

HYDRAULIC FILL MANUAL

Hydraulic Fill Manual

For dredging and reclamation works

Editors

Jan van 't Hoff

Van 't Hoff Consultancy B.V., Zeist, The Netherlands

Art Nooy van der Kolff

Royal Boskalis Westminster, Papendrecht, The Netherlands



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

CURNET publication: 244

ISBN: 978-0-415-69844-3

Keywords

Fill, fill area, reclamation area, dredgers, dredging methods, compaction, soil improvement, soil investigation, soil data, borrow area, fill design, fill strength, fill stiffness, soft soils, liquefaction, monitoring.

Readers interest

Infrastructural managers and engineers, consultants, planning and other consenting authorities, environmental advisors, Contractors, civil engineers, geotechnical engineers, hydraulic engineers.

Classification

AVAILABILITY Unrestricted

CONTENT Advice/guidance

STATUS Committee-guided

USERS Infrastructural managers and engineers, consultants, consenting authorities, environmental regulators, Contractors,

Disclaimer

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, including photocopying and recording, without the written permission of the copyright-holder (CURNET, CIRIA), application for which should be addressed to the publisher. Such written permission must also be obtained before any part of this publication is stored in a retrieval system of any nature.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold and/or distributed with the understanding that neither the authors nor the publisher is thereby engaged in rendering a specific legal or any other professional service. While every effort has been made to ensure the accuracy and completeness of the publication, no warranty or fitness is provided or implied, and the authors and publisher shall have neither liability nor responsibility to any person or entity with respect to any loss or damage arising from its use.

Referencing this publication

When referencing this publication in other written material please use the information below:

Title: Hydraulic Fill Manual (1st edition)

Editors: Jan van 't Hoff & Art Nooy van der Kolff

Date: November 2012

Publisher: CRC Press/Balkema Taylor & Francis Group

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

© 2012 CURNET, Gouda, The Netherlands

Typeset by V Publishing Solutions (P) Ltd, Chennai, India

Printed and Bound by CPI Group (UK) Ltd, Croydon, CR0 4YY.

Published by: CRC Press/Balkema

P.O. Box 447, 2300 AK Leiden, The Netherlands

e-mail: Pub.NL@taylorandfrancis.com

www.crcpress.com – www.taylorandfrancis.co.uk – www.balkema.nl

Library of Congress Cataloging-in-Publication Data

Hydraulic fill manual for dredging and reclamation works/editors, Jan van 't Hoff, Van 't Hoff Consultancy B.V., Zeist, The Netherlands, Aart Nooy van der Kolff, Royal Boskalis Westminster, Papendrecht, The Netherlands.

pages cm

Includes bibliographical references and index.

ISBN 978-0-415-69844-3 (hardback : alk. paper)

1. Hydraulic filling. I. Hoff, Jan van 't. II. Kolff, Aart Nooy van der.

TA750.H85 2012

627'.5--dc23

2012032875

ISBN: 978-0-415-69844-3 (Hbk)

ISBN: 978-0-203-11998-3 (eBook)

RECOMMENDATION

There are many reference books and sources of information on dredging techniques and dredging equipment but very little has been written solely on planning, design and construction of land reclamation using hydraulic fill. This manual, a first of its kind, is an ideal reference for all involved in the development of such infrastructure projects. Written and reviewed by expert practitioners who have been involved in many such projects around the world, this manual provides a useful and practical overview and reference guide for clients, developers, consultants and contractors who are engaged in planning, design and construction of reclamation works.

A lot of hard work has gone into the development and compilation of this manual. It is our pleasure to be able to recommend this document to all those involved in the civil engineering and dredging industries.

Piet Besselink	Executive Board Royal Haskoning DHV
Payam Foroudi	Global Technology Director, Ports and Maritime – Halcrow Group Ltd
Jan de Nul	Managing Director, Jan de Nul N.V.
Ronald Paul	Chief Operation Officer, Port of Rotterdam Authority
Frank Verhoeven	Member of the Board of Management, Royal Boskalis Westminster N.V.
Wim Vlasblom	Professor, Emeritus Delft University of Technology

CONTENTS

PREFACE	xvii
ACKNOWLEDGEMENTS	xxi
NOTATION	xxv
ABBREVIATIONS	xxix
1 INTRODUCTION TO THE MANUAL	1
1.1 Land reclamation by hydraulic filling	1
1.2 History and prospects	1
1.3 Context and objectives	3
1.4 Design philosophy	5
1.5 Structure, content and use	6
2 PROJECT INITIATION	11
2.1 General	11
2.2 Basic elements of a land reclamation project	13
2.2.1 Conceptual design	14
2.2.2 Availability of fill sources	14
2.2.3 Data collection	14
2.2.4 Environmental requirements	15
2.2.5 Feasibility study	16
2.2.6 Initial project planning	20
2.2.7 Legal aspects	20
2.2.8 Types of contracts	20
2.3 Design	24
2.3.1 Design phases	24
2.4 Considerations for selecting construction method	25
2.5 Systems Engineering	26
3 DATA COLLECTION	31
3.1 Introduction	32
3.2 Interpretation of data, contractual aspects	34
3.3 Desk study	37
3.4 Required data	38
3.4.1 Bathymetrical or topographical data	38
3.4.2 Geological and geotechnical information	39

3.4.2.1	Geological and geotechnical information in the borrow area	39
3.4.2.2	Geological and geotechnical information of the subsoil in the reclamation area	44
3.4.3	Hydraulic, meteorological, morphological and environmental data	44
3.4.3.1	Hydraulic data	45
3.4.3.2	Meteorological data	46
3.4.3.3	Morphological and environmental data	49
3.4.4	Seabed obstructions	50
3.5	Typical sand search site investigation	51
3.6	Reporting	54
3.6.1	Soil and rock classification and description	54
3.6.2	Soil classification based on CPT measurements	57
3.7	Use of data during different project stages	59
3.8	Geostatistical methods	61
3.8.1	General	61
3.8.2	Methods	61
3.8.3	Geostatistical software	63
4	DREDGING EQUIPMENT	67
4.1	Introduction	69
4.2	Dredging equipment	71
4.2.1	Suction dredging	71
4.2.2	Mechanical dredging	74
4.2.3	Other types of equipment	77
4.2.4	Combinations of equipment or dredge chains	77
4.3	Operational limitations	79
4.3.1	Waves and swell	79
4.3.2	Currents	81
4.3.3	Hindrance to shipping and other parties	81
4.3.4	Environmentally driven limitations	82
4.4	Dredging of fill material	83
4.4.1	Introduction	83
4.4.2	Volume and dimensions of borrow area	84
4.4.3	Minimum thickness of fill deposits	84
4.4.4	Dredgeability	85
4.5	Transport of fill	87
4.5.1	Introduction	87
4.5.2	Hydraulic transport through a pipeline	87
4.5.3	Transport by trailing suction hopper dredger or barge	88
4.6	Utilisation characteristics of dredging equipment	89
4.7	Basis of cost calculation for dredging	96

5	SELECTION BORROW AREA	101
5.1	Considerations for the selection of a borrow area	102
5.2	Quality of the potential fill material	103
5.2.1	Change of the grading as a result of dredging	104
5.2.2	Alternative fill materials	104
5.3	Data collection in the borrow area	105
5.3.1	Data collection for quality assessment	105
5.3.2	Data collection for quantity assessment	106
5.3.3	Data collection for dredgeability assessment	106
5.4	Quantity of fill material available	107
5.4.1	Bulking	107
5.4.2	Losses	108
5.4.3	Slope stability	109
5.4.4	Geo-statistical methods	111
5.5	Boundary conditions	111
6	PLANNING AND CONSTRUCTION METHODS RECLAMATION	113
6.1	Planning of the works	115
6.1.1	Introduction	115
6.1.2	Work preparation	116
6.1.2.1	Establishment of project team	117
6.1.2.2	Provision of housing and offices for personnel	117
6.1.2.3	Execution of engineering works	117
6.1.2.4	Create access to site and development of lay-down areas	118
6.1.2.5	Preparation and mobilization of equipment	118
6.1.3	Construction and monitoring	118
6.1.4	Demobilisation, clean-up and maintenance	119
6.1.5	Example of a project schedule	119
6.2	Work plan for reclamation works	121
6.3	Placement methods	121
6.4	Construction of containment bunds	122
6.4.1	General	122
6.4.2	Methods of bund construction	125
6.5	Placement of fill material	129
6.5.1	Underwater placement in bulk of fill material	129
6.5.2	Placement of fill material using a discharge pipeline	131
6.5.3	Rainbowing	134
6.5.4	Spraying	136
6.6	Fill mass properties related to method of placement	137
6.7	Management of poor quality materials	139
6.7.1	Use of cohesive or fine grained materials	139
6.7.2	Settling ponds	139

7	GROUND IMPROVEMENT	143
7.1	Introduction	145
7.2	Benefits of ground improvement	145
7.3	Overview of ground improvement techniques	146
7.4	Pre-loading with or without vertical drains	149
7.4.1	Purpose and principle of pre-loading	149
7.4.2	Vertical drains	153
7.5	Compaction	156
7.5.1	Introduction	156
7.5.2	Vibratory surface compaction	156
7.5.3	Deep vibratory compaction	157
7.5.3.1	General	157
7.5.3.2	Vibratory probes without jets	161
7.5.3.3	Vibroflotation	163
7.5.4	Dynamic compaction techniques	167
7.5.5	Explosive compaction	170
7.6	Soil replacement	172
7.6.1	Introduction	172
7.6.2	Soil removal and replacement	172
7.6.3	Stone columns	173
7.6.3.1	Purpose and principle	173
7.6.3.2	Execution of stone columns by the vibro-replacement technique	173
7.6.4	Sand compaction piles (closed end casing)	176
7.6.5	Geotextile encased columns	176
7.6.6	Dynamic replacement	178
7.7	Admixtures and in-situ soil mixing	180
8	DESIGN OF RECLAMATION AREA	183
8.1	Design philosophy	185
8.2	Basic mass properties	187
8.2.1	Strength of fill mass: Bearing capacity and slope stability	187
8.2.2	Stiffness of fill mass: Settlements, horizontal deformations and tolerances	188
8.2.3	Density of the fill mass and subsoil: Resistance against liquefaction	189
8.2.4	Permeability of fill mass: Drainage capacity	190
8.2.5	Platform level: Safety against flooding and erosion	190
8.3	Density	190
8.3.1	Definition of key parameters	191
8.3.2	Density ratios	192
8.3.3	The use of densities or density ratios in specifications	194
8.3.4	Effect of grain size distribution on the density of a soil sample	196

8.3.5	Density measurement	198
8.3.5.1	Measurement of reference densities (minimum and maximum density)	198
8.3.5.2	Direct measurement of in situ density	199
8.3.5.3	Indirect measurement of relative density by cone penetration testing	199
8.3.5.4	Indirect measurement of relative density by SPT testing	201
8.3.5.5	Measurement of in situ state parameter ψ by cone penetration testing	201
8.3.6	Typical relative density values of hydraulic fill before compaction	202
8.4	Strength of the fill mass and subsoil (bearing capacity and slope stability)	202
8.4.1	Introduction	202
8.4.2	Shear strength	204
8.4.2.1	High quality fill material	204
8.4.2.2	Poor quality fill material	210
8.4.2.3	Assessment of shear strength	215
8.4.3	Relevant failure modes	221
8.4.3.1	Introduction	221
8.4.3.2	Safety approach	222
8.4.3.3	Analytical calculation models versus Finite Element Method (FEM)	227
8.4.3.4	Bearing capacity	228
8.4.3.5	Punch through	232
8.4.3.6	Squeezing	234
8.4.3.7	Slope stability of fill and subsoil	236
8.4.3.7.1	Design methods	236
8.4.3.7.2	Limit Equilibrium Methods	238
8.4.3.7.3	Finite Element Method	242
8.4.3.8	Construction of a slope on soft soil	243
8.4.3.9	Effect of groundwater flow on slope stability	244
8.4.3.10	Earthquakes and slope stability	250
8.4.3.11	Stabilising measures for slope stability	250
8.4.3.11.1	Optimizing the slope geometry by using counterweight berms	251
8.4.3.11.2	Staged construction	251
8.4.3.11.3	Soil replacement (sand key)	252
8.4.3.11.4	Stone columns, sand compaction piles	252
8.4.3.11.5	Geosynthetics	253

8.5	Stiffness and deformation	254
8.5.1	Introduction	254
8.5.2	Stiffness	254
8.5.2.1	General considerations	254
8.5.2.2	Stiffness of subsoil	256
8.5.2.3	Stiffness of fill material	257
8.5.3	Deformations	258
8.5.3.1	General considerations	258
8.5.3.2	Settlement calculation methods	260
8.5.3.3	Additional considerations	262
8.5.3.4	Vertical deformation of a reclamation surface	264
8.5.3.5	Vertical deformations of structures	269
8.5.3.6	Horizontal deformations	270
8.5.4	Techniques for limiting settlement	271
8.6	Liquefaction and earthquakes	272
8.6.1	Overview	272
8.6.2	History of understanding	275
8.6.3	Flow slides versus Cyclic softening	280
8.6.4	Assessing liquefaction susceptibility	282
8.6.4.1	Codes & Standards	283
8.6.4.2	Loading: Estimating CSR by site response analysis	285
8.6.4.3	Resistance, Step 1: Susceptibility to large deformations	289
8.6.4.4	Resistance, Step 2: Evaluation of CRR	292
8.6.5	Movements caused by liquefaction	296
8.6.5.1	Slope deformations	296
8.6.5.2	Lateral spreads	299
8.6.5.3	Settlements	300
8.6.6	Fill characterization for liquefaction assessment	303
8.6.6.1	Necessity for in situ tests	303
8.6.6.2	Required number of CPT soundings	305
8.6.6.3	CPT calibration	306
8.6.6.4	Supporting laboratory data	307
8.6.7	Note on soil type (Calcareous and other non-standard sands)	307
9	SPECIAL FILL MATERIALS AND PROBLEMATIC SUBSOILS	309
9.1	Cohesive or fine-grained fill materials	311
9.1.1	Introduction	311
9.1.2	Segregation of fines	313
9.1.3	Soft clay or soft silt	315
9.1.3.1	Suitability of soft (organic) clay or silt as fill material	316

	9.1.3.2	Workability of clay	316
	9.1.3.3	Effects of winning method	317
	9.1.3.4	Measures to improve the fill properties after disposal	318
	9.1.3.5	Construction aspects of soft soils in case of application above the waterline	334
	9.1.3.6	Construction aspects of soft soils in case of application below the waterline	336
	9.1.4	Stiff clay or silt	336
9.2		Carbonate sand fill material	342
	9.2.1	Introduction	342
	9.2.2	Origin and composition of carbonate sands	343
	9.2.3	Typical properties of carbonate sands	344
	9.2.4	Mechanical behaviour of carbonate sands	349
	9.2.5	The use of carbonate sand as fill	357
	9.2.5.1	Typical behaviour during dredging and hydraulic transport	357
	9.2.5.2	Cone Penetration and Standard Penetration testing in carbonate sands	359
	9.2.5.3	Laboratory testing	361
	9.2.5.4	Field compaction	363
9.3		Hydraulic rock fill	364
	9.3.1	Introduction	364
	9.3.2	Lump size	364
	9.3.3	Compaction and measurement of compaction result	364
	9.3.4	Grading	367
	9.3.5	Fines	367
	9.3.6	Wear and tear	368
	9.3.7	Pumping distance during rock dredging	368
	9.3.8	Specifications rock fill	369
9.4		Problematic subsoils	370
	9.4.1	Sensitive clay	370
	9.4.2	Peat	372
	9.4.3	Glacial soils	374
	9.4.4	Sabkha	375
	9.4.5	Karst	379
	9.4.6	Laterite	383
10		OTHER DESIGN ITEMS	387
	10.1	Introduction	388
	10.2	Drainage	388
	10.2.1	Infiltration	390
	10.2.2	Surface runoff	390
	10.2.3	Artificial drainage systems	391

10.3	Wind erosion	394
10.4	Slope, bank and bed protection	398
10.5	Interaction between reclamation and civil works	400
10.5.1	General	400
10.5.2	Foundations	400
10.5.3	Construction sequence	401
10.5.4	Impact on existing structures	402
10.6	Earthquakes	405
10.7	Tsunamis	409
11	MONITORING AND QUALITY CONTROL	413
11.1	Introduction	414
11.2	Quality Control Plan	417
11.3	Monitoring and testing	420
11.3.1	Geometry	420
11.3.2	Fill material properties	420
11.3.2.1	Grain size distribution	420
11.3.2.2	Minimum and maximum dry densities	422
11.3.2.3	Mineralogy	422
11.3.3	Fill mass properties	422
11.3.3.1	Shear strength	422
11.3.3.2	Stiffness	425
11.3.3.3	Density, relative compaction and relative density	428
11.3.4	Environmental monitoring	431
12	TECHNICAL SPECIFICATIONS	433
12.1	Introduction	434
12.2	Roles and responsibilities	434
12.3	Checklist project requirements	437
12.4	Commented examples of technical specifications	442
12.4.1	Introduction	442
12.4.2	Description of the works	443
12.4.3	Standards	444
12.4.4	Data collection (see Chapter 3)	444
12.4.5	Dredging equipment and working method (see Chapter 4)	445
12.4.6	Selection borrow area—quality fill material (see Chapter 5)	447
12.4.7	Construction methods reclamation area (see Chapter 6)	450
12.4.8	Environmental impact	452
12.4.9	Design of a land reclamation (see Chapter 8)	453
12.4.10	Ground improvement (see Chapter 7)	458

12.4.11	Special fill materials (see Chapter 9)	461
12.4.12	Other design aspects (see Chapter 10)	462
12.4.13	Monitoring and quality control (see Chapter 11)	463
12.4.13.1	Geometry	464
12.4.13.2	Testing fill material properties (see Section 11.3.2)	466
12.4.13.3	Testing fill mass properties (see Section 11.3.3)	467
12.4.13.4	Settlement monitoring (see Appendix B.5.3)	470
12.4.13.5	Performance testing	470
12.4.13.6	Reporting	472
12.4.13.7	Monitoring and Quality Control Program (see Section 11.2)	472
APPENDICES		
A	Equipment	477
B	Field and Laboratory Tests	529
C	Correlations and Correction Methods	593
D	Geotechnical Principles	609
REFERENCES		627

PREFACE

Hydraulic fills are often used to reclaim land for large infrastructure projects such as airports, harbours, industrial and domestic areas and roads. The quality of the borrow material and construction methods are crucial for the quality of the end product. The end product or application will ask specific performance requirements and the characteristics of the fill mass will determine how well these performance criteria are met.

Given the fundamental importance of hydraulic fill to infrastructure projects, a need was felt for a single volume bundling the wide range of the design and construction aspects of hydraulic fills. The Hydraulic Fill Manual is the result.

The Manual represents the concerted effort of Clients, Consultants and Contractors to arrive at a rational and transparent process of project initiation, design, specification and construction of hydraulic fills. The aim of the book is to point the way for each particular project to realise an optimum design based on:

- the available quality and quantity of fill material;
- boundary conditions like the soil conditions, bathymetry, wave climate and tectonic setting of the proposed fill area;
- the selection of dredging equipment with its related construction methods;
- appropriate functional and performance requirements.

Such an optimum design is achieved by making the process from project initiation to construction a clear, iterative process. The Manual promotes this iterative process in which the results of each step are compared with the starting points and results of the previous step and/or with the functional requirements of the project.

This process follows the “System Engineering” approach, a method often applied to the realisation of engineering projects. The underlying idea of this approach is that process transparency and the implementation of sound engineering principles should lead the involved parties to suitable specifications for the construction of the hydraulic fill. Suitability of specifications implies that the functional requirements of the fill mass will be met within the wanted safety margins (and, hence, without excessive costs), but at the same time ensures that the hydraulic fill can be constructed in a feasible and economic manner. This will reduce excessive costs, unwanted disputes, arbitrations and lawsuits.

As it is the intention of the authors that the Manual can be used all over the world on land reclamation projects by hydraulic filling it will not necessarily adhere to (local) standards, norms and/or Codes of Practice. When considered to be relevant references to such documents will be made, but this will be limited to generally accepted and often used systems like the American Standards, the British Standards and/or the European Codes. It may nevertheless be important to be fully informed about the local codes and standards as they may form part of the jurisdiction of the country in which the project has to be realized.

For Clients the Manual presents the most important elements of a land reclamation project (planning, design, data collection, legal and contractual aspects) and explains how the land reclamation forms part of an overall cost-benefit analysis. Clients and Consultants will also learn that to make a project feasible, the fill material may not have to be restricted to sandy material but that



with certain technical measures and under certain conditions, cohesive and fine-grained materials (clay, silt) also may be used. The use of carbonate sands is also highlighted.

The Manual also advises about the various types of dredging equipment, fill material and soil improvement techniques and what geotechnical data are required for production estimates of dredging equipment and for analysing the suitability of fill material. Emphasis is placed on how to translate performance and functional requirements into measurable properties of the fill mass, with special attention focussed on density, strength and stiffness characteristics and to liquefaction and breaching.

The Manual concludes with examples of practical geotechnical specifications for the construction of a fill mass.

Readers are warned that for proper understanding of design issues some background knowledge in geotechnical engineering is required. For specialist knowledge the reader is referred to handbooks on these subjects.

ACKNOWLEDGEMENTS

This publication is the result of a joint project of Clients, Consultants and Contractors from Belgium, United Kingdom and the Netherlands. The overall management has been performed by CUR Building & Infrastructure. The manual has been reviewed by CIRIA/UK.

Authors/ reviewers	Ken Been	Golder Associates
	Rik Bisschop	Arcadis
	Erik Broos	Port of Rotterdam Authority
	Egon Bijlsma	Arcadis
	Henk Cloo	Royal Haskoning DHV
	Jurgen Cools	Royal Haskoning DHV
	David Dudok van Heel	Rotterdam Municipality Consultancy
	Arnoud van Gelder	Royal Haskoning DHV
	Reimer de Graaff	Arcadis
	Jarit de Gijt	Rotterdam Municipality/Delft University of Technology
	Robert de Heij	Witteveen + Bos
	Ilse Hergarden	Royal Haskoning DHV
	Jan van 't Hoff	Van 't Hoff Consultancy bv
	Richard de Jager	Royal Boskalis Westminster N.V.
	Dirk-Jan Jaspers Focks	Witteveen + Bos
	Mike Jefferies	Golder Associates
	Wouter Karreman	Van Oord Dredging and Marine Contractors
	Lieve De Kimpe	Van Oord Dredging and Marine Contractors
	Edwin Koeijers	Rotterdam Municipality Consultancy
	Rob Lohrmann	Witteveen + Bos
	Joop van der Meer	Van Oord Dredging and Marine Contractors
	Piet Meijers	Deltares
	Patrick Mengé	DEME Group/Dredging International
	Mario Niese	Royal Haskoning DHV
	Art Nooy van der Kolff	Royal Boskalis Westminster N.V.
	Cissy de Rooij	Royal Boskalis Westminster N.V.
	Rob Rozing	Arcadis
	Berten Vermeulen	Jan de Nul

Editors	Jan van 't Hoff & Art Nooy van der Kolff	
Peer reviewers	In response to a request from CUR Bouw & Infra CIRIA has managed a peer review of this manual. This review was conducted by the following UK experts:	
	John Adrichem	Royal Haskoning DHV
	Ken Been	Golder Associates
	Nick Bray	HR Wallingford
	Gijsbert Buitenhuis	Royal Haskoning DHV
	Chris Capener	Royal Haskoning DHV
	Chris Chiverrell	CIRIA
	Scott Dunn	HR Wallingford
	Payam Foroudi	Halcrow
	Helge Frandsen	Royal Haskoning DHV
	Prasad Gunawardena	Mott MacDonald
	Greg Haigh	Arup
	Mike Jefferies	Golder Associates
	David Jordan	Scot Wilson/HR Wallingford
	Roderick Nichols	Halcrow
	Philip Smith	Royal Haskoning DHV
CIRIA Project Managers peer reviews	Kristina Gamst	
	Gillian Wadams	
Review English translation	Marsha Cohen	
Technical review	Chris Chiverrell	CIRIA
	Aad van den Thoorn	CURNET
Executive steering board	Jurgen Cools	Royal Haskoning DHV
	Jarit de Gijt	Rotterdam Municipality/ Delft University of Technology
	Jan van 't Hoff	Van 't Hoff Consultancy bv
	René Kolman	IADC
	Joop Koenis (upto Dec. 2010)	CUR Bouw & Infra
	Dirk Luger	Deltares
	Art Nooy van der Kolff	Royal Boskalis Westminster N.V.
	Daan Rijks (upto Dec. 2009)	Royal Boskalis Westminster N.V.
	Ger Vergeer (from Jan. 2011)	CUR Bouw & Infra
	Wim Vlasblom (chair)	Delft University of Technology

The overall project management has been performed by CUR Building & Infrastructure: Joop Koenis (up to Dec. 2010) en Ger Vergeer (from Jan. 2011)

Project
sponsors

Ministry of Infrastructure and the Environment, International Dredging Association (IADC) , China Communications Construction Company (CCCC), Foundation FCO-GWW, Port of Rotterdam Authority, Inros Lackner, PAO Delft University

CUR wishes to thank the following organisations for providing photographs: DEME, Jan de Nul, Royal Boskalis Westminster, Van Oord Dredging and Marine Contractors, Port of Rotterdam Authority.

NOTATION

a_g	= Ground acceleration	(m/s ²)
B	= Bulk Modulus	(kPa)
B_q	= CPT excess pore pressure ratio $B_q = (u_c - u_0)/(q_t - \sigma_{v0})$	(-)
c'	= Effective cohesion	(kPa)
c_u	= Undrained shear strength	(kPa)
c_v	= Vertical coefficient of consolidation	(m ² /year)
c_h	= Horizontal coefficient of consolidation	(m ² /year)
c'_k	= Characteristic effective cohesion	(kPa)
$c_u(t)$	= Undrained shear strength at time t after loading	(kPa)
$c_{u,0}$	= Initial undrained shear strength	(kPa)
$c_{u,k}$	= Characteristic undrained shear strength	(kPa)
c_u^u	= Undrained shear strength at the upper side of a soft layer	(kPa)
c_u^l	= Undrained shear strength at the lower side of a soft layer	(kPa)
C_α	= Peak ground acceleration	(m/s ²)
C_α	= Secondary compression index	(-)
C_c	= Compression index	(-)
C_c	= Coefficient of curvature	(-)
C_r	= Recompression index	(-)
C_u	= Coefficient of uniformity	(-)
d_e	= Equivalent diameter of the zone of influence of a drain	(m)
d_w	= Equivalent diameter of a cylindrical drain column	(m)
d_q, d_c	= Depth factors	(-)
D_{50}	= Mean grain size	(mm)
e	= Void ratio	(-)
e_0	= Void ratio of layer with initial thickness h_0	(-)
e_p	= Void ratio of layer with thickness h_p after primary settlement	(-)
E	= Modulus of Elasticity	(kPa)
E_{dyn}	= Dynamic Modulus	(kPa)
E_y	= Young's Modulus	(kPa)
E_{DMT}	= Dilatometer Modulus	(kPa)
E_{PLT}	= Plate Load Test Modulus	(kPa)
E_{PMT}	= Pressiometer Modulus	(kPa)
E_s or E_{oed} or M	= Constrained Modulus	(kPa)
E_{sec}	= Secant Modulus	(kPa)

E_{\tan}	= Tangent Modulus	(kPa)
E_u	= Undrained Modulus	(kPa)
E_0	= Young's Modulus at very small deformations	(kPa)
E_{50}	= Young's Modulus at 50% of the failure stress	(kPa)
F_R	= Friction Ratio CPT test	(-)
G	= Shear Modulus	(kPa)
G_0	= Shear Modulus at very low strain	(kPa)
G_{50}	= Shear Modulus at very low strain	(kPa)
h_0	= Initial thickness of layer	(m)
h_p	= Thickness of the considered layer after primary settlement	(m)
H	= Layer thickness	(m)
i_q, i_c, i_γ	= Inclination factors	(-)
I_{S50}	= Point load strength	(MPa)
I_p	= Plasticity index	(-)
I_c	= Consistency index	(-)
I_L	= Liquidity index	(-)
K_0	= Coefficient of active earth pressure at rest	(-)
k_h	= Horizontal seismic coefficient	(-)
k_v	= Vertical seismic coefficient	(-)
k_y	= Yield coefficient	(-)
M	= Earthquake magnitude	(-)
M, E_s or E_{oed}	= Constrained Modulus	(kPa)
M_L	= Local magnitude	(-)
M_S	= Surface wave magnitude	(-)
M_W	= Moment magnitude of earthquake	(·)
n	= Porosity	(-)
n_0	= Initial porosity	(-)
N'	= Number of blows per per foot (300 mm) penetration of SPT	(-)
N_k	= Empirical factor to correlate the undrained shear strength to the cone resistance	(-)
N_q, N_c, N_γ	= Bearing capacity factors	(-)
p'	= Mean effective stress	(kPa)
p_a	= Atmospheric pressure	(kPa)
q_{allow}	= Allowable load	(kPa)
q_c	= Measured cone resistance	(MPa)
q_{ck}	= Characteristic cone resistance for liquefaction assessment	(MPa)
q_t	= Corrected cone resistance	(MPa)
Q	= Dimensionless CPT resistance based on mean stress, $Q = (q_t - \sigma_{v0})/\sigma'_{v0}$	(-)
Q_u	= CPT resistance modified on pore pressure	(-)
Q_u	= Ultimate bearing capacity	(kPa)

q_u	= Unconfined compressive strength	(kPa)
r_d	= Response coefficient	(-)
R_e	= Relative void ratio	(-)
R_n	= Relative porosity	(-)
R_c	= Degree of compaction	(-)
s_r	= Residual undrained shear strength	(kPa)
s_q, s_c, s_γ	= Shape factors	(-)
S	= Degree of saturation	(-)
S_{min}	= Minimum settlement to be reached at time of hand-over	(m)
S_{total}	= Total primary settlement	(m)
t	= Time	(year)
t_p	= Time at end of primary settlement (full consolidation)	(year)
t_f	= Time at which the secondary compression has to be calculated	(year)
T_h	= Time factor for horizontal consolidation	(-)
T_s	= Fundamental period	(s)
T_v	= Time factor	(-)
u_2	= Pore pressure measured behind the cone	(kPa)
u_0	= In situ pore pressure	(kPa)
U_v	= Average degree of consolidation due to vertical drainage	(-)
UCS	= Unconfined compressive strength	(MPa)
U_h	= Average degree of consolidation due to horizontal drainage	(-)
U_{vh}	= Average degree of consolidation	(-)
$U_{(t)}$	= Degree of consolidation at time t after loading	(-)
w	= Water content	(-)
wL	= Liquid limit	(-)
wP	= Plastic limit	(-)
α	= Peak horizontal ground acceleration	(m/s ²)
γ	= Volumetric weight	(kN/m ³)
γ_{dry}	= Dry unit weight	(kN/m ³)
γ_{sat}	= Saturated unit weight	(kN/m ³)
ϵ_g	= Shear strain	(-)
Δe	= Change in void ratio from a layer with initial void ratio e_0	(-)
Δh	= Compression of layer with initial thickness h_0	(m)
Δh_s	= Secondary compression of layer with thickness h_p	(m)
$\Delta \sigma'$	= Effective stress increment in the middle of the considered layer	(kPa)
$\Delta \sigma'_{ref}$	= Reference stress (usually taken equal to 1 kPa)	(kPa)

ΔS_{allow}	= Allowable residual settlement at time of hand-over	(m)
λ	= Slope of CSL for semi-log idealization	(-)
ρ	= Density	(kg/m ³)
ρ_b	= Bulk density	(kg/m ³)
ρ_d	= Dry density	(kg/m ³)
ρ_g	= Particle density	(kg/m ³)
ρ_s	= Density of solid particles	(kg/m ³)
ρ_{sat}	= Saturated density	(kg/m ³)
σ	= Normal stress	(kPa)
σ'_0	= Initial effective stress in the middle of the considered layer with initial thickness h_0	(kPa)
σ'_m	= Mean effective stress	(kPa)
σ'_n	= Effective normal stress	(kPa)
σ'_p	= Pre-consolidation stress in the middle of the considered layer with initial thickness h_0	(kPa)
σ_{v0}	= Total stress	(kPa)
σ'_v	= Effective vertical stress at foundation level next to foundation	(kPa)
σ'_{v0}	= Effective vertical stress	(kPa)
$\Delta\sigma'_v$	= Increase effective vertical stress due to loading after full consolidation	(kPa)
$\sigma'_{v,0}$	= Effective vertical stress at foundation level	(kPa)
ϕ'	= Effective friction angle	(°)
ϕ'_{crit}	= Critical state friction angle	(°)
ϕ'_k	= Characteristic effective friction angle	(°)
ϕ'_{max}	= Peak effective friction angle	(°)
ϕ'_s	= Secant friction angle	(°)
ϕ_u	= Undrained friction angle	(°)
τ	= Shear strength	(kPa)
ψ	= State parameter	(-)

ABBREVIATIONS

ADCP	Acoustic Doppler Current Profilers
CBR	California Bearing Ratio
CIRIA	Construction Industry Research and Information Association
CPT	Cone Penetration Test
CRR	Cyclic Resistance Ratio
CSL	Critical State Locus
CSR	Cyclic Stress Ratio
CSWS	Continuous Surface Wave System
CTD	Conductivity, temperature, depth meter
CUR	Centre for Civil Engineering, Research and Codes
DC	Dynamic Compaction
DIN	German Institute for Standardization
DO	Dissolved Oxygen
DSM	Deep Soil Mixing
EAU	Recommendations of the Committee for Waterfront Structures Harbours and Waterways EAU 2004
EC7	Eurocode 7
EC	Explosive Compaction
ECM	Electromagnetic Current Meter
EMS	European Macroseismic Scale
FEM	Finite Element Method
FS	Factor of Safety
FS	Safety Against Instability
FS_L	$CRR/CSR =$ Safety Against Failure by Liquefaction
GEC	Geotextile Encased Columns
GWL	Ground Water Level
HEIC	High Energy Impact Compaction
ISSMGE	International Society for Soil Mechanics and Geotechnical Engineering
LAT	Lowest Astronomical Tide
LEM	Limit Equilibrium Method
MBES	Multibeam Echo Sounding
MDD	Maximum Dry Density
MPM	Material Point Method
MSL	Mean Sea Level
NTU	Nephelometric Turbidity Units
NCEER	National Center for Earthquake Engineering Research
OCR	Over Consolidation Ratio
PGA	Peak Ground Acceleration

PIANC	Permanent International Commission for Navigation Congresses
PLT	Plate Load Test
PVD	Prefabricated Vertical Drain
RIC	Rapid Impact Compaction
RQD	Rock Quality Designation
SASW	Spectral Analysis of Surface Waves
SCR	Solid Core Recovery
SLS	Serviceability Limit State
SPT	Standard Penetration Test
SSM	Shallow Soil Mixing
SSS	Side Scan Sonar
TCR	Total Core Recovery
TSS	Total Suspended Solids
ULS	Ultimate Limit State
ZLT	Zone Load Test

CHAPTER 1

INTRODUCTION TO THE MANUAL

1.1 Land reclamation by hydraulic filling

Land reclamation is generally defined as the process of creating new land by raising the elevation of a seabed, riverbed or other low-lying land ('filling') or by pumping out the water from a watery area that is enclosed by dikes ('polder construction').

Land reclamation by filling may be undertaken by dry earth movement, but also by hydraulic filling. Hydraulic filling is defined as the creation of new land by the following consecutive activities:

1. dredging of fill material in a borrow area or dredging area by floating equipment (dredgers);
2. transport of fill material from the borrow area to the reclamation site by dredger, barge or pipeline;
3. placement of fill material as a mixture of fill material and (process) water in the reclamation area.

It is the hydraulic filling that forms the main subject of this Manual. For information on other reclamation methods like dry earth movement or the construction of polders reference is made to other publications like manuals, guides, state of the art reports and/or codes of practice that more specifically deal with these techniques.

In most cases land reclamation will be a part of a more comprehensive project such as the construction of a port, an airport, a housing project or an industrial complex. Whereas superstructures will not be discussed in this Manual, their presence will impose certain requirements on the quality of the reclaimed land, its response to external forces such as currents, waves, precipitation and wind and its ability to withstand hazards such as earthquakes and tsunamis.

1.2 History and prospects

Archaeological evidence indicates that land reclamation is not a recent invention, but has existed for thousands of years. Some 2000 years ago inhabitants of the swampy and tidal areas along the Wadden Sea in the north of The Netherlands and Germany lived on so-called 'terpen' or 'wierden', artificial dwelling mounds built to protect themselves against flooding in periods of high water levels. Further attempts to prevent their agricultural land from being flooded by the sea included the construction of dikes between those dwelling mounds.

Around 1500 A.D. a new method of land reclamation came into use: “Polders” were constructed by building a ring dike in shallow watery areas, after which the water was removed from the enclosed low-lying area by windmill-driven pumps. Once steam engines became available in the 19th century some of the windmills were replaced by pumping stations.

A transformational moment came with the development of the modern centrifugal pump that enabled the current large-scale reclamation projects by hydraulic filling. According to the International Association of Dredging Companies (*Terra et Aqua*, 2005) one of the first major reclamation works (Bay of Abidjan, Ivory Coast) was carried out in the 1960s.

As a result of the strong growth of the world’s population and the subsequent urbanisation and economic development, in particular in densely populated coastal areas, the last decades have witnessed an ever-increasing demand for new land. This demand has resulted in a large number of reclamation projects ranging from numerous small-scale projects all over the world to well-known, large-scale projects such as the Palm Island Project in Dubai or the construction of Maasvlakte 2 in Rotterdam Europoort, The Netherlands (see Figure 1.1).

Demographic forecasts suggest that in the foreseeable future this demand for new land will remain or even increase, see Figure 1.2.



Figure 1.1 Construction of Maasvlakte 2 in progress, Rotterdam Europoort, The Netherlands, October 2011.

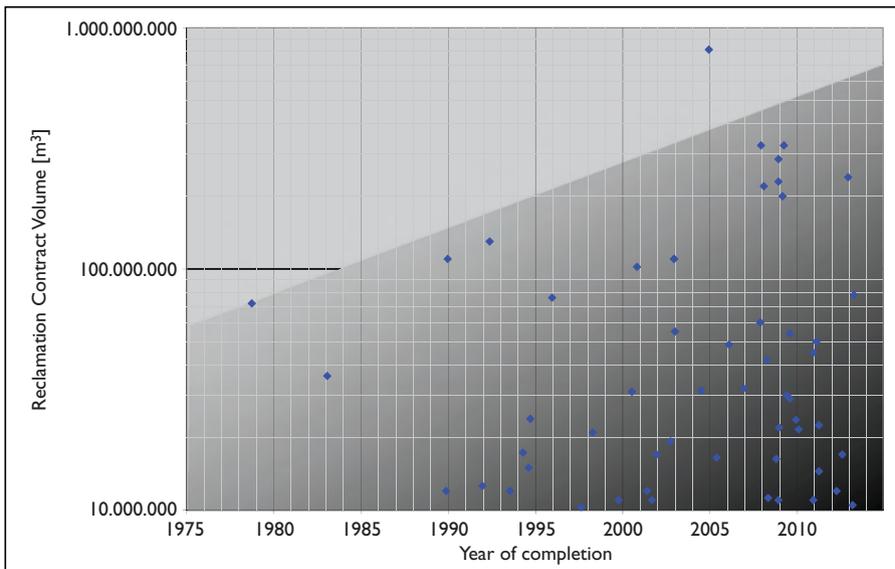


Figure 1.2 *Trend of reclamation contract volumes over the past 30 years.*

1.3 Context and objectives

This Hydraulic Fill Manual is written to supply the wants of the dredging industry to create a handbook that helps to improve the understanding between the various parties (i.e., Clients, Consultants and Contractors) involved in a hydraulic fill project. It contains the latest developments in the field of design and construction of hydraulic fills and presents clear guidelines for initiation, design and construction of a hydraulic fill project.

The design and construction of a hydraulic fill project requires specific knowledge of a wide variety of disciplines, such as hydraulic, geotechnical and environmental engineering in combination with practical know-how and experience in dredging and filling techniques.

Moreover, a new generation of dredging equipment, increasing awareness of the marine environment and the tendency to reduce construction time (i.e., return on investment period) will affect the design and construction methods requiring new standards.

Worldwide experience indicates that in recent years the technical specifications of reclamation projects have become more stringent. No rational basis for such a trend exists as the intended use of this newly created land (i.e., functional requirements) has not changed significantly nor has an increase of failures been reported. In a number of cases this trend has led to inadequate and conflicting specifications, to construction requirements that could not be met and/or to excessive costs for

fill treatment and testing. These developments frustrate the tender process, cause serious problems during construction and quality control and may lead to long-lasting, costly arbitration.

This Hydraulic Fill Manual has been written to avoid these problems. It includes theoretical and practical guidelines for the planning, design, construction and quality control of hydraulic fills.

The Manual covers the interfaces between the areas of interest of the contractual parties usually involved in reclamation projects (see Figure 1.3). It will:

- enable the Client to understand and properly plan a reclamation project;
- provide the Consultant with adequate guidelines for design and quality control;
- allow the Contractor to work within known and generally accepted guidelines and realistic specifications.

This Manual is believed to be the first handbook to date that covers all these aspects that are relevant to the construction of hydraulic fills.

The authors and reviewers have endeavoured to gather the most up-to-date knowledge regarding the design and construction of hydraulic fills with the goal that with time this Manual will be a standard for all parties involved in the implementation of hydraulic fill projects.

The structure of the Manual assumes that the design and construction of a hydraulic fill should be a rational process that ultimately results in the best and most economical match between the specified properties of the land reclamation, the requirements imposed by its future use and the environment in which it is located.

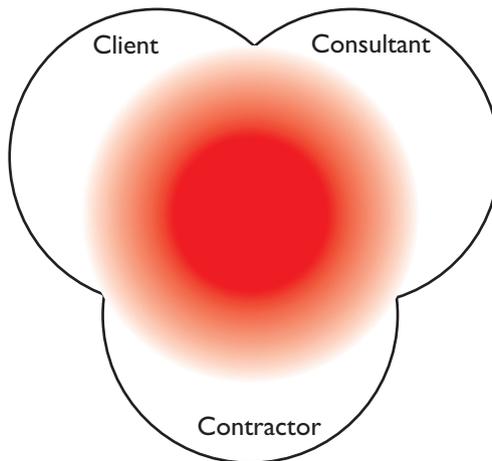


Figure 1.3 *Focus of the Manual: Interfaces between three contractual partners.*

1.4 Design philosophy

Land reclamation projects are undertaken for various purposes and under varying conditions. The performance requirements imposed on a fill depend on the future use of the reclamation and, hence, they vary for each individual project.

Boundary conditions are often site and project specific as well. Physical site conditions, such as wave climate, currents, water depth, subsoil properties and the vulnerability of the environment to dredging and reclamation activities will differ from one site to another. The quality and quantity of the fill available for construction will strongly depend on the location of the project. These conditions will not only affect the design of a reclamation, but they must also be taken into account when selecting the most suitable dredging equipment and construction method.

A rational design must integrate the functional and performance requirements considering the boundary conditions of the project in order to adequately specify the geometry and properties of the fill mass. The same rationality must be applied with respect to the construction of the reclamation requiring an appropriate selection of equipment and working method.

Functional and performance requirements

A functional requirement defines what a system must do, while a performance requirement specifies something about the system itself and how well it performs its function. A fill mass (and its subsoil) can be regarded as a system with functional and performance requirements.

Starting point of a design must always be the future land use. The functional requirements of the fill mass follow directly from the intended use of the fill area. These functional requirements may be formulated in general terms (for instance: “*the reclamation area must accommodate an airfield with runways, aprons, a terminal building and a traffic control tower*”), but can also be more specific (for instance: “*the fill mass must support a structure founded on a strip footing having a width of 1.5 m, an embedment depth of 1.0 m and a bearing load of 80 kPa*”) which may vary over the area depending on the lay-out of the future development.

The functional requirements and the design of the superstructures (i.e., their Ultimate Limit State and/or Serviceability Limit State, see section 8.4.1) lead to performance requirements of the fill mass such as maximum allowable settlement of the superstructures (buildings, roads, storage areas, runways, revetments, tunnels, etc.), and sufficient safety against slope failure or liquefaction. The required basic mass properties like strength, stiffness, density and permeability can be derived from these performance requirements.

The definition of functional requirements and their subsequent translation into performance criteria form the basis of System Engineering, see section 2.5, which may be used as a tool to control the development cycle of a reclamation project.

Following an approach in terms of functional and performance requirements, the design of a reclamation project becomes an iterative process. Functional requirements, dictated by structural criteria and other project-dependent boundary conditions, will not be discussed in this Manual.

1.5 Structure, content and use

Rather than following a chronological sequence of events (project initiation, design and construction), the structure chosen for this Manual intends to put the main emphasis on the design of a land reclamation. To that end the first chapters describe not only the collection of data required for the design but also present basic information on dredging equipment and construction methods before touching upon the design aspects.

The Manual concludes with a discussion of the technical specifications that result from a design. Additional information can often be found in the referenced Appendices. Figure 1.4 illustrates the set-up of this Manual.

Following the scheme of Figure 1.4 the contents of this Manual can briefly be summarised as follows:

Chapter 2: Project initiation, gives an overview of the most relevant elements in the procedure to realise a reclamation project and the way they are related to each other. It introduces the development cycle to realize a project, including the iterative nature of that cycle and concludes with an illustrative scheme of activities leading to the construction of a reclamation project.

Chapter 3: Data collection, presents the data required for the design of a hydraulic fill project. It deals not only with the type of information needed for the design, but also with the methods to collect the information, the reporting and the processing of data.

Commonly used dredging equipment and its use can be found in Chapter 4: Dredging equipment. Possibilities and limitations of the various types of dredgers and their vulnerability to the physical conditions of the project site are also included.

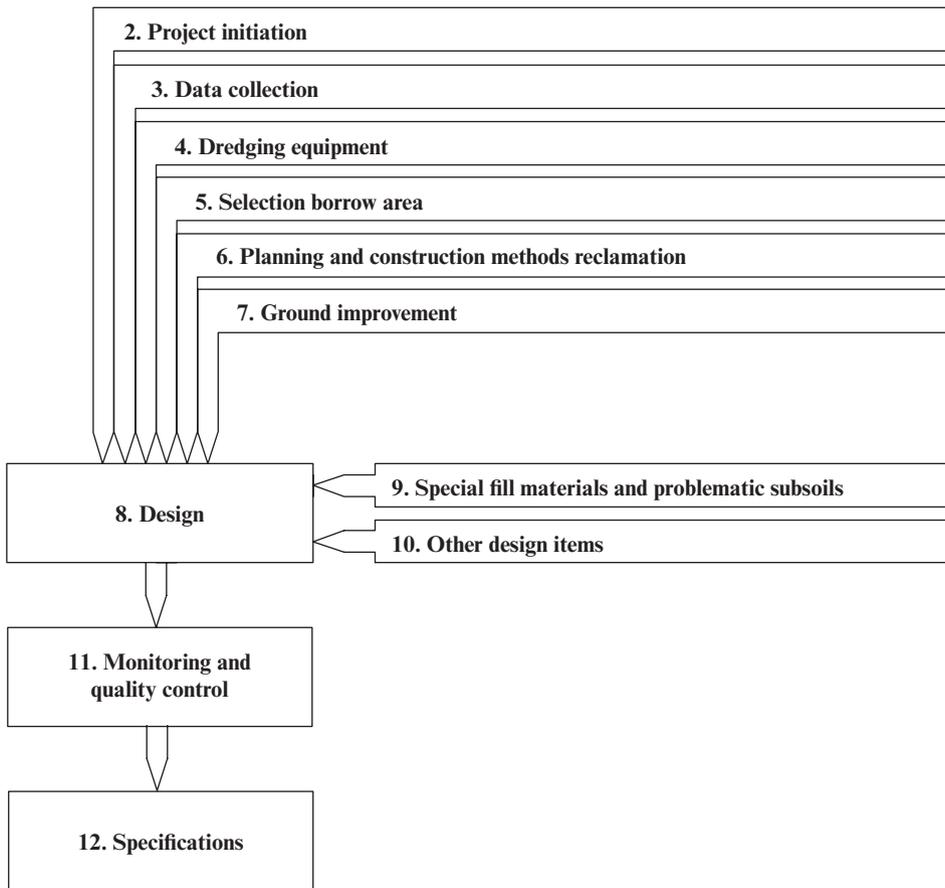


Figure 1.4 *Structure of the Manual.*

The feasibility of a project strongly depends on the availability of sufficient suitable fill material in the vicinity of the reclamation site. Chapter 5: Selection borrow area, describes the most important criteria for the selection of a borrow area.

Chapter 6: Planning and construction methods reclamation, deals with the construction methods of a reclamation area. This not only includes the deposition of the material, but also the planning, preparation and monitoring of the operations.

In the case where the existing subsoil and/or the fill behaviour do not meet the requirements, ground improvement may be required. Chapter 7: Ground improvement, gives an overview of the most relevant ground improvement techniques.

Chapter 8: Design, discusses the geotechnical design of a land reclamation. The main sections deal with density, (shear) strength, stiffness and deformations of the fill mass. A special section of this chapter is dedicated to the phenomena liquefaction and breaching.

In some areas of the world land reclamation projects have to be undertaken using cohesive materials or carbonate sands rather than with the more frequently encountered quartz sands. Furthermore, some subsoils may exhibit a different behaviour when loaded by fill. Chapter 9: Special fill materials and problematic subsoils, describes the behaviour of these special fill materials and problematic subsoils.

In addition to the geotechnical behaviour, a design should also take into account aspects like drainage of the reclaimed area, wind erosion, and slope, bed and bank protection. A short introduction to these subjects and some relevant references are presented in Chapter 10: Other design items.

Chapter 11: Monitoring and quality control, is about monitoring and quality control requirements during and after construction of the reclamation.

Finally, Chapter 12: Specifications, makes recommendations for specifying the construction of a hydraulic fill area which logically follow from the engineering philosophy adopted in this Manual.



