

HANDBOOK OF PORT AND HARBOR ENGINEERING

GEOTECHNICAL AND STRUCTURAL ASPECTS

Gregory P. Tsinker, Ph.D., P.E.



CHAPMAN & HALL



International Thomson Publishing

New York • Albany • Bonn • Boston • Cincinnati • Detroit • London • Madrid • Melbourne
Mexico City • Pacific Grove • Paris • San Francisco • Singapore • Tokyo • Toronto • Washington

Contents

| | |
|---|----------|
| Dedication | v |
| Preface | xix |
| Introduction | xxv |
| Contributors | xxxvii |
| | |
| 1 THE MARINE ENVIRONMENT AND ITS EFFECTS ON PORT DESIGN AND CONSTRUCTION | 1 |
| 1.1 Introduction | 1 |
| 1.1.1 General | 1 |
| 1.1.2 Seawater and Fouling | 4 |
| 1.2 Water-level Variations | 8 |
| 1.3 Weather Factors | 10 |
| 1.4 Wind | 12 |
| 1.4.1 General | 12 |
| | vii |

| | | |
|----------|---|-----------|
| 1.4.2 | Wind Parameters | 14 |
| 1.5 | Currents | 16 |
| 1.6 | Waves | 19 |
| 1.6.1 | General | 19 |
| 1.6.2 | The Sea State Parameters | 26 |
| 1.6.3 | Wave Theories | 31 |
| 1.6.4 | Design Wave | 33 |
| 1.7 | Ice | 37 |
| 1.7.1 | Introduction | 38 |
| 1.7.2 | Ice Covers | 39 |
| 1.7.3 | Effects of Ice on Port Operations | 47 |
| 1.7.4 | Cold Temperature and Ice Effects on Marine Structures Design | 54 |
| | References | 61 |
| 2 | PORT (HARBOR) ELEMENTS: DESIGN PRINCIPLES AND CONSIDERATIONS | 69 |
| 2.1 | General | 69 |
| 2.1.1 | Port Classification | 70 |
| 2.1.2 | Port Details and Definitions | 71 |
| 2.2 | Ships and their Influence on Port Design | 73 |
| 2.2.1 | Ships | 73 |
| 2.2.2 | Ship Influence on Port Design | 74 |
| 2.3 | Access (Navigation) Channel | 78 |
| 2.3.1 | General | 78 |
| 2.3.2 | Navigational and Operational Parameters | 79 |
| 2.3.3 | Environmental Parameters | 81 |
| 2.3.4 | Layout | 82 |
| 2.3.5 | Channel Cross Section | 84 |
| 2.3.6 | Economic Considerations | 96 |

| | | |
|--------|--|-----|
| 2.4 | Port (Harbor) Entrance | 98 |
| 2.5 | Port Water Area (Harbor) | 106 |
| 2.5.1 | Basin Sizes | 107 |
| 2.6 | Location, Orientation, Size, and Shape of the Port | 112 |
| 2.6.1 | Selection of Port Location | 112 |
| 2.6.2 | Size and Orientation of Marine Facilities | 115 |
| 2.6.3 | Harbor Area Requirements | 115 |
| 2.7 | Quay Basin | 119 |
| 2.8 | Offshore Installations | 121 |
| 2.8.1 | Offshore Bottom-Fixed Marine Facilities | 121 |
| 2.8.2 | Single-Point Offshore Moorings | 123 |
| 2.9 | Port-Related Marine Structures | 124 |
| 2.9.1 | Land Requirements | 124 |
| 2.9.2 | Dust and Noise Control | 127 |
| 2.9.3 | Berth Requirements | 128 |
| 2.9.4 | Structures | 130 |
| 2.9.5 | Selection of the Most Cost Effective Structure for Dock Construction | 151 |
| 2.9.6 | Constructability | 153 |
| 2.10 | Structural Materials | 154 |
| 2.10.1 | Structural Concrete | 155 |
| 2.10.2 | Underwater Concreting | 172 |
| 2.10.3 | Precast Concrete | 178 |
| 2.10.4 | Structural Steel in Port Engineering | 180 |
| 2.10.5 | Structural Timber | 195 |
| 2.11 | Breakwaters | 198 |
| 2.12 | In-Harbor Slope Protection | 203 |
| 2.13 | Aids to Navigation | 204 |
| 2.14 | Mooring Accessories | 205 |

| | | |
|----------|---|------------|
| 2.15 | Fender Systems | 206 |
| 2.15.1 | Timber Fenders | 208 |
| 2.15.2 | Solid Rubber Fenders | 210 |
| 2.15.3 | Pneumatic Fenders | 216 |
| 2.15.4 | Foam-Filled Fenders | 222 |
| 2.15.5 | Other Fender Systems | 222 |
| 2.15.6 | Fenders Failure | 226 |
| 2.15.7 | General Principles in Fender System Selection and Design | 226 |
| | References | 232 |
| 3 | DESIGN LOADS | 243 |
| 3.1 | General | 243 |
| 3.2 | Environmental Loads | 244 |
| 3.2.1 | Wind | 245 |
| 3.2.2 | Currents | 248 |
| 3.2.3 | Waves | 251 |
| 3.3 | Mooring Loads | 260 |
| 3.3.1 | Mooring Lines Arrangement | 261 |
| 3.3.2 | Mooring Line Materials | 262 |
| 3.3.3 | Mooring Forces | 262 |
| 3.4 | Loads From Cargo Handling and Hauling Equipment and Uniform Distributed Loads | 267 |
| 3.4.1 | General Considerations | 267 |
| 3.4.2 | Design Load Assumptions | 269 |
| 3.4.3 | Uniform Distributed Cargo Loads and Miscellaneous Live Loads | 271 |
| 3.4.4 | Rubber Tire and Crawler Track Mounted Equipment | 272 |
| 3.4.5 | Rail-Mounted Cargo | 279 |
| 3.4.6 | Fixed-Base Equipment | 282 |
| 3.5 | Ship Impact (by M. Shiono in collaboration with G. Tsinker) | 283 |
| 3.6 | Ice Loads | 293 |
| 3.6.1 | General | 293 |
| 3.6.2 | Environmental Driving Forces | 294 |
| 3.6.3 | Ice-Crushing Load | 295 |
| 3.6.4 | Loads Due to Ice Bending Mode of Failure | 297 |

| | | |
|----------|--|------------|
| 3.6.5 | Forces Due to Ice Sheet Adfreeze to the Structure | 299 |
| 3.6.6 | Vertical Loads on Piles or Piers Due to Changes in Water Level | 300 |
| 3.6.7 | Ice Load of Thermal Origin | 301 |
| 3.6.8 | Other Ice-Induced Loads | 302 |
| 3.7 | Seismic Loads (by W. S. Dunbar) | 302 |
| 3.7.1 | Seismic Ground Motion | 303 |
| 3.7.2 | Descriptions of Ground Motion | 307 |
| 3.7.3 | Design Ground Motion Estimation | 312 |
| 3.7.4 | Design Loads | 318 |
| 3.8 | Load Combinations | 319 |
| | References | 320 |
| 4 | GEOTECHNICAL ASPECTS OF SOIL-STRUCTURE INTERACTION DESIGN CONSIDERATIONS | 331 |
| 4.1 | General | 331 |
| 4.2 | Subsurface Investigation | 333 |
| 4.3 | Soil Liquefaction and Evaluation of Liquefaction Potential (by G. Tsinker and W. S. Dunbar) | 334 |
| 4.4 | Basic Design and Construction Considerations | 342 |
| 4.4.1 | Modern Trends | 342 |
| 4.4.2 | Bottom-Fixed Structures | 343 |
| 4.4.3 | Safety Considerations | 345 |
| 4.4.4 | Construction Procedure | 347 |
| 4.5 | Soils and Bedrock | 348 |
| 4.5.1 | Gravel and Sand | 348 |
| 4.5.2 | Silt and Clay | 349 |
| 4.5.3 | Bedrock | 350 |
| 4.6 | Properties and Characteristics of Soils | 352 |
| 4.6.1 | Shear Strength | 354 |
| 4.6.2 | Compressibility (Consolidation) | 356 |
| 4.6.3 | Permeability | 357 |

| | | |
|----------|---|------------|
| 4.7 | Lateral Soil Pressure | 358 |
| 4.7.1 | Active Earth Pressure | 359 |
| 4.7.2 | Effects of Wall Movement | 368 |
| 4.7.3 | Effects of Time-Dependent Changes in Soil | 374 |
| 4.7.4 | Effect of Ambient Temperature on Earth Pressures | 376 |
| 4.7.5 | Effects of Backfill Freezing | 376 |
| 4.7.6 | Passive Earth Pressure | 376 |
| 4.7.7 | Earth Pressure at Rest | 380 |
| 4.7.8 | Compaction-Induced Pressure | 381 |
| 4.8 | Friction Forces on Walls | 381 |
| 4.9 | Dynamic Soil Pressures | 382 |
| 4.9.1 | Mononobe–Okabe Formulation | 383 |
| 4.9.2 | Effect of Saturated Backfill | 385 |
| 4.9.3 | Hydrodynamic Pressures | 385 |
| 4.9.4 | Effect of Wall Inertia | 386 |
| 4.9.5 | Selection of Ground Motions | 387 |
| 4.9.6 | Effect of Wall Movements | 387 |
| | References | 388 |
| 5 | GRAVITY-TYPE QUAY WALLS | 397 |
| 5.1 | General | 397 |
| 5.2 | Basic Structural Arrangements | 403 |
| 5.2.1 | Blockwork Structures | 403 |
| 5.2.2 | Quay Walls Composed of Floated-in Concrete Caissons | 409 |
| 5.2.3 | Quay Walls Composed of Large-Diameter Cylinders | 428 |
| 5.2.4 | Cribwork Quay Walls | 435 |
| 5.2.5 | Steel Sheet-Pile Cell Bulkheads | 439 |
| 5.2.6 | Quay Walls | 446 |
| 5.2.7 | Gravity-Type Walls | 452 |
| 5.3 | Basic Design Considerations | 461 |
| 5.3.1 | Loads and Forces Load Combinations | 461 |
| 5.3.2 | Basic Static Principles | 464 |
| 5.4 | Design of Blockwork Quay Walls | 478 |
| 5.4.1 | Basic Design Principles | 478 |

| | | | |
|--------|--|-----|-----|
| 5.4.2 | Design Phase 1 | 480 | |
| 5.4.3 | Design Phase 2 | 483 | |
| 5.4.4 | Design Phase 3 | 484 | |
| 5.4.5 | Design Phase 4 | 484 | |
| 5.5 | Design of Quay Walls Comprised of Floated-in Concrete Caissons | | 485 |
| 5.5.1 | Basic Design Principles | 485 | |
| 5.5.2 | Buoyancy and Buoyant Stability of a Caisson | 485 | |
| 5.5.3 | Buoyancy and Stability of a Damaged Caisson | 489 | |
| 5.5.4 | Caisson Launch | 490 | |
| 5.5.5 | Towing and Sinking | 496 | |
| 5.5.6 | Structural Design | 497 | |
| 5.6 | Design of Quay Walls Composed of Large-Diameter Cylinders | | 500 |
| 5.7 | Design of L-Shaped Walls | | 504 |
| 5.7.1 | Basic Requirements | 504 | |
| 5.7.2 | Design of Cantilever Walls | 506 | |
| 5.7.3 | Design of Counterfort Wall | 507 | |
| 5.7.4 | Design of Wall Constructed from Prefabricated Components with Internal Anchorage | 508 | |
| 5.7.5 | Design of Wall Constructed from Prefabricated Components with External Anchorage | 508 | |
| 5.8 | Design of Cellular-type Steel Sheet-pile Bulkheads | | 511 |
| 5.8.1 | Introduction | 511 | |
| 5.8.2 | Conventional Design Method | 512 | |
| 5.8.3 | Horizontal Shear (Cummings') Method | 518 | |
| 5.8.4 | Brinch Hansen Method | 519 | |
| 5.8.5 | Seismic Design of Cellular Bulkheads | 519 | |
| 5.8.6 | Deflection of Cellular Bulkhead | 520 | |
| 5.8.7 | Effects of Concentrated Horizontal Loads on Sheet-Pile Cell | 522 | |
| 5.9 | Design of Cribwork-type Quay Walls | | 522 |
| 5.10 | Reinforced Earth Quay (by D. Weinreb and P. Wu) | | 524 |
| 5.10.1 | General Concept | 524 | |
| 5.10.2 | Design of Reinforced Earth Marine Structures | 532 | |
| 5.10.3 | Construction of Reinforced Earth Walls Underwater | 536 | |
| | References | | 542 |

| | |
|--|------------|
| 6 SHEET-PILE BULKHEADS | 549 |
| 6.1 Introduction | 549 |
| 6.1.1 Sheet-Piling—Background | 549 |
| 6.1.2 Anchoring Systems | 552 |
| 6.1.3 Sequence of Construction | 555 |
| 6.2 Sheet-Piling—Structural and Driving Aspects | 555 |
| 6.2.1 Timber Sheet Piles | 556 |
| 6.2.2 Steel Sheet Piles | 558 |
| 6.2.3 Concrete Sheet Piles | 561 |
| 6.2.4 Selection of Sheet-Pile Section | 570 |
| 6.3 Anchor Systems | 571 |
| 6.3.1 Anchor System Comprised of Tie-Rods and Anchorages | 572 |
| 6.3.2 Anchor System Comprised of Raked Piles | 576 |
| 6.3.3 Ground (Rock) Anchors | 583 |
| 6.4 Wall Capping | 589 |
| 6.5 Construction Methods | 591 |
| 6.5.1 Construction Sequence | 591 |
| 6.5.2 Sheet-Pile Driving | 592 |
| 6.5.3 Pile Jetting | 596 |
| 6.5.4 Earthwork | 602 |
| 6.6 Earth Pressures on Flexible Walls: State-of-the-Art Review | 606 |
| 6.7 Design of Sheet-pile Walls | 623 |
| 6.7.1 Design Criteria | 623 |
| 6.7.2 Design of Cantilever Walls | 625 |
| 6.7.3 Design of Anchored Bulkheads | 630 |
| 6.7.4 Design of Sheet-Pile Bulkheads Anchored by Raked Piles | 643 |
| 6.8 Sheet-Pile Bulkheads Built on Creep Soils | 653 |
| 6.8.1 Cantilever Sheet-Pile Bulkhead | 655 |
| 6.8.2 Single-Anchor Sheet-Pile Bulkhead | 657 |
| 6.8.3 Multianchor Sheet-Pile Bulkhead | 661 |
| 6.9 Anchorage Design | 665 |

| | | |
|----------|---|------------|
| 6.9.1 | Piled Anchorages | 666 |
| 6.9.2 | Sheet-Pile Anchor Wall | 667 |
| 6.9.3 | Individual Vertical Anchor Piles | 669 |
| 6.9.4 | Deadman (Plate) Anchor | 670 |
| 6.10 | Waling and Tie-Rod Design | 672 |
| 6.11 | Ground (Rock) Anchors | 673 |
| 6.12 | Overall Stability | 679 |
| 6.13 | Seismic Design of Anchored Sheet-Pile Walls (by W. S. Dunbar) | 682 |
| 6.13.1 | Observed Failure Modes | 682 |
| 6.13.2 | Seismic Design Procedure | 683 |
| 6.13.3 | Assumption | 683 |
| 6.13.4 | Factor of Safety Against Failure by Rotation | 683 |
| 6.13.5 | Size and Location of Anchor Block | 684 |
| 6.13.6 | Balanced Design Procedure | 685 |
| 6.14 | Sheet-Pile Wall Failure | 686 |
| | References | 688 |
| 7 | PILED WATERFRONT STRUCTURES | 695 |
| 7.1 | Introduction | 695 |
| 7.2 | General | 697 |
| 7.2.1 | Structural Schemes and Structural Components | 697 |
| 7.2.2 | Prefabrication | 701 |
| 7.3 | Open Pile Structures With Suspended Decks | 701 |
| 7.3.1 | Open Piled Offshore Piers | 702 |
| 7.3.2 | Piling | 710 |
| 7.3.3 | Suspended Deck Structures for Marginal Wharves | 711 |
| 7.3.4 | Basic Design Principles | 712 |
| 7.3.5 | Suspended Deck Structures Founded on Large-Diameter Cylindrical Piles | 718 |
| 7.3.6 | Protection from Ship Impact | 722 |

| | | |
|----------|--|------------|
| 7.3.7 | Pile Anchoring in Foundation Soil and the Deck Structure | 724 |
| 7.4 | Relieving Platforms | 725 |
| 7.5 | Structural Elements | 734 |
| 7.5.1 | Pile Foundation | 735 |
| 7.5.2 | Superstructure | 776 |
| 7.5.3 | Underdeck Slope | 782 |
| 7.6 | Pile-Soil Interaction | 795 |
| 7.6.1 | General | 795 |
| 7.6.2 | Piles Under Axial Static Load | 803 |
| 7.6.3 | Pile Settlement | 817 |
| 7.7 | Laterally Loaded Piles | 820 |
| 7.7.1 | General | 820 |
| 7.7.2 | Conventional Design Methods | 822 |
| 7.7.3 | Broms' Method | 826 |
| 7.7.4 | Subgrade Reaction Approach | 829 |
| 7.7.5 | Laterally Loaded Socketed Piles | 836 |
| 7.8 | Piled Marine Structures Design Methods | 837 |
| 7.8.1 | Design Criteria | 837 |
| 7.8.2 | Design Methods | 838 |
| | References | 865 |
| 8 | OFFSHORE DEEP WATER TERMINALS | 879 |
| 8.2 | Layout | 881 |
| 8.2.1 | Dry Bulk Loading/Unloading Facilities | 882 |
| 8.2.2 | Liquid Bulk Loading/Unloading Terminals | 886 |
| 8.3 | Mooring System | 888 |
| 8.3.1 | Basic Structural Concepts | 890 |
| 8.4 | Dolphins and Platforms | 893 |
| 8.4.1 | Breasting Dolphins | 893 |
| 8.4.2 | Piled Breasting Dolphins | 895 |
| 8.4.3 | Gravity-Type Dolphins | 896 |

| | | | |
|-----------|---|-----|------------|
| 8.4.4 | Steel Jacket-Type Structures | 898 | |
| 8.4.5 | Fenders | 898 | |
| 8.4.6 | Mooring Dolphins | 898 | |
| 8.4.7 | Loading/Unloading Platforms | 899 | |
| 8.4.8 | Access Trestles and Catwalks | 899 | |
| 8.5 | Structural Design | | 901 |
| 8.5.1 | Marine Foundation and its Effects on Structural Design | 901 | |
| 8.5.2 | Basic Design Procedures | 903 | |
| | References | | 914 |
| 9 | MODERNIZATION OF EXISTING MARINE FACILITIES | | 917 |
| 9.1 | Introduction | | 917 |
| 9.2 | Modernization of Mooring Structures | | 919 |
| 9.2.1 | Modernization of Gravity-Type Quay Walls | 920 | |
| 9.2.2 | Modernization of Piled Wharves | 925 | |
| 9.2.3 | Modernization of Sheet-Pile Bulkheads | 925 | |
| 9.2.4 | New Wall Construction | 929 | |
| 9.3 | Modernization of Waterfront Structures: Characteristic Examples | | 930 |
| 9.3.1 | Gravity-Type Quay Walls | 930 | |
| 9.3.2 | Modification of Piled Coal-Loading Pier No. 6 at Norfolk, Virginia | 940 | |
| 9.3.3 | Use of Piled Structures and Sheet-Pile Walls for Modernization of Existing Structures | 942 | |
| 9.3.4 | Construction of Brand New Structures | 949 | |
| | References | | 949 |
| 10 | BREAKWATER DESIGN (by S. Takahashi) | | 951 |
| 10.1 | Historic Development of Breakwaters | | 952 |
| 10.1.1 | Structural Types | 952 | |
| 10.1.2 | Conditions for Breakwater Selection | 956 | |
| 10.1.3 | Comparison of Sloping- and Vertical-Type Breakwaters | 956 | |
| 10.1.4 | Historical Development of Breakwaters | 957 | |
| 10.2 | Design of Conventional Vertical Breakwaters | | 977 |

| | | |
|--------|--|------|
| 10.2.1 | Examples of Conventional Vertical Breakwaters | 977 |
| 10.2.2 | Wave Transmission and Reflection by Vertical Walls | 978 |
| 10.2.3 | Wave Forces on Vertical Walls | 981 |
| 10.2.4 | Design of Rubble-Mound Foundation | 1001 |
| 10.2.5 | Rubble-Mound Toe Protection Against Scouring | 1005 |
| 10.3 | Design of New Types of Vertical Breakwater | 1006 |
| 10.3.1 | Perforated Wall Breakwater | 1007 |
| 10.3.2 | Inclined Walls | 1015 |
| 10.4 | Design of Horizontally Composite Breakwaters | 1020 |
| 10.4.1 | Wave Transmission and Reflection | 1021 |
| 10.4.2 | Wave and Block Load on a Vertical Wall | 1022 |
| 10.4.3 | Stability of Wave-Dissipating Concrete Blocks | 1023 |
| 10.5 | Design of Rubble-Mound Breakwaters | 1024 |
| 10.5.1 | Wave Transmission and Reflection | 1025 |
| 10.5.2 | Design of Armor Layer | 1027 |
| 10.5.3 | Inner Layers, Core, Toe, and Wave Screen | 1034 |
| | References | 1036 |
| | Index | 1045 |