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,

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

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

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 a 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
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	Roderick Nichols	Halcrow
	Philip Smith	Royal Haskoning DHV
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Review English translation	Marsha Cohen	
Technical review	Chris Chiverrell	CIRIA
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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_o	= 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.*

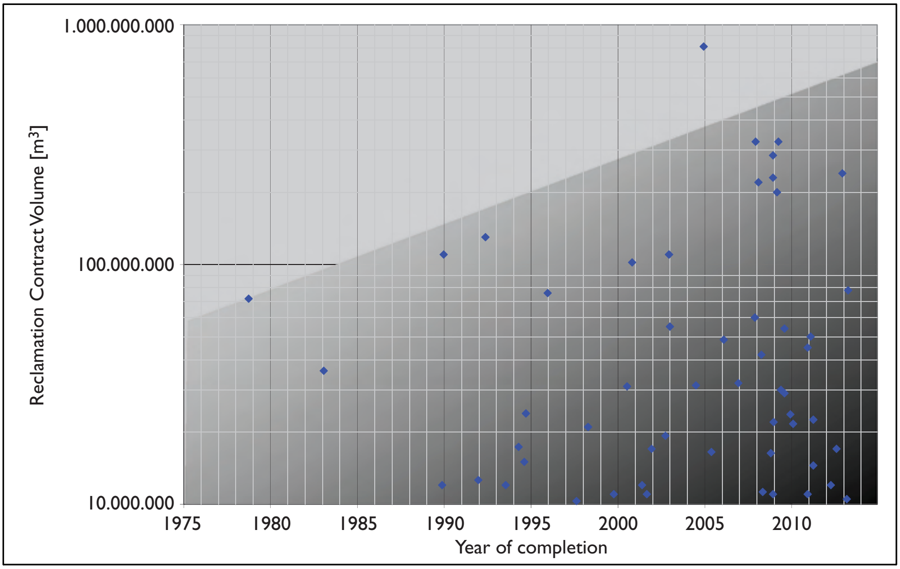

Figure 1.2 *Trend of reclamation contract volumes over the past 30 years.*

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.

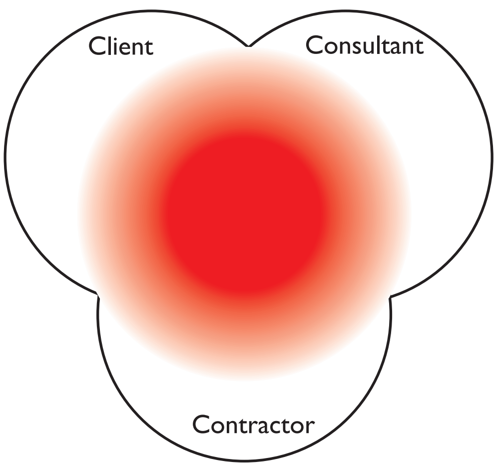

Figure 1.3 *Focus of the Manual: Interfaces between three contractual partners.*

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.

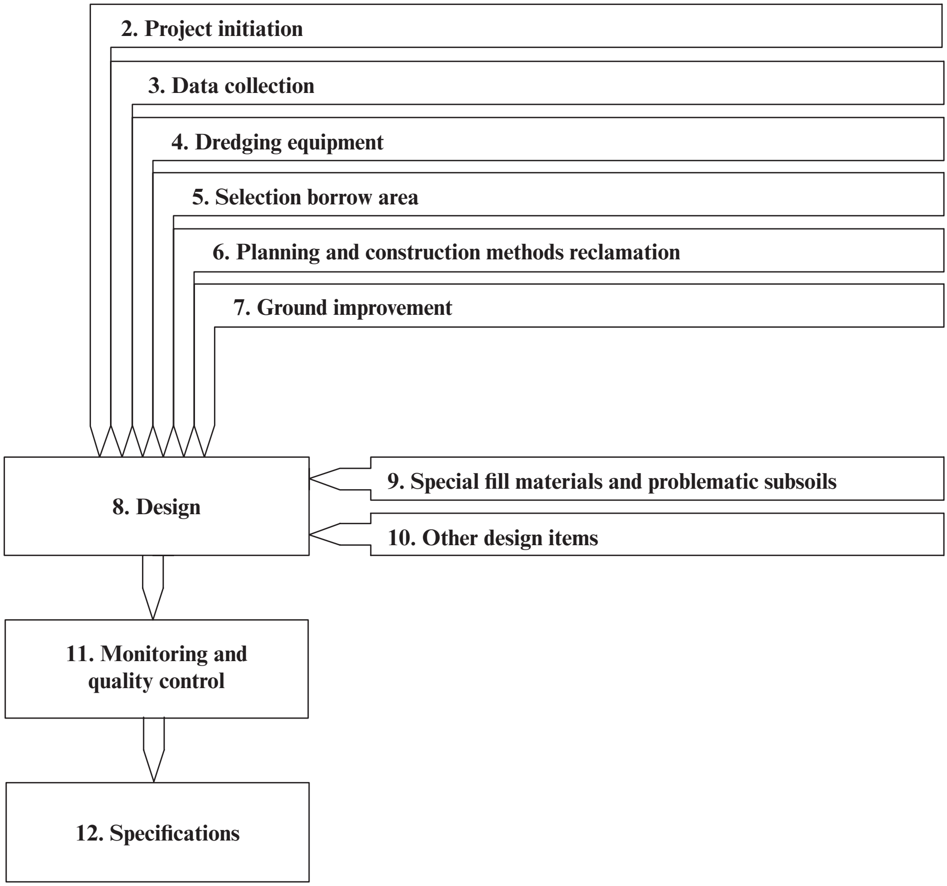

Figure 1.4 *Structure of the Manual.*

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.