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Substation Structure Design Guide

Second Edition



Recommended Practice for Design and Use

Task Committee on Substation Structure Design

Edited by George T. Watson, P.E.

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Task Committee on Substation Structural Design

Sponsored by
the Task Committee on Substation Structural Design of the
Electrical Transmission Structures Committee of the
Special Design Issues Technical Administrative Committee of the
Technical Activities Division of the
Structural Engineering Institute of the
American Society of Civil Engineers

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A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to the average engineer in his or her everyday work, rather than findings that may be useful only occasionally or rarely. It is not in any sense a "standard," however, nor is it so elementary or so conclusive as to provides a "rule of thumb" for nonengineers.

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In February 1962 (and revised in April 1982), the Board of Direction voted to establish a series titled "Manuals and Reports on Engineering Practice" to include the manuals published and authorized to date, future Manuals of Professional Practice, and Reports on Engineering Practice. All such manual or report material of the Society would have been refereed in a manner approved by the Board Committee on Publications and would be bound, with applicable discussion, in books similar to past manuals. Numbering would be consecutive and would be a continuation of present manual numbers. In some cases of joint committee reports, bypassing of journal publications may be authorized.

A list of available Manuals of Practice can be found at https://ascelibrary.org/page/books/s-mop.

CONTENTS

PREFACE ..... **xi**

BLUE RIBBON PANEL REVIEWERS ..... **xiii**

ACKNOWLEDGMENTS ..... **xv**

DEDICATION ..... **xv**

1. INTRODUCTION **1**
References 3

2. DEFINITIONS, ELECTRICAL EQUIPMENT, AND STRUCTURE TYPES **5**
2.1 Purpose 5
2.2 Definitions, Substation Types, and Components 5
2.2.1 Substation 5
2.2.2 Switchyard or Switching Station 5
2.2.3 Unit Substation 6
2.2.4 Transmission Line 6
2.2.5 Air-Insulated Substation 7
2.2.6 Gas-Insulated Substation, GIS 7
2.2.7 Electrical Clearance 8
2.2.8 Buswork System 8
2.2.9 Short-Circuit Force 9
2.2.10 Dead-End Structures 9
2.2.11 Box-Type Structure 10
2.2.12 Shielding Mast 11
2.2.13 Lightning Mast 12
2.3 Electrical Equipment and Supports 13
2.3.1 Power Transformer and Autotransformer 13
2.3.2 Shunt Reactor 13
2.3.3 Current-Limiting Inductor or Air Core Reactor 13
2.3.4 Line Trap 15
2.3.5 Coupling Capacitor Voltage Transformer 16
2.3.6 Disconnect Switch 16
2.3.7 Circuit Switcher (Load Interrupter Switch) 18
2.3.8 Circuit Breaker 19
2.3.9 Potential and Current Transformers 21
2.3.10 Capacitor Bank 21

2.3.11 Surge Arrester 23
2.3.12 Neutral Grounding Resistor 23
2.3.13 Cable Terminator 24
2.3.14 Insulator 24
2.3.15 Bus Duct 25
2.3.16 Fire Barriers 27
2.3.17 Control Enclosures 27
2.3.18 Transformers 27
2.4 Definition of Responsibilities 28
2.4.1 Owner 28
2.4.2 Structure Designer 28
2.4.3 Supplier or Fabricator 28
References 28

3. LOADING CRITERIA FOR SUBSTATION STRUCTURES 29
3.1 Basic Loading Conditions 29
3.1.1 Dead Loads 29
3.1.2 Equipment Operating Loads 29
3.1.3 Terminal Connection Loads for Electrical Equipment 30
3.1.4 Wire Tension Loads 30
3.1.5 Extreme Wind Loads 32
3.1.6 Ice Loads with Concurrent Wind 44
3.1.7 Seismic Loads 48
3.1.8 Short-Circuit (Fault) Loads 67
3.1.9 Construction and Maintenance Loads 70
3.1.10 Wind-Induced Oscillations 71
3.1.11 Loading Criteria for Deflection Limitations 71
3.1.12 National Electrical Safety Code Loads 72
3.1.13 State and Local Regulatory Loads 72
3.2 Application of Loads 73
3.3 Load Factors and Combinations 73
3.4 Alternate Design Loads and Load Factors 78
3.5 Serviceability Considerations 78
References 79

4. DEFLECTION CRITERIA (FOR OPERATIONAL LOADING) 81
4.1 Structure Classifications and Deflection Limits 81
4.1.1 Deflection Analysis and Criteria 81
4.1.2 Class A Structures 82
4.1.3 Class B Structures 84
4.1.4 Class C Structures 85
4.2 Special Considerations for Deflection Analysis 85
4.2.1 Multiple-Use Structures 85
4.2.2 Rotational Limitation 85
4.2.3 Anchorage and Member Connection Restraints 85
4.2.4 Gross versus Net Deflections 86
4.2.5 Shielding Masts and Other Tall, Slender Structures 86
4.2.6 Rigid Bus Vertical Deflection Criteria 87
4.3 Summary 87
Reference 88

5. METHOD OF ANALYSIS 89
5.1 Overview 89
5.2 Stress Criterion versus Deflection Criterion 89
5.3 The Structure Model 89
5.3.1 Individual Members and Connections 90
5.3.2 Truss Model 90
5.3.3 Frame Model 90
5.3.4 Finite-Element Model 91
5.3.5 Loads and Support Conditions 91
5.4 Static Analysis Method 92
5.4.1 Approximate Analysis 92
5.4.2 First-Order Elastic Analysis 92
5.4.3 Second-Order Elastic Analysis 92
5.4.4 First-Order Inelastic Analysis 93
5.4.5 Analysis Requirements in Commonly Used Documents 93
5.5 Dynamic Analysis Method 95
5.5.1 Steady-State Analysis 95
5.5.2 Eigenvalue Analysis: Natural Frequencies and Normal Modes 95
5.5.3 Response Spectrum Analysis 96
5.6 Recommendation for an Analysis Method 96
5.6.1 Static Analysis 96
5.6.2 Dynamic Analysis 96
5.7 Analysis of Short-Circuit Events 97
5.7.1 Rigid Bus Analysis Methods 98
5.7.2 Rigid Bus Analysis Methods Discussion 98
5.7.3 Short-Circuit Analysis Considerations 100
References 102

6. DESIGN 103
6.1 General Design Principles 103
6.2 Design Methods 103
6.3 Steel Structures 104
6.3.1 Ultimate Strength Design 104
6.4 Concrete Structures 105
6.4.1 Reinforced Concrete Structures 106
6.4.2 Prestressed Concrete Structures 106
6.4.3 Prestressed Concrete Poles 106
6.5 Aluminum Structures 106
6.5.1 Typical Substation Alloys and Tempers 106
6.5.2 Applications to Substation Structures 107
6.5.3 Use Limitation with Aluminum Substation Structures 107
6.5.4 Aluminum Connections 107
6.5.5 Aluminum Design Resources 108
6.6 Wood Structures 108
6.6.1 Ultimate Strength Design 108
6.6.2 Allowable Strength Design 108
6.7 Seismic Design Guidelines 108
6.7.1 Structures That Support Electrical Equipment Qualified for IEEE 693 109
6.7.2 Structures Not Covered by IEEE 693 109

6.8 Base Plate Design 109
6.8.1 Determination of Anchor Rod Loads 111
6.8.2 Determination of Base Plate Thickness 111
6.8.3 Anchor Rod Holes in Base Plates 112
6.8.4 Base and Flange Plate Design for Deflection-Sensitive Structures 113
6.9 Rigid Bus Design 113
6.9.1 Bus Layout Configuration 113
6.9.2 Rigid Bus Materials and Shapes 114
6.9.3 Fittings and Couplers 114
6.9.4 Insulators 115
6.9.5 Bus System Design 116
6.9.6 Rigid Bus Seismic Considerations 116
6.10 Special Considerations 117
6.10.1 Precautions Regarding the Magnetic Fields of Air Core Reactors 117
6.10.2 Vortex-Induced Oscillation and Vibration 119
6.10.3 Galvanizing Steel Considerations 120
6.10.4 Painted or Metallized Steel Considerations 120
6.10.5 Member Connection Design 120
6.10.6 Weathering Steel Structures 122
6.10.7 Guyed Substation Structures 122
6.10.8 Aluminum with Dissimilar Materials 122
References 123

7. FOUNDATIONS 125
7.1 Foundation Types 126
7.1.1 Shallow Foundations 126
7.1.2 Deep Foundations 127
7.1.3 Direct Embedment 128
7.1.4 Helical Screw Anchor Piles 128
7.2 Geotechnical Subsurface Exploration 129
7.2.1 General 129
7.2.2 Existing Geological Data 129
7.2.3 Site-Specific Subsurface Exploration 129
7.3 Additional Design Considerations 131
7.3.1 Frost Action 131
7.3.2 Expansive or Collapsible Soils 131
7.3.3 Corrosion 132
7.3.4 Seismic Loads and Dynamic Loads 132
7.3.5 Soil–Structure Interaction 133
7.4 Loading Considerations 133
7.4.1 Load Application 133
7.4.2 Load Combinations 134
7.5 Durability of Concrete 135
7.6 Special Considerations 135
7.6.1 Operational Loads 135
7.6.2 Construction Loads 136
7.6.3 Group Effects 136
7.6.4 Slopes and Excavations 136
7.6.5 Constructability 137

7.6.6 Settlement, Rotation, and Deflection 137
7.6.7 Uplift 138
7.6.8 Seismic Base Isolation 138
7.6.9 Grounding 138
7.6.10 National Electrical Safety Council District Loading and Foundation Design 140
References 141

8. CONNECTIONS TO FOUNDATIONS 143
8.1 Foundation Types and Anchorage Systems 144
8.1.1 Spread Footing Foundation 144
8.1.2 Drilled Pier Foundation 146
8.1.3 Anchor Rods Installed without Grout Beneath Base Plates 147
8.1.4 Embedded Structural Steel 147
8.2 Anchor Materials 147
8.3 Anchor Arrangements and General Design Considerations 149
8.3.1 Base Plates Supported by Anchor Rods with Leveling Nuts 151
8.3.2 Anchor Rods with Base Plates on Concrete or Grout 152
8.4 Anchors Cast in Place 152
8.4.1 Types of Anchors 152
8.4.2 Design Considerations for Anchor Steel 153
8.4.3 Design Considerations for Concrete 160
8.5 Post-installed Anchors in Concrete 162
8.5.1 Types and Application 162
8.5.2 Design 163
8.5.3 Installation 163
References 164

9. QUALITY CONTROL AND QUALITY ASSURANCE 167
9.1 General 167
9.2 Steel Structures 168
9.2.1 Material 168
9.2.2 Welding 168
9.2.3 Fabrication Inspection 168
9.2.4 Structure Coating 170
9.3 Aluminum Structures 170
9.3.1 Material 170
9.3.2 Welding 170
9.3.3 Fabrication 171
9.3.4 Inspection 171
9.3.5 Structure Coating 171
9.4 Concrete Structures 171
9.4.1 Reinforced Concrete 171
9.4.2 Prestressed Concrete Poles 172
9.4.3 Inspection 172
9.5 Wood Structures 172
9.5.1 Material and Treatment 172
9.5.2 Manufacturing and Fabrication 172
9.5.3 Inspection 172

9.6 Shipping 172
9.7 Handling and Storage 173
References 173

10. CONSTRUCTION, MAINTENANCE, AND TESTING 175
10.1 Construction 175
10.2 Maintenance 175
10.3 Worker Safety 176
10.4 Full-Scale Structural Proof Tests 176
References 177

11. RETROFIT OF EXISTING SUBSTATION INFRASTRUCTURES 179
11.1 General 179
11.2 Alternative Methods for Retrofit or Reinforcement of Substation Infrastructures 180
11.2.1 Types of Structures That May Require Reinforcement/Repair 180
11.2.2 Retrofit Methods 181
11.2.3 Methods of Anchorage Retrofit 183
11.2.4 Considerations When Retrofitting Steel Structures 183
11.2.5 Structure Finish and Its Consideration to the Retrofit Process 184
11.3 Environmental Concerns When Retrofitting Substations 185
11.3.1 Asbestos in Existing Substations 185
11.3.2 Demolition Activities 186
11.3.3 Renovation Activities 186
11.3.4 Soil Contamination in Existing Substations 186
11.4 Enhancing Security and Resilience of Electrical Substations 186
11.5 Retrofit Design Considerations 187
11.6 Installation 190
References 190

12. OIL CONTAINMENT AND BARRIER WALLS 191
12.1 General 191
12.2 Oil Containment 191
12.2.1 General 191
12.2.2 Containment Systems 192
12.2.3 Oil Retention Drainage 193
12.2.4 Design Considerations 193
12.3 Types of Barrier Walls 194
12.3.1 General 194
12.3.2 Firewalls 194
12.3.3 Sound Walls 195
12.3.4 Ballistic Walls and Blast Walls 195
References 196

APPENDIX A: EXAMPLES 199

APPENDIX B: SHORT-CIRCUIT FORCES 233

APPENDIX C: SEISMIC DESIGN PARAMETERS 245

APPENDIX D: DRAFT PRE-STANDARD SUBSTATION CIVIL/STRUCTURAL DESIGN STANDARD 249

INDEX 321

PREFACE

The Subcommittee on the Design of Substation Structures under the Committee on Electrical Transmission Structures from the Structural Engineering Institute of ASCE developed this Manual of Practice (MOP). The subcommittee membership represented utilities, manufacturers, consulting firms, and general interest. The combined expertise of the subcommittee members contributed to make this a valuable substation structure design guide for the utility industry.

The primary purpose of this MOP is to document electrical substation structural design practice and to provide guidance and recommendations for the design of outdoor electrical substation structures. This MOP covers a review of structure types and typical electrical equipment. Guidelines for analysis methods, structure loads, deflection criteria, member and connection design, structure testing, quality control, quality assurance, connections used in foundations, detailing, fabrication, construction, and maintenance issues are presented. This second edition also includes a chapter on foundation types used in substations. A chapter on retrofitting existing structures was included along with a chapter on oil containment and barrier walls. Appendix D is included as a draft prestandard to show what this MOP might look like if it were advanced to become a standard. In addition to Appendix D, Appendixes A, B, and C were added to cover various examples of structure design (Appendix A), a detailed explanation of short-circuit forces application to substation structures (Appendix B), and supplemental information on application of seismic forces as it applies to substation structures. The recommendations presented herein are based on the professional experience of the subcommittee members. Although the subject matter of this manual has been thoroughly researched, its application should be based on sound engineering judgment.

The subcommittee wishes to thank the peer review committee for their assistance and contributions to this document.

BLUE RIBBON PANEL REVIEWERS

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DEDICATION

Thomas A. Amundsen

This edition of the manual is dedicated to Thomas A. Amundsen. Tom provided 40 years of service to our industry and was instrumental in supporting, contributing, and mentoring this subcommittee's activities. His legacy lives on in this manual and with the engineers he developed, trained, and impacted over his life.

CHAPTER 1
INTRODUCTION

The purpose of this Manual of Practice (MOP) is to provide structural design guidance and a comprehensive resource for outdoor electrical substation structures and foundations. Engineers using this MOP may substitute or modify these recommendations on the basis of experience, research results, or test data. This MOP promotes the best utility practices for structural loads and design of electrical substation structures and acceptable electrical system performance. Electrical substations are an important component of the electrical system connecting the generation, overhead lines, and delivery points. The structure design loads provide an acceptably safe and reliable performance. This MOP uses the applicable ASCE 7-22 (ASCE 2022) wind, ice, and seismic loading in conjunction with overhead line tensions, and electrical clearances, as the basis of substation structure design. The application of these loads to substation structures is according to the procedures of this MOP.

The 113 committee has referenced many documents and included the specific year of publication where it was appropriate. As the various documents are revised, the reader should investigate what portion was changed and determine whether the changes impact the design of the substation structure. The term *latest edition* was avoided when referencing most documents.

Chapter 2, "Definitions, Electrical Equipment, and Structure Types," provides an overview of electrical equipment, identifies the various components and structure types, and describes structure configurations. With the exception of Chapter 11, "Retrofit of Existing Substation Infrastructure," the recommendations herein apply to new substation structures and foundations that support electrical equipment, rigid bus, and other conductors. Utilities should develop structure and foundation retrofit design criteria.

The electrical equipment supported by substation structures or foundations can be of significant weight, be subjected to substantial forces, and have attachments of porcelain or composite components. Guidelines for structural loads, deflection limits, analysis, design, foundations and anchorage, fabrication (quality assurance/quality control), maintenance, and construction of substation structures are presented. Oil containment and barrier walls are covered in Chapter 12, "Oil Containment and Barrier Walls." The structural loads and load combinations provided in this MOP can be regarded as minimum requirements. The selection of appropriate loads and load combinations for specific applications is the responsibility of the owner.

This MOP addresses steel, concrete, wood, aluminum, and porcelain or composite insulators used for the design of substation structures. Design equations are provided when references to existing structural design standards and codes (e.g., ACI, American Institute of Steel Construction, American Institute of Timber Construction, and ASCE) are not applicable.

Some figures (i.e., maps and graphs) are shown for information; the user of these figures can consult the original reference for more detail.

In the past, the utility industry has used both the allowable strength design (ASD) and ultimate strength design (USD) methods for substation structural design. ASD is a method of proportioning structural members such that elastically computed stresses produced in the members by nominal loads do not exceed specified allowable stresses. USD is a method of proportioning structural members such that the computed forces produced in the members by the factored loads do not exceed the member design strength [also called Load and Resistance Factor Design (LRFD)].

A significant issue discussed during the revision of this MOP was the direction it should take with respect to the design of substation structures using either ASD or USD concepts. It was decided that USD is the preferred approach for the structural analysis and design of structures. However, ASD may be used for foundation–soil interaction design if the limiting soil parameters are specified accordingly (e.g., allowable soil bearing pressure) and seismic qualification according to IEEE 693-2018 (Chapter 6, "Design," Section 6.5.5.2, "Allowable Strength Design according to IEEE 693"). In this MOP, the terms *ASD loads* and *service loads* are used interchangeably relative to deflection loading and foundation design.

Guidelines for the determination of substation structure loads for wind, ice, seismic forces, short circuit, line tensions, equipment reactions, operation, construction, maintenance, structure testing, and regulatory codes (e.g., IEEE 2023, PUC 2017) are provided in Chapter 3, "Loading Criteria for Substation Structures." The specific recommendations are based on structure type, such as dead-end structures, equipment, and bus supports. Recommended load factors and load combinations are presented.

The seismic load section complements IEEE 693 (IEEE 2018), which addresses the seismic design of electrical equipment and their supports (dedicated or intermediate supports). Dedicated supports are designed to exclusively support a single piece of equipment such as a pedestal for a current transformer (CT) or the concrete foundation under a power transformer. An intermediate support is a structural member or subassembly between the equipment and the primary substation structure (i.e., substation rack structure). This MOP references IEEE 693 (IEEE 2018) and provides seismic requirements for structures not covered by that reference.

Substation structures and the electrical equipment they support should be considered as a system. Excessive movement of structure supporting electrical equipment can cause the electrical equipment to experience mechanical damage, operational difficulties, and electrical faults. Recommended deflection limits and structure classes are defined in Chapter 4, "Deflection Criteria."

Analysis techniques and structural modeling concepts as they relate to substation structures are discussed in Chapter 5, "Method of Analysis." Both static and dynamic analyses are covered. Guidelines are given for selecting the appropriate analysis method for different structural behaviors, such as large versus small displacement theory, and nonlinear analysis.

Chapter 6, "Design," lists design standards for various materials of construction, and considerations for the design of rigid bus, insulators, base plates, structural connections, and other special considerations that include, but are not limited to, wind and seismic loading. This MOP, in general, notes only exceptions to these design standards and references other documents for the appropriate information.

The owner should designate each electrical installation (substation or circuit pathway) as either essential or nonessential based on its relative criticality to the power system. Installations of specific equipment designated as essential are those that are vital to power delivery and cannot be bypassed in the system or are undesirable to lose because of economic or operational

considerations. Essential items range from equipment to support structures. Equipment that can be bypassed for short-term emergency operations may be considered nonessential.

Foundation design is discussed in Chapter 7, "Foundations," which reviews the types of foundations that are commonly used to support substation equipment and structures and outlines the geotechnical, seismic, durability, and other considerations for foundation design. The design of substation structure anchorage connection to foundations is presented in Chapter 8, "Connections to Foundations." Many types of anchorages are used to connect substation structures to their foundations. The most common anchorage is anchor rods cast in reinforced concrete. This MOP provides design recommendations for this type of anchorage. Special design considerations for anchorages subjected to seismic loads are covered.

Guidelines for quality control and quality assurance programs for substation structures are presented in Chapter 9, "Quality Control and Quality Assurance." Recommendations on when it is appropriate to test a unique substation structure design concept or perform individual component testing are provided in Chapter 10, "Construction, Maintenance, and Testing." Requirements for seismic testing are covered in IEEE 693 (IEEE 2018). Chapters have been added to this revision to address the retrofit of existing substations (Chapter 11, "Retrofit of Existing Substation Infrastructure,") and oil containment and barrier walls (Chapter 12, "Oil Containment and Barrier Walls").

Appendix D has a substation design draft pre-standard that has been added to this edition. The ASCE Task Committee on Substation Structure Design envisions the need for a design standard for substation facilities. The appendix presents the recommendations of this committee written in a prescriptive form for review and comment.

REFERENCES

ASCE. 2022. *Minimum design loads and associated criteria for buildings and other structures.* ASCE 7-22. Reston, VA: ASCE.

IEEE (Institute of Electrical and Electronics Engineers). 2018. *Recommended practice for seismic design of substations*. IEEE 693-2018. Piscataway, NJ: IEEE.

IEEE. 2023. *National electrical safety code.* ANSI C2-2023. Piscataway, NJ: IEEE.

PUC (Public Utility Commission). 2017. *State of California rule for overhead electric line construction*. General Order 95. Sacramento, CA: Public Utility Commission.

CHAPTER 2

DEFINITIONS, ELECTRICAL EQUIPMENT, AND STRUCTURE TYPES

2.1 PURPOSE

Substation and switchyard structures are used to support above-grade components and electrical equipment such as cable bus, rigid bus, and strain bus conductors; switches; surge arresters; insulators; and others. Substation and switchyard structures can be fabricated from angles that form chords, trusses, and braced frames. Wide flanges, tubes (round, square, and rectangular), pipes, and polygonal tubes (straight or tapered) are also used in substation structures. The common materials that are utilized are concrete, steel, aluminum, and wood.

This chapter provides an overview of electrical equipment, identifies the various components and structure types, and describes structure configurations. Photographs of selected substation structures and equipment are also included in this section. The photographs are shown for reference and pictorial purposes only, and inclusion of any equipment is not meant to be an endorsement of any manufacturer. The structures shown are not necessarily representative of all engineering applications and support types to be utilized.

2.2 DEFINITIONS, SUBSTATION TYPES, AND COMPONENTS

2.2.1 Substation

Substations are commonly defined as facilities where power voltage or other characteristics of power are transformed, redirected, or to adjust power quality in the electric transmission system. Larger substations may contain control enclosures, transformers, interrupting and switching devices, and surge protection (Figure 2-1). A substation may include one or more step-up or step-down power transformers operating at multiple voltages. Voltages may be transformed for transmission or distribution purposes.

2.2.2 Switchyard or Switching Station

The term *switchyard* is typically applied to the assemblage of switches, power circuit breakers, bus, and auxiliary equipment that are used to redirect power from the generators of a power plant and distribute it to the transmission lines at various points. Switchyards do not include the use of power transformers to transform voltages. Most electrical substations