX .....                                            | 629 |

# **CHAPTER 1**

## **INTRODUCTION**



ARCADIS offers governments, port institutions, private terminal operators and shipping lines all the disciplines necessary for an integrated approach. These include:

**Planning**

Master planning and transport studies, Nautical studies, Hydraulic and morphological modelling, Environmental impact assessments

**Terminal Development**

Containers, General cargo, Dry- and liquid bulk, Fast ferry and ro-ro, Cruise terminals and Marinas

**Related Marine Works**

Contaminated sediments, Flood and pollution control

**Engineering Services**

Structural design, Geotechnical design, Ship mooring simulations, Feasibility studies and contract & tender preparation

**Management Services**

Project management, Risk management, Port facility management, Asset management

**Hinterland**

Locks and waterways, Rail, Road and pipe connections

ARCADIS looks ahead, takes the lead, develops, delivers results.

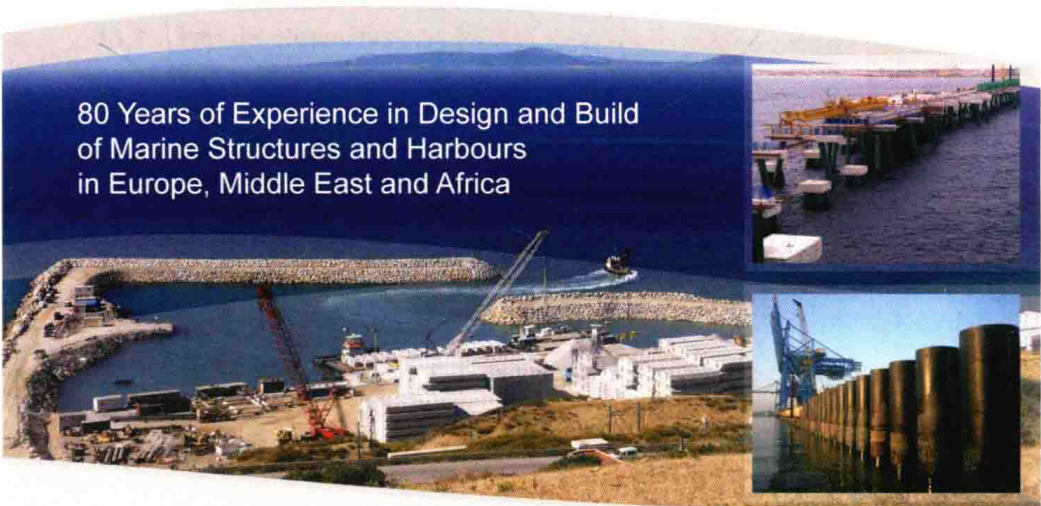
ports@arcadis.com www.arcadis.com

Tel +31 (0)10 253 2128



| Beyond Challenges |

80 Years of Experience in Design and Build of Marine Structures and Harbours in Europe, Middle East and Africa



BESIX nv, Gemeenschappenlaan 100  
1200 Brussel - België  
communication@besix.com  
www.besix.com

CONTENTS

1.1 FUNCTION OF QUAY WALLS ..... 5

1.2 OBJECTIVE OF THIS BOOK ..... 6

1.3 COMPOSITION OF THE BOOK ..... 7

REFERENCES ..... 8



# CHAPTER 1

## INTRODUCTION

### 1.1 Function of quay walls

Quay walls are earth-retaining structures at which ships can berth. They are usually equipped with bollards to provide moorings for ships and fendering to absorb the impacts of the vessels. Quay walls are used for the transshipment of goods by cranes or heavy equipment that move alongside the ship. The superstructure is robustly constructed and the quay is usually equipped with rails for cranes and with channels for the cables that supply power to the cranes. The foundation must provide the necessary stability. The entire structure must be able to satisfy numerous requirements imposed by soil conditions, water levels, and the size of ships and loads, supplemented by the specific demands placed upon it by the users, operators, Port Authorities, harbor master, linesman, pilot service and the asset managers of the quay.

From the earliest days, quay walls have played an essential role in the transshipment of freight. Owing to the increase in transport over water, the role of quay walls in determining



Photo 1.1 Entrance to the Port of Rotterdam [Port of Rotterdam N.V.]