

PRINCIPLES OF SEDIMENT TRANSPORT
IN
RIVERS, ESTUARIES AND COASTAL SEAS

PART II: Supplement (update) 2006

by

Leo C. van Rijn



Universiteit Utrecht
Department of Physical Geography



WL | delft hydraulics

Other publications:

*Principles of Fluid Flow and Surface Waves in Rivers, Estuaries,
Seas and Oceans by Leo C. van Rijn, 1990*

*Principles of Coastal Morphology,
by Leo C. van Rijn, 1998*

*Principles of Sedimentation and Erosion Engineering in Rivers, Estuaries,
Seas and Oceans by Leo C. van Rijn, 2005*

Manual of Sediment Transport Measurements (update 2006)

**Aqua Publications
The Netherlands
(WWW.AQUAPUBLICATIONS.NL)**

PRINCIPLES OF SEDIMENT TRANSPORT
IN
RIVERS, ESTUARIES AND COASTAL SEAS
PART II: Supplement (update) 2006

Leo C. van Rijn

Professor Fluid Mechanics and Sediment Transport
University of Utrecht, The Netherlands

Senior Hydraulic Engineer, Delft Hydraulics
Delft, The Netherlands



AQUA PUBLICATIONS

***Published in The Netherlands
Loose leaf Edition and CD-ROM 2006***

Aqua Publications
The Netherlands
(WWW.AQUAPUBLICATIONS.NL)

CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG, THE NETHERLANDS

Rijn, Leo C. van

Principles of sediment transport in rivers, estuaries and coastal seas

Author: Leo C. van Rijn

Publisher: Aqua Publications (www.aquapublications.nl)

Part I and II (Edition 2006): ISBN 978-90-800356-9-0 Loose Leaf Volume

Subject headings: Sediment transport and fluid mechanics

Copyright 2006 by Aqua Publications

All rights reserved. No part of this publication may be reproduced in any form or by any means without the prior written permission of the publisher.

FOR THOSE WHO CONTINUE TO LIKE SEDIMENTS

CONTENTS PART I: EDITION 1993

| | | |
|----------|---|------------|
| 1 | INTRODUCTION (Part I) | 1.1 |
| 1.1 | Definitions | 1.1 |
| 1.2 | History | 1.3 |
| 1.3 | Symbols and units | 1.4 |
| 1.4 | Characteristic parameters | 1.5 |
| 2 | FLUID VELOCITIES AND BED SHEAR STRESSES (Part I) | 2.1 |
| 2.1 | Introduction | 2.1 |
| 2.2 | Currents | 2.1 |
| 2.2.1 | Current boundary layer..... | 2.1 |
| 2.2.2 | Hydraulic regimes | 2.2 |
| 2.2.3 | Velocity distribution over the depth..... | 2.4 |
| 2.2.4 | Fluid mixing coefficient..... | 2.4 |
| 2.2.5 | Bed-shear stress and bed friction..... | 2.5 |
| 2.3 | Waves | 2.7 |
| 2.3.1 | Near-bed orbital velocities | 2.7 |
| 2.3.2 | Wave-boundary layer | 2.9 |
| 2.3.3 | Hydraulic regimes in waves | 2.10 |
| 2.3.4 | Velocity distribution in wave boundary layer | 2.11 |
| 2.3.5 | Bed-shear stress and bed friction..... | 2.15 |
| 2.3.6 | Breaking waves | 2.18 |
| 2.3.7 | Mass transport in non-breaking waves..... | 2.20 |
| 2.3.8 | Mass transport by breaking waves | 2.28 |
| 2.4 | Combined current and waves | 2.28 |
| 2.4.1 | Introduction | 2.28 |
| 2.4.2 | Wave characteristics..... | 2.29 |
| 2.4.3 | Current velocities and bed-shear stresses | 2.29 |
| | References..... | 2.48 |
| 3 | FLUID AND SEDIMENT PROPERTIES (Part I) | 3.1 |
| 3.1 | Fluid properties | 3.1 |
| 3.1.1 | Introduction | 3.1 |
| 3.1.2 | Fluid density..... | 3.1 |
| 3.1.3 | Fluid viscosity | 3.1 |
| 3.2 | Sediment properties..... | 3.3 |
| 3.2.1 | Introduction | 3.3 |
| 3.2.2 | Density and porosity..... | 3.5 |
| 3.2.3 | Shape | 3.7 |
| 3.2.4 | Size | 3.9 |
| 3.2.5 | Particle fall velocity | 3.11 |
| 3.2.6 | Angle of (natural) repose..... | 3.17 |
| | References..... | 3.19 |
| 4 | INITIATION OF MOTION (Part I) | 4.1 |
| 4.1 | Initiation of motion in currents..... | 4.1 |
| 4.1.1 | Introduction | 4.1 |
| 4.1.2 | Critical bed-shear stress | 4.1 |
| 4.1.3 | Critical depth-averaged velocity | 4.14 |
| 4.1.4 | Design of stable channels..... | 4.16 |
| 4.1.5 | Examples and problems | 4.19 |

CONTENTS PART I: EDITION 1993

| | | |
|----------|---|------------|
| 4.2 | Initiation of motion in waves..... | 4.23 |
| 4.2.1 | Critical velocity | 4.23 |
| 4.2.2 | Critical bed-shear stress | 4.23 |
| 4.2.3 | Examples and problems | 4.25 |
| 4.3 | Initiation of motion for combined currents and waves..... | 4.27 |
| 4.3.1 | Critical bed-shear stress | 4.27 |
| 4.3.2 | Examples and problems | 4.29 |
| 4.4 | Initiation of suspension in currents | 4.31 |
| 4.4.1 | Critical bed-shear stress | 4.31 |
| 4.4.2 | Critical depth-averaged velocity | 4.32 |
| 4.4.3 | Examples and problems | 4.32 |
| | References..... | 4.34 |
| 5 | BED FORMS (Part I) | 5.1 |
| 5.1 | Introduction | 5.1 |
| 5.2 | Bed forms in unidirectional currents | 5.1 |
| 5.2.1 | Classification..... | 5.1 |
| 5.2.2 | Shape and dimensions of bed forms..... | 5.7 |
| 5.2.3 | Examples and problems | 5.22 |
| 5.3 | Bed forms in non-steady currents..... | 5.24 |
| 5.3.1 | Non-steady river flow..... | 5.24 |
| 5.3.2 | Tidal flow | 5.28 |
| 5.3.3 | Examples and problems | 5.32 |
| 5.4 | Bed forms in waves | 5.32 |
| 5.4.1 | Classification..... | 5.32 |
| 5.4.2 | Shape and dimensions of bed forms..... | 5.33 |
| 5.4.3 | Examples and problems | 5.42 |
| 5.5 | Bed forms in currents and waves | 5.43 |
| 5.5.1 | Classification..... | 5.43 |
| 5.5.2 | Shape and dimensions of bed forms..... | 5.46 |
| 5.5.3 | Examples and problems | 5.51 |
| | References..... | 5.53 |
| 6 | EFFECTIVE BED ROUGHNESS (Part I) | 6.1 |
| 6.1 | Introduction | 6.1 |
| 6.2 | Current-related bed roughness..... | 6.1 |
| 6.2.1 | Introduction | 6.1 |
| 6.2.2 | Available methods..... | 6.1 |
| 6.2.3 | Methods based on bed-form parameters | 6.1 |
| 6.2.4 | Methods based on integral parameters | 6.11 |
| 6.2.5 | Comparison of methods | 6.15 |
| 6.2.6 | Examples and problems | 6.16 |
| 6.3 | Wave-related bed roughness | 6.18 |
| 6.3.1 | Available method | 6.18 |
| 6.3.2 | Examples and problems | 6.21 |
| 6.4 | Bed roughness in combined currents and waves..... | 6.23 |
| 6.4.1 | Available method | 6.23 |
| 6.4.2 | Examples and problems | 6.24 |
| | References..... | 6.26 |

CONTENTS PART I: EDITION 1993

| | | |
|----------|---|------------|
| 7 | BED MATERIAL SUSPENSION AND TRANSPORT IN STEADY UNIFORM CURRENTS (Part I)..... | 7.1 |
| 7.1 | Introduction | 7.1 |
| 7.2 | Bed-load transport | 7.2 |
| 7.2.1 | Introduction and definitions | 7.2 |
| 7.2.2 | Characteristics of moving bed-load particles | 7.4 |
| 7.2.3 | Particle pick-up from the bed | 7.13 |
| 7.2.4 | Deterministic bed-load transport formulae..... | 7.20 |
| 7.2.5 | Bed-load transport at low shear stress | 7.29 |
| 7.2.6 | Bed-load transport at steep slopes | 7.29 |
| 7.2.7 | Bed-load transport of non-uniform material | 7.33 |
| 7.2.8 | Comparison of bed-load transport formulae | 7.38 |
| 7.2.9 | Stochastic bed-load transport formulae | 7.38 |
| 7.2.10 | Examples and problems | 7.43 |
| 7.3 | Suspended load transport | 7.49 |
| 7.3.1 | Introduction | 7.49 |
| 7.3.2 | Mass balance equation suspended sediment | 7.51 |
| 7.3.3 | Fluid and sediment mixing coefficient..... | 7.53 |
| 7.3.4 | Concentration profiles | 7.55 |
| 7.3.5 | Velocity profiles in lower regime..... | 7.59 |
| 7.3.6 | Reference concentration and reference level..... | 7.61 |
| 7.3.7 | Suspended sediment size in case of non-uniform bed material..... | 7.65 |
| 7.3.8 | Suspended load transport rates | 7.67 |
| 7.3.9 | Stratification effects in high-concentration suspensions | 7.75 |
| 7.4 | Total load transport | 7.91 |
| 7.4.1 | Prediction methods..... | 7.91 |
| 7.4.2 | Comparison of methods | 7.95 |
| 7.4.3 | Examples and problems | 7.98 |
| | References..... | 7.105 |
| 8 | BED MATERIAL SUSPENSION AND TRANSPORT IN WAVES (Part I)..... | 8.1 |
| 8.1 | Introduction | 8.1 |
| 8.2 | Identification of transport processes..... | 8.2 |
| 8.2.1 | Non-breaking waves..... | 8.2 |
| 8.2.2 | Breaking waves | 8.8 |
| 8.2.3 | Vector presentation of fluxes | 8.10 |
| 8.3 | Analysis of measured concentration profiles and transport rates | 8.11 |
| 8.3.1 | Instantaneous concentrations..... | 8.11 |
| 8.3.2 | Time-averaged concentrations | 8.15 |
| 8.3.3 | Sediment load and transport rate | 8.27 |
| 8.4 | Computation of time-averaged concentration profiles | 8.35 |
| 8.4.1 | Introduction | 8.35 |
| 8.4.2 | Time-averaged convection-diffusion equation..... | 8.36 |
| 8.4.3 | Particle size of suspended sediment | 8.38 |
| 8.4.4 | Sediment mixing coefficient for non-breaking waves..... | 8.38 |
| 8.4.5 | Sediment mixing coefficient for breaking waves..... | 8.46 |
| 8.4.6 | Reference concentration in near-bed region..... | 8.48 |
| 8.4.7 | Methods for computation of time-averaged concentration profiles | 8.51 |

CONTENTS PART I: EDITION 1993

| | | |
|-----------|---|-------------|
| 8.5 | Computation of sediment transport rates..... | 8.58 |
| 8.5.1 | Introduction | 8.58 |
| 8.5.2 | Sediment transport models | 8.58 |
| 8.5.3 | Sediment transport formulae | 8.59 |
| 8.5.4 | Influence of bed slope on bed-load transport | 8.67 |
| 8.6 | Examples and problems | 8.68 |
| | References..... | 8.73 |
| 9 | BED MATERIAL SUSPENSION AND TRANSPORT IN COMBINED WAVES AND CURRENTS (Part I)..... | 9.1 |
| 9.1 | Introduction | 9.1 |
| 9.2 | Analysis of measured concentration profiles and transport rates | 9.1 |
| 9.2.1 | Time-averaged concentration profiles | 9.1 |
| 9.2.2 | Sediment transport rates | 9.9 |
| 9.3 | Computation of time-averaged concentration profiles | 9.16 |
| 9.3.1 | Methods | 9.16 |
| 9.3.2 | Comparison of measured and computed concentration profiles | 9.17 |
| 9.4 | Computation of sediment transport in non-breaking waves..... | 9.24 |
| 9.4.1 | Methods | 9.24 |
| 9.4.2 | Comparison of measured and computed transport rates..... | 9.27 |
| 9.5 | Computation of sediment transport in breaking waves | 9.29 |
| 9.5.1 | Methods | 9.29 |
| 9.5.2 | Comparison of measured and computed transport rates..... | 9.33 |
| 9.6 | Examples and problems | 9.34 |
| | References..... | 9.37 |
| 10 | BED MATERIAL TRANSPORT, EROSION AND DEPOSITION IN NON-STEADY AND NON-UNIFORM FLOW (Part I) | 10.1 |
| 10.1 | Introduction | 10.1 |
| 10.2 | Sediment transport in non-steady flow..... | 10.1 |
| 10.2.1 | River flow | 10.1 |
| 10.2.2 | Tidal flow | 10.1 |
| 10.3 | Sediment transport in non-uniform conditions..... | 10.10 |
| 10.3.1 | General | 10.10 |
| 10.3.2 | Erosion and scour near structures..... | 10.14 |
| 10.3.3 | Deposition in channels | 10.19 |
| | References..... | 10.29 |
| 11 | TRANSPORT OF COHESIVE MATERIALS (Part I)..... | 11.1 |
| 11.1 | Introduction | 11.1 |
| 11.2 | Cohesion, plasticity, viscosity and yield stress | 11.2 |
| 11.3 | Flocculation..... | 11.7 |
| 11.4 | Settling | 11.9 |
| 11.4.1 | Influence of salinity..... | 11.9 |
| 11.4.2 | Influence of concentration..... | 11.9 |
| 11.4.3 | Influence of water depth and flow velocity..... | 11.11 |
| 11.4.4 | Influence of measuring instrument..... | 11.12 |

CONTENTS PART I: EDITION 1993

| | | |
|-----------|---|-------------|
| 11.5 | Deposition | 11.15 |
| 11.5.1 | Introduction | 11.15 |
| 11.5.2 | Concentrations larger than 10 kg/m ³ | 11.15 |
| 11.5.3 | Concentrations from 0.3 to 10 kg/m ³ | 11.15 |
| 11.5.4 | Concentrations smaller than 0.3 kg/m ³ | 11.19 |
| 11.5.5 | Critical bed-shear stress for deposition | 11.21 |
| 11.5.6 | Deposition rates | 11.22 |
| 11.6 | Consolidation | 11.22 |
| 11.7 | Erosion | 11.28 |
| 11.7.1 | Introduction | 11.28 |
| 11.7.2 | Consolidated hard deposits | 11.29 |
| 11.7.3 | Consolidated soft deposits | 11.31 |
| 11.7.4 | Erosion rates | 11.34 |
| 11.7.5 | Bed forms and roughness | 11.34 |
| 11.8 | Transport of mud by currents | 11.35 |
| 11.8.1 | (Quasi) steady flow | 11.35 |
| 11.8.2 | Non-steady (tidal) flow | 11.36 |
| 11.9 | Transport of mud by waves | 11.42 |
| | References | 11.46 |
| 12 | MATHEMATICAL MODELS OF SEDIMENT TRANSPORT (Part I) | 12.1 |
| 12.1 | Introduction | 12.1 |
| 12.2 | Flow models | 12.2 |
| 12.2.1 | Introduction | 12.2 |
| 12.2.2 | Three-dimensional flow models | 12.3 |
| 12.2.3 | Two-dimensional horizontal flow model for estuaries and seas | 12.8 |
| 12.2.4 | Two-dimensional vertical flow model | 12.10 |
| 12.2.5 | One-dimensional flow model for rivers or estuaries | 12.11 |
| 12.3 | Wave models | 12.14 |
| 12.3.1 | Introduction | 12.14 |
| 12.3.2 | Basic equations | 12.14 |
| 12.3.3 | Two-dimensional horizontal models for combined refraction, diffraction, shoaling and dissipation | 12.16 |
| 12.3.4 | Two-dimensional models for combined refraction, shoaling and dissipation | 12.21 |
| 12.4 | Sediment transport and morphological models | 12.26 |
| 12.4.1 | Introduction | 12.26 |
| 12.4.2 | Basic equations of sediment transport | 12.26 |
| 12.4.3 | Three-dimensional models | 12.38 |
| 12.4.4 | Two-dimensional vertical models | 12.42 |
| 12.4.5 | Two-dimensional horizontal models | 12.50 |
| 12.4.6 | One-dimensional models | 12.55 |
| | References | 12.58 |

CONTENTS PART I: EDITION 1993

| | | |
|-----------|--|-------------|
| 13 | MEASURING INSTRUMENTS FOR SEDIMENT TRANSPORT, SETTLING VELOCITY AND WET BULK DENSITY (Part I) | 13.1 |
| 13.1 | Introduction | 13.1 |
| 13.2 | Measuring facilities | 13.1 |
| 13.3 | Measuring principles | 13.3 |
| 13.3.1 | Suspended load transport | 13.3 |
| 13.3.2 | Bed-load transport | 13.4 |
| 13.4 | Measuring statistics | 13.6 |
| 13.4.1 | General aspects..... | 13.6 |
| 13.4.2 | Sampling site | 13.6 |
| 13.4.3 | Number of measurements for suspended load transport | 13.6 |
| 13.4.4 | Number of measurements for bed-load transport..... | 13.15 |
| 13.4.5 | Sampling frequency..... | 13.16 |
| 13.5 | Computation of sediment transport | 13.17 |
| 13.5.1 | Suspended load transport per unit width | 13.17 |
| 13.5.2 | Total load transport per unit width | 13.22 |
| 13.5.3 | Total load transport in cross-section | 13.22 |
| 13.5.4 | Tide-integrated total load | 13.24 |
| 13.6 | Instruments for bed-load transport | 13.25 |
| 13.6.1 | Introduction | 13.25 |
| 13.6.2 | Trap sampling | 13.25 |
| 13.6.3 | Bed-form tracking | 13.32 |
| 13.7 | Instruments for suspended load transport..... | 13.33 |
| 13.7.1 | Introduction | 13.33 |
| 13.7.2 | Bottle and trap samplers..... | 13.34 |
| 13.7.3 | Pump samplers | 13.48 |
| 13.7.4 | Optical and acoustical samplers | 13.53 |
| 13.7.5 | Comparison of suspended load samplers | 13.60 |
| 13.7.6 | Selection of suspended load sampler..... | 13.63 |
| 13.8 | Instruments for particle size and settling velocity | 13.65 |
| 13.8.1 | General aspects..... | 13.65 |
| 13.8.2 | Sieve instruments | 13.66 |
| 13.8.3 | Sedimentation methods | 13.67 |
| 13.8.4 | Coulter Counter..... | 13.72 |
| 13.8.5 | In-situ Laser diffraction..... | 13.72 |
| 13.8.6 | In-situ video camera..... | 13.73 |
| 13.8.7 | Selection of instruments..... | 13.73 |
| 13.9 | Instruments for bed material sampling..... | 13.74 |
| 13.9.1 | Introduction | 13.74 |
| 13.9.2 | Grab, dredge and scoop samplers..... | 13.75 |
| 13.9.3 | Core samplers | 13.75 |
| 13.10 | Instruments for in-situ measurement of wet bulk density | 13.76 |
| 13.10.1 | General aspects..... | 13.76 |
| 13.10.2 | Mechanical core sampler..... | 13.76 |
| 13.10.3 | Acoustic probe | 13.77 |
| 13.10.4 | Nuclear radiation probe..... | 13.77 |
| | References..... | 13.81 |

APPENDICES (Part I)

- A:** TRANSPOR1993-program; Computation of sediment transport in current and in wave direction
- B:** Sand transport in closed conduits
- C:** Side-wall roughness correction method of Vanoni-Brooks
- D:** Pollution aspects of sediments

CONTENTS PART II: SUPPLEMENT (UPDATE) 2006

| | | |
|----------|--|-------------|
| 2 | FLUID VELOCITIES AND BED SHEAR STRESSES (Part II) | 2.53 |
| 2.3.5 | Time-averaged bed-shear stress | 2.53 |
| 2.3.6 | Shoaling and breaking waves | 2.54 |
| 2.3.7 | Mass transport in non-breaking waves | 2.60 |
| 2.3.8 | Mass transport by breaking waves | 2.28 |
| 2.4.3 | Current velocities and bed-shear stresses | 2.71 |
| | References | 2.78 |
| 3 | FLUID AND SEDIMENT PROPERTIES (Part II) | 3.21 |
| 3.2.1 | Sediment classification..... | 3.21 |
| 3.2.2 | Density and porosity..... | 3.22 |
| 3.2.4 | Particle Size | 3.24 |
| 3.2.5 | Particle fall velocity | 3.26 |
| 3.2.6 | Angle of (natural) repose..... | 3.30 |
| | References..... | 3.33 |
| 4 | INITIATION OF MOTION (Part II) | 4.37 |
| 4.1 | Initiation of motion in currents..... | 4.37 |
| 4.1.2 | Critical bed-shear stress | 4.37 |
| 4.2 | Initiation of motion in waves..... | 4.57 |
| 4.2.1 | Critical velocity | 4.57 |
| 4.3 | Initiation of motion for combined currents and waves..... | 4.57 |
| 4.3.2 | Critical velocity | 4.57 |
| 4.4 | Initiation of suspension in currents | 4.59 |
| 4.4.1 | Critical bed-shear stress | 4.59 |
| | References..... | 4.61 |
| 5 | BED FORMS (Part II) | 5.59 |
| 5.2 | Bed forms in unidirectional currents | 5.59 |
| 5.2.2 | Shape and dimensions of bed forms..... | 5.60 |
| 5.3 | Bed forms in non-steady currents..... | 5.64 |
| 5.3.1 | Non-steady river flow..... | 5.64 |
| 5.3.2 | Tidal flow | 5.65 |
| 5.4 | Bed forms in waves | 5.66 |
| 5.4.1 | Classification..... | 5.66 |
| 5.4.2 | Shape and dimensions of bed forms..... | 5.68 |
| 5.5 | Bed forms in currents and waves | 5.80 |
| 5.5.1 | Classification..... | 5.80 |
| 5.5.2 | Shape and dimensions of bed forms..... | 5.84 |
| | References..... | 5.87 |

CONTENTS PART II: SUPPLEMENT (UPDATE) 2006

| | | |
|----------|---|--------------|
| 6 | EFFECTIVE BED ROUGHNESS (Part II) | 6.29 |
| 6.1 | Introduction | 6.29 |
| 6.2 | Current-related bed roughness..... | 6.29 |
| 6.2.3 | Methods based on grain and bed-form parameters..... | 6.29 |
| 6.2.4 | Methods based on integral parameters | 6.36 |
| 6.3 | Wave-related bed roughness | 6.41 |
| 6.3.1 | Available method | 6.41 |
| 6.4 | Bed roughness in combined currents and waves..... | 6.43 |
| 6.4.1 | Definitions, processes and available methods | 6.43 |
| | References..... | 6.53 |
| | | |
| 7 | BED MATERIAL SUSPENSION AND TRANSPORT IN STEADY UNIFORM CURRENTS (Part II) | 7.112 |
| 7.1 | Introduction | 7.112 |
| 7.2 | Bed-load transport | 7.116 |
| 7.2.2 | Characteristics of bed-load transport processes in the lower regime | 7.116 |
| 7.2.3 | Particle pick-up from the bed | 7.117 |
| 7.2.4 | Deterministic bed-load transport formulae..... | 7.122 |
| 7.2.5 | Bed-load transport at low and high shear stress | 7.131 |
| 7.2.6 | Bed-load transport at sloping beds | 7.143 |
| 7.2.7 | Bed-load transport of non-uniform material | 7.159 |
| 7.2.9 | Stochastic bed-load transport formulae | 7.174 |
| 7.3 | Suspended load transport | 7.181 |
| 7.3.6 | Reference concentration and reference level..... | 7.181 |
| 7.3.7 | Suspended sediment size in case of non-uniform bed material..... | 7.182 |
| 7.3.8 | Suspended load transport rates | 7.190 |
| 7.3.9 | Stratification effects in high-concentration suspensions | 7.196 |
| 7.4 | Total load transport | 7.212 |
| 7.4.1 | Prediction methods..... | 7.212 |
| | References..... | 7.214 |
| | | |
| 8 | BED MATERIAL SUSPENSION AND TRANSPORT IN WAVES (Part II) | 8.78 |
| 8.2 | Identification of transport processes..... | 8.78 |
| 8.3 | Analysis of measured concentration profiles and transport rates | 8.93 |
| 8.3.1 | Instantaneous concentrations..... | 8.93 |
| 8.3.2 | Time-averaged concentrations | 8.97 |
| 8.3.3 | Sediment load and transport rate (wave-related transport experiments) | 8.101 |
| 8.4 | Computation of time-averaged concentration profiles | 8.124 |
| 8.4.4 | Sediment mixing | 8.124 |
| 8.4.6 | Reference concentration..... | 8.127 |
| 8.5 | Computation of sediment transport rates..... | 8.128 |
| 8.5.2 | Sediment transport models | 8.128 |
| 8.5.3 | Practical sediment transport formulae for oscillatory flow | 8.138 |
| 8.5.5 | Computed cross-shore transport rates based on field data at Terschelling site | 8.156 |
| | References..... | 8.158 |

CONTENTS PART II: SUPPLEMENT (UPDATE) 2006

| | | |
|-----------|---|--------------|
| 9 | BED MATERIAL SUSPENSION AND TRANSPORT IN COMBINED WAVES AND CURRENTS (Part II) | 9.39 |
| 9.1 | Introduction | 9.39 |
| 9.2 | Analysis of measured concentration profiles and transport rates | 9.39 |
| 9.2.1 | Time-averaged concentration profiles | 9.39 |
| 9.2.2 | Sand transport in combined steady and oscillatory flow | 9.52 |
| 9.3 | Computation of time-averaged concentration profiles and sediment transport | 9.61 |
| 9.3.1 | Methods | 9.61 |
| 9.4 | Computation of sediment transport in non-breaking waves | 9.66 |
| 9.4.1 | Definition and methods | 9.66 |
| 9.4.2 | Comparison of methods | 9.74 |
| 9.4.3 | Application of TR004-model (Appendix A2) | 9.77 |
| 9.4.4 | Multi-Fraction method for suspended transport of non-uniform sediments | 9.89 |
| 9.5 | Computation of sediment transport in breaking waves | 9.93 |
| 9.5.1 | Methods | 9.93 |
| 9.5.2 | Comparison of methods | 9.100 |
| 9.5.2 | Effect of particle size on longshore transport formulae | 9.105 |
| | References | 9.107 |
| | | |
| 11 | TRANSPORT OF COHESIVE MATERIALS (Part II) | 11.49 |
| 11.1 | Introduction | 11.49 |
| 11.3 | Flocculation | 11.50 |
| 11.3.1 | Analysis of measurements | 11.50 |
| 11.3.2 | Modelling of flocculation | 11.54 |
| 11.4 | Settling | 11.56 |
| 11.4.2 | Influence of concentration | 11.56 |
| 11.4.4 | Influence of measuring instrument | 11.59 |
| 11.5 | Deposition | 11.60 |
| 11.6 | Consolidation | 11.61 |
| 11.6.1 | Processes | 11.61 |
| 11.6.2 | Consolidation model of Gibson | 11.62 |
| 11.6.3 | Empirical long-term consolidation models | 11.62 |
| 11.7 | Erosion | 11.63 |
| 11.7.3 | Consolidated soft deposits | 11.63 |
| 11.7.4 | Erosion rates | 11.66 |
| 11.7.6 | Saturation | 11.69 |
| 11.8 | Transport of mud by currents | 11.71 |
| 11.8.1 | Wash-load in quasi-steady river flow | 11.71 |
| 11.8.2 | Non-steady (tidal) flow | 11.74 |
| 11.9 | Transport of mud by waves | 11.80 |
| 11.10 | Transport processes in the case of sand-mud mixtures | 11.82 |
| 11.10.1 | Processes | 11.82 |
| 11.10.2 | Experimental results | 11.84 |
| | References | 11.88 |

CONTENTS PART II: SUPPLEMENT (UPDATE) 2006

13 MEASURING INSTRUMENTS FOR SEDIMENT TRANSPORT, SETTLING VELOCITY AND WET BULK DENSITY (Part II) 13.87

13.1 Introduction 13.87

13.7 Instruments for suspended load transport 13.88

13.7.4 Optical and acoustical samplers 13.99

13.7.5 Comparison of suspended load samplers 13.60

13.7.6 Selection of suspended sediment sensors 13.129

13.8 Instruments for particle size and settling velocity 13.130

13.8.3 Particle size and concentration by Laser Diffraction (LISST, COULTER, PARTEC)..... 13.130

13.8.6 In-situ photo and video camera 13.144

13.8.8 Particle size and velocity by Phase Doppler Anemometry (PDA)..... 13.150

13.8.9 Particle size by Phase Laser Reflectance (PARTEC Laser)..... 13.153

13.11 Instruments of bed level detection..... 13.155

13.11.1 Introduction 13.155

13.11.2 Mechanical bed level detection in combination with DGPS 13.155

13.11.3 Acoustic bed level detection (Echo-sounding instruments)..... 13.156

13.11.4 Optical bed level detection..... 13.159

13.11.5 Conclusions..... 13.160

13.12 Instruments for velocity, pressure and wave height 13.165

13.12.1 Velocity sensors 13.165

13.12.2 Fluid pressure and wave height..... 13.167

APPENDIX (Part II)

A2: TRANSPOR2004-program; Computation of sediment transport in current and in wave direction

PREFACE

This 2006-update reflects the scientific and engineering progress of sediment transport processes in rivers, estuaries and coastal seas in the period between 1993 and 2006. Since 1993 many papers have been produced in the field of sediment transport. Most papers can be classified as refinements of existing theories; some papers are aimed at exploring new ideas and directions. Focus points are: initiation of motion, bed forms and associated bed roughness, sediment transport in steady flow (river flow) and in combined steady and oscillatory flow (coastal transport).

Initiation of motion of fine sediment particles down to the silt range has been studied by various researchers (Chapter 4), as the fine sediment range is not well covered by the classic experimental results of Shields. In addition, the effect of cohesive material on the critical bed-shear stress of the sand particles has been an important research topic, which is of crucial importance for the sediment transport processes in estuaries.

Bed forms also is a continuous research topic (see Chapter 5), because of its importance for the effective bed roughness (see Chapter 6), particularly in estuaries and coastal seas where it is hardly feasible to measure the water surface slope. The generation of wave-induced ripples in coastal seas has got much attention by many researchers analyzing both theoretical and experimental (field) results. The author has for the first time tried to combine all available data into a predictive method for (apparent) bed roughness, which is a basic input parameter for sediment transport. Verification of the apparent bed roughness concept in conditions with currents plus waves remains of vital importance and should be a focus point in future research. The availability of new research facilities such as the large-scale coastal basin at Vicksburg (USA) will help to improve our knowledge of coastal flows and transport.

Research on sand transport in steady flow conditions (river flow) has been focussed on the high-shear stress regime with sheet flow transport. Furthermore, the effects of slope and mixed beds on the initiation and movement of sediment particles have got new attention (see Chapter 7). Various researchers have shown that the dispersive stress concept of Bagnold can be used to derive simple expressions for the sheet flow characteristics which ultimately leads to a Meyer-Peter Mueller type of bed-load transport formula for the upper regime. The deterministic Bagnold approach accurately predicts the onset of avalanching for realistic values of the dynamic friction coefficient. Bed-load transport at low flows near initiation of motion is problematic because of the stochastic nature of the particle movement. Experimental research shows particle movement and transport for bed-shear stresses smaller than 20% of the critical bed-shear stress according to Shields. The studies of sediment suspensions have mainly focussed on the effect of the sediments on the mixing properties of the system. Sediment suspensions of relatively high concentrations often behave as stratified suspensions in which turbulence damping in the near-bed region plays a crucial role affecting the effective roughness of the flow system. Different results have been obtained for flat bed and non-flat bed conditions, emphasizing the importance of bed forms. For very fine sediments (see Chapter 11) it has been shown that the flow becomes saturated due to collapse of turbulence depending on the Richardson number. Fine sediments can be transported at very large quantities (up to 1000 kg/m^3) as a result of the presence of hindered settling processes reducing the effective settling velocity to very small values (0.1 mm/s). These phenomena have been observed and reported for the Yellow River in China.

Sediment transport studies in coastal flows (see Chapters 8 and 9) still suffer from a tremendous lack of reliable field data, particularly for the deeper shoreface region. Most of the attention has been focussed on the sand transport processes in the shallow surf and swash zones with emphasis on phenomena such as phase lags between instantaneous concentrations and velocities in rippled bed conditions and enhanced bed-shear stresses in conditions with asymmetric waves. Although our knowledge of sand transport processes in the rippled bed regime has increased considerably due to various experimental studies in wave tunnels in Scotland and in The Netherlands, much work remains to be done on this topic which is of great importance for the morphological modelling of beaches and related problems (erosion, nourishment, impact of structures).

Finally, the knowledge on instruments for measuring particle size, settling velocity and sediment transport has been updated focussing on the recent boost of new electronic equipment based on optical and acoustical techniques (see Chapter 13).