

Substation Structure Design Guide

**Recommended Practice for
Design and Use**

**ASCE Manuals and Reports on Engineering Practice
Volume 113**

Editor:

George T. Watson

ISBN: 978-1-7138-9334-9

Printed from e-media with permission by:

Curran Associates, Inc.
57 Morehouse Lane
Red Hook, NY 12571

Some format issues inherent in the e-media version may also appear in this print version.

Copyright© (2023) by American Society of Civil Engineers
All rights reserved.

Printed with permission by Curran Associates, Inc. (2024)

For permission requests, please contact American Society of Civil Engineers
at the address below.

American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, VA 20191
USA

Phone: (800) 548-2723
Fax: (703) 295-6333

www.asce.org

Additional copies of this publication are available from:

Curran Associates, Inc.
57 Morehouse Lane
Red Hook, NY 12571 USA
Phone: 845-758-0400
Fax: 845-758-2633
Email: curran@proceedings.com
Web: www.proceedings.com

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 Retrofiting 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