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FINAL REPORT

State of Practice and Literature Review on Foundations for Coastal Traffic Signal Mast Arm Structures

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16. Abstract

This report presents a state of practice and literature review study conducted as part of NCDOT Research Project RP 2018-17 on foundations for coastal mast arm traffic signal structures. The original scope of this project involved experimental and computation research on alternative foundation systems for support of coastal mast arm traffic signal structures in areas with high wind loads, limited right-of-way, and poor geotechnical conditions. However, at the request of the Steering and Implementation Committee (SIC) of this project, the focus was changed to entail a state of practice (SOP) study to document the foundation systems used by coastal departments of transportation to support coastal mast arm traffic signal structures. A total of 12 DOTs participated in this SOP study. The main objective of this SOP study was to document the predominant foundation systems used and identify any special foundation design practices used for mast arm traffic signal structures in coastal environments with high wind loads, small right-of-way, and poor geotechnical conditions.

The SOP study revealed that the most commonly used foundation system to support coastal traffic signal mast arm structures was a single conventional drilled shaft. Occasional use of a drilled shaft with wing walls was reported by NCDOT, VDOT, and ALDOT for structures with high torsional loading demand on the foundation. However, both VDOT and ALDOT reported that in recent years their practice was moving towards eliminating wing walls in the foundation design due to construction and installation difficulties. The SOP study also revealed large differences in the procedure for selecting wind speed and the associated foundation loading demand. These differences are attributed to variations in timelines for transitioning from allowable stress design (ASD) to load and resistance factor design (LRFD) as well as significant changes in the load factors and wind speed maps used in the design of mast arm traffic signal structures. These differences make the comparison of design practices between coastal DOTs challenging.

This report also includes a literature review that summarizes research on drilled shafts under the complex, multi-directional loading present in traffic signal mast arm structures. Specifically, the combined eccentric lateral and gravity loads on mast arm traffic signal structures lead to axial, shear, flexural, and torsional loads transferred to the mast arm foundation. The few experimental studies to date that have investigated the behavior of drilled shafts under these combined loads have highlighted significant reductions in lateral load capacity of drilled shafts when they are simultaneously subjected to torsion. However, all SOP participants use decoupled approaches for the design of drilled shafts supporting traffic signal mast arm structures that do not account for these interaction effects. The literature review also presents a summary of alternative foundation systems that have been proposed for supporting coastal mast arm traffic signal structures including driven post-grouted concrete piles, large driven pipe piles driven open or closed ended, and finned pipe piles.

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EXECUTIVE SUMMARY

This is the final report for NCDOT Research Project RP 2018-17 on foundations for coastal mast arm traffic signal structures. This report presents a summary state of practice and literature review on foundation systems for coastal mast arm traffic signal structures. The original scope of this project involved experimental and computation research on alternative foundation systems for the support of coastal mast arm traffic signal structures in areas with high wind loads, limited right-of-way, and poor geotechnical conditions. However, at the request of the Steering and Implementation Committee (SIC) of this project, the focus was changed to entail a state of practice (SOP) study to document the foundation systems used by coastal departments of transportation to support coastal mast arm traffic signal structures. The SOP study involved developing and administering a survey questionnaire that was distributed to all coastal U.S. Departments of Transportations. A total of 12 DOTs participated in this survey questionnaire. The main objective of this survey was to document the foundation systems used and any special foundation design practices used in the support of mast arm traffic signal structures in coastal environments that often involve exposure to high wind loads, small right-of-way, and poor geotechnical conditions. The survey was complemented with follow-up phone interviews with participation of NCDOT engineers from the geotechnical unit and also review of documentation provided by the transportation departments, including design aids, construction drawings and standards. This report presents a summary of the main findings of the SOP study related to the types of foundations used, design methodologies and procedures used, design wind loading used, and extent and scope of geotechnical investigation typically used for these structures in coastal environments.

The SOP study revealed that the most commonly used foundation system to support coastal mast arm traffic signal structures was a single conventional drilled shaft. Occasional use of a drilled shaft with wing walls was reported by NCDOT, VDOT, and ALDOT for structures with high torsional loading demand on the foundation. However, VDOT and ALDOT reported that in recent years their practice was moving towards eliminating the use of wing walls due to construction and installation difficulties. The SOP study also revealed large differences in the procedure for selecting wind speed and the associated foundation loading demand. These differences are attributed to variations in timelines for transitioning from allowable stress design (ASD) to load and resistance factor design (LRFD) as well as significant changes

in the load factors and wind speed maps used in the design of mast arm traffic signal structures. These differences make the comparison of design practices between coastal DOTs challenging.

At the request of the SIC, design practices between FDOT and NCDOT were compared. Personnel from the geotechnical unit of NCDOT were interested in identifying why current NCDOT design practice often requires the use of a drilled shaft with wing walls when a similar mast arm structure designed according to current FDOT practices in coastal Florida, with similar wind loading demand and mast arm dimensions used by NCDOT, would consist of a single drilled shaft without wingwalls. Therefore, this report also includes comparison examples suggested by the project SIC members from the NCDOT geotechnical unit. These comparison examples are presented in Chapter 4 based on a fictitious mast arm traffic signal structure in a coastal site designed using current NCDOT and FDOT procedures. The comparison is challenging due to the fact that, at the time of the study, NCDOT was still using ASD design practice and ASCE 7-05 wind speed maps, while FDOT had already fully adopted LRFD based design and ASCE 7-10 wind speed maps. Therefore, recognizing inherent differences between ASD and LRFD and the significant changes in the wind speed maps and associated load factors that occurred during the transition to ASCE 7-10, the comparison problems assumed that the same design wind speed of 170 mph applies to both agencies. However, it is acknowledged that the ASD nominal design wind speed for use with the 5th Edition AASHTO LTS would be lower by about 22% with respect to the LRFD-based ultimate design wind speed (ASCE 7-10). It is important to note that the design wind speed selection was not part of the scope of this study but is certainly is a critical factor in the design process of these foundation systems. The comparison problems revealed important differences in the design approach used by both agencies, particularly with respect to the mobilized unit side friction during torsion. NCDOT estimates the mobilized side friction based on the current 2010 FHWA drilled shaft manual, while FDOT uses a modified expression that is depth independent and yields unit side friction values about 40% to 100% higher than those predicted using the FHWA drilled shaft manual for embedment depths of 10 ft and 30 ft, respectively. Therefore, this difference alone results in shallower drilled shaft embedment depth requirements for FDOT designs.

This report also includes a literature review that summarizes research on drilled shafts under the complex, multi-directional loading present in mast arm traffic signal structures. Specifically, the combined eccentric lateral and gravity loads on mast arm traffic signal structures lead to axial, shear, flexural, and torsional loads transferred to the mast arm foundation. Most current design approaches adopt a decoupled approach for the analysis, where the failure loads are predicted separately for the axial loading, lateral loading, and torsional loading. However, experimental research has revealed that a significant reduction in lateral load capacity occurs when the drilled shaft is simultaneously subjected to torsion. However, the SOP study revealed that all participants use a decoupled approach for the design of drilled shafts supporting mast arm traffic signal structures that do not account for these interaction effects. The literature review also revealed an important gap in terms of static methods for predicting unit skin friction when the foundation is subjected to torsion loading combined with axial and bending forces. The current FHWA drilled shaft manual does not provide guidelines for skin friction for this loading case and the static methods used are based on experimental data from compression axial load tests. Finally, the literature review included a summary of some alternative foundation systems that have been proposed for supporting coastal traffic signal mast arm structures at sites with poor geotechnical conditions. For example, FDOT has reported investigating the feasibility of using driven post-grouted concrete piles, with the intent of the post-grouting along the shaft being able to enhance the torsion capacity. Other alternative foundation systems identified include large driven pipe piles that can be driven open or closed ended, and finned pipe piles.

TABLE OF CONTENTS

DISCLAIMER iii
ACKNOWLEDGMENTS..... iv
EXECUTIVE SUMMARY..... v
LIST OF FIGURES x
LIST OF TABLES xii
LIST OF ABREVIATIONS..... xiii
LIST OF SYMBOLS xiv
1. Introduction..... 1
2. State of practice study on foundations for coastal mast arm traffic signal structures..... 3
2.1. Introduction..... 3
2.2. Coastal state DOTs considered for this study 3
2.3. Methodology 4
2.4. Review of resources at each coastal DOT..... 4
2.5. Mast arm structures..... 4
2.6. Design wind speeds..... 6
2.7. Foundation types used for coastal traffic signal structures 8
2.8. Drilled shafts..... 11
2.8.1. Range of dimensions reported by SOP participants..... 11
2.8.2. Design procedures used by SOP participants..... 12
3. Failures or poor performance of coastal traffic signal mast arm structures..... 14
3.1. Introduction..... 14
3.2. Recent hurricanes in Southeast US 14
3.3. Reported failures or poor performance 14
4. Comparative design examples 16
4.1. Introduction..... 16
4.2. Drilled shaft embedment depths for design example using FDOT procedures 18
4.2.1. Embedment length requirements to resist lateral loading moment demand 19
4.2.2. Embedment length requirements to resist torsion loading demand 21
4.2.3. Summary of FDOT embedment depth results for comparison example..... 21
4.3. Drilled shaft embedment depths for design example using NCDOT procedures 21
4.3.1. NCDOT embedment length requirements to resist lateral loading moment..... 21
4.3.2. NCDOT embedment length requirements to resist torsion loading..... 25
4.3.3. Comparison of required lengths based on torsion loading..... 28

4.4. Comparison of minimum required embedment lengths for Comparison Example............. 30
4.4.1. Comparison of required lengths based on lateral loading 30
4.4.2. Comparison of required lengths based on torsion loading 31
5. Literature Review.. 34
5.1. Introduction 34
5.2. Performance of drilled shafts under combined lateral and torsional loading 34
5.2.1. Centrifuge tests at UF reported by Hu et al. (2006) 36
5.2.2. Full-scale torsion tests at silty clay test site Oregon State University....................... 39
5.2.3. Full-scale load tests of drilled shaft supported mast arms by UF research group 40
5.2.4. Unit skin friction for torsion capacity 41
5.3. Alternative foundation systems 43
5.4. Summary 44
6. Summary and conclusions 45
References 47
Appendix A – Websites used to compile design and construction information A-1
Appendix B – Tables with summary of survey questionnaire and follow-up conference .... ……..B-1
Appendix C- Summary of standard designs C-1
Appendix D – Copy of survey questionnaires responses from coastal DOTs D-1

LIST OF FIGURES

Figure 2-1: Map showing participants of SOP study. 3
Figure 2-2: Schematic of a typical mast arm structure. 5
Figure 2-3: Groundline loading demand for drilled shafts as a function of mast arm length. 5
Figure 2-4: Range of mast arm lengths reported by SOP participants. 6
Figure 2-5: Isotach wind speed map for continental USA by ASCE 7-05 (2009). 7
Figure 2-6: Summary map of maximum coastal wind speeds. 8
Figure 2-7: Examples design drawings for drilled shafts with wingwalls. 10
Figure 2-8: Micropiles and cap adapted from NCDOT (2012). 11
Figure 2-9: Range of dimensions of drilled shafts reported by SOP participants. 12
Figure 3-1: Mast arm failure in Fajardo, Puerto Rico – Hurricane Maria 2017 15
Figure 4-1: Mast arm structure and drilled shaft with soil profile used in comparison examples. 17
Figure 4-2: Soil reaction assumed by Broms (1964) for short single piles in sands. 19
Figure 4-3: Summary FDOT embedment depth results for comparison example (Case No. 1 Only). 21
Figure 4-4: Schematic showing pile model used in P-Y curve analyses of laterally loaded piles. 22
Figure 4-5: Typical Reese et al. (1974) p-y curve for laterally loaded piles in sands. 23
Figure 4-6: Summary FDOT embedment depth results for comparison example - Case No. 1. 28
Figure 4-7: Summary NCDOT embedment depths for comparison example – Load Case No. 2. 29
Figure 4-8: Summary NCDOT embedment depths for comparison example – Load Case No. 3. 30
Figure 4-9: Ratio of FDOT to NCDOT torsion side friction capacity as a function of depth. 32
Figure 5-1: Timeline showing selected research on drilled shafts under lateral and torsional loading. 35
Figure 5-2: Details of centrifuge model testing by Hu et al. (2006). 36
Figure 5-3: Predicted lateral load based on Broms (1964) versus experimental loads by Hu (2003). 37
Figure 5-4: Influence of torsion on lateral load capacity of drilled shafts (Hu et al., 2006). 36
Figure 5-5: Details of torsional load testing at the OSU test site by Li et al. (2017). 39
Figure 5-6 –Subsurface profile and field testing setup by Thiyyakkandi et al. (2016). 40
Figure 5-7: Reduction of lateral load capacity versus torsion loading level (Thiyyakkandi et al. 2016). 41
Figure 5-8: Photos of grouted precast pile reported by Thiyyakkandi et al. (2017).. 43
Figure 5-9: Photo of SPINFIN finned pipe pile (Image from PND Engineers). 44
Figure B-1: SOP summary of NCDOT B-2
Figure B-2: SOP summary of FDOT B-3
Figure B-3: SOP summary of MassDOT B-4
Figure B-4: SOP summary of VDOT B-5
Figure B-5: SOP summary of SCDOT B-6
Figure B-6: SOP summary of GDOT B-7
Figure B-7: SOP summary of ALDOT B-8
Figure B-8: SOP summary of MDOT B-9
Figure B-9: SOP summary of LaDOT B-10
Figure B-10: SOP summary of TxDOT B-11
Figure B-11: SOP summary of ODOT B-12
Figure B-12: SOP summary of WSDOT B-13
Figure C-1: Wind speed zone in North Carolina (NCDOT) C-2
Figure C-2: North Carolina embedment depth and diameter selection (NCDOT) C-3
Figure C-3: Standard Mast Arm Assemblies Document (FDOT 2016). C-4
Figure C-4: Lateral Moment Equation (FDOT 2016). C-4
Figure C-5: Spreadsheet of Florida DOT Drilled Shaft Dimensions (FDOT 2016). C-5
Figure C-6: Florida DOT Drilled Shaft Dimensions (FDOT 2016). C-6
Figure C-7: Florida DOT Drilled Shaft Dimensions (FDOT 2016). C-6
Figure C-8: Virginia Plan MP-3 Document (VDOT 2016a). C-7
Figure C-9: Virginia Plan PF-8 Document (VDOT 2016a) C-8
Figure C-10: TS-06 Standard Drawing Modify from (GDOT 2010). C-9

Figure C-11: Georgia Drilled Shafts Diameters (GDOT 2010). C-10
Figure C-12: Georgia reinforcement drilled shafts. (GDOT 2010). C-11
Figure C-13: Zones of Georgia Corresponding to geotechnical parameters (GDOT 2010). C-12
Figure C-14: MDOT Drilled Shaft Dimensions. C-13
Figure C-15: LaDOT signal foundation zone. C-14
Figure C-16: Foundation size selection table. C-14
Figure C-17: Texas Plan TS-FD-12 Document (TxDOT 2012). C-15
Figure C-18: Washington Plan J-26 Document (WSDOT 2018). C-16
Figure C-19: Washington Plan J-26 Document (WSDOT 2018). C-17

LIST OF TABLES

Table 2-1: Standards used for selection of design wind speeds for mast arm traffic signal structures......... 7
Table 2-2: Standards use by coastal states in the SOP.. 8
Table 2-3: Summary of design procedures for drilled shaft foundations... 13
Table 4-1: Comparison examples requested by SIC members of NCDOT RP2018-17 18
Table 4-2: Input parameters for p-y curves for comparison example 24
Table 4-3: Comparison of minimum embedment depths required to carry lateral load demand................ 31
Table 4-4: Comparison of minimum embedment depths required to carry torsional load demand............ 31
Table 5-1: Summary of test conditions considered by Hu et al. (2006)... 36
Table A-1: Websites used to compile design and construction information for each sop participant…...A-1

LIST OF ABBREVIATIONS	
NCDOT	North Carolina Department of Transportation
FDOT	Florida Department of Transportation
SCDOT	South Carolina Department of Transportation
VDOT	Virginia Department of Transportation
GDOT	Georgia Department of Transportation
ALDOT	Alabama Department of Transportation
MDOT	Mississippi Department of Transportation
LaDOT	Louisiana Department of Transportation
TxDOT	Texas Department of Transportation
WSDOT	Washington Department of Transportation
ODOT	Oregon Department of Transportation
MassDOT	Massachusetts Department of Transportation
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
AASHTO-LTS	AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals
LRFD	Load & Resistance Factor Design
ASD	Allowable Strength Design
mph	Miles per hour
MRI	Mean Recurrence Interval
DS	Drilled Shaft
SPT	Standard Penetration Test
TCP	Texas Cone Penetrometer
ft	Feet

LIST OF SYMBOLS	
β	Torsion beta side friction coefficient
Φ	Resistance factor in LRFD
ϕ'	Effective friction angle
γ	Total unit weight
γ_{sat}	Saturated unit weight
γ_w	Water unit weight
γ'	Effective unit weight
ω_{FDOT}	FDOT torsional side friction coefficient
c’	Effective cohesion
C_d	Drag coefficient
D	Diameter
f_S	Unit side friction
G	Gust effect factor
I_r	Wind importance factor
K_z	Height and exposure factor
K_d	Directionality factor
L	Embedment depth of drilled shaft
M	Moment
N_{60}	SPT blow counts for a hammer energy of 60%
Q_p	Pile weight
Q_s	Side resistance
Q_t	Tip resistance
Q_u	Ultimate capacity of drilled shafts (Bored Pile)
Su	Undrained shear strength
T	Torsion
V	Wind speed
W_p	Wind pressure

1. Introduction

This final report for NCDOT Research Project RP 2018-17 on foundations for coastal mast arm traffic signal structures entails a state of practice study and a literature review. Specifically, this report summarizes the findings of a survey questionnaire followed up with phone interviews to 12 coastal U.S Departments of Transportation to document their practices related to foundation systems used for the support of mast arm traffic signal structures. The focus included type of foundations, design methodologies and procedures, wind loading, and typical geotechnical investigations used for these projects in coastal environments. The focus was on structures located in coastal regions with poor geotechnical ground conditions (low average SPT blow counts and high ground water table) and exposed to high wind speeds. The SOP compiled information regarding the following aspects:

- Mast arm structure dimensions,
- Design wind speeds and associated design codes,
- Foundation systems used (including range of dimensions).
- Level of geotechnical investigation typically required by the state DOT,
- Typical design and contractual procedures,
- Review of state design standards and designs aids (e.g. spreadsheets, Mathcad),
- Information regarding possible total or partial failures, or poor performance, of any coastal mast arm structures (including foundations).

The SOP is presented in Chapter 2 and key relevant information compiled during the survey and phone interviews is presented in Appendices A, B, C and D.

This report also includes a literature review (See Chapter 5) that focused on topics relevant to the ongoing NCDOT RP 2018-17. Topics investigated include:

- Laterally loaded piles: Methods and accuracy of predicting failure loads,
- Torsion loading on piles: Methods and accuracy of predicting failure loads,
- Combined lateral and torsion loading: Methods and accuracy of predicting failure loads,
- Experimental research on drilled shafts subjected to combined lateral and torsion loadings:
    - Centrifuge tests,
    - Full-scale tests,
- Alternative foundations systems.

This report is organized in 6 chapters and 4 appendices. In addition to this introduction chapter, Chapters 2 and 3 describe and summarize the findings of the state of practice study. Chapter 2 presents the methodology and a summary of the results, while Chapter 3 includes a summary of the reported failures, or poor performance, of coastal traffic signal mast arm structures reported by the SOP participants. Chapter 4 presents an illustrative design example to compare current design used by NCDOT procedures and assumptions to those used by FDOT for a fictitious mast arm traffic signal structure under the same design conditions (i.e. wind speed and geotechnical conditions). Chapter 5 presents the findings of the literature review, and Chapter 6 provides a summary and conclusions.

2. State of practice study on foundations for coastal mast arm traffic signal structures

2.1. Introduction

This chapter presents a summary of a state of practice (SOP) study carried out to compare design and construction practices related to foundation systems for coastal mast arm traffic signal structures. The following subsections present a synthesis of the compiled information related to: range of mast arm structures, foundation systems used and identification of the most popular system used in each state, range of dimensions (embedment depth and diameter) for drilled shaft foundations, and a summary of the design approach used to consider combined lateral and torsion loading. The survey questionnaire used is presented in Appendix B and the responses received by the participants is included in Appendix C.

2.2. Coastal state DOTs considered for this study

The survey questionnaire was completed by the 12 coastal DOTs shown in Figure 2-1.

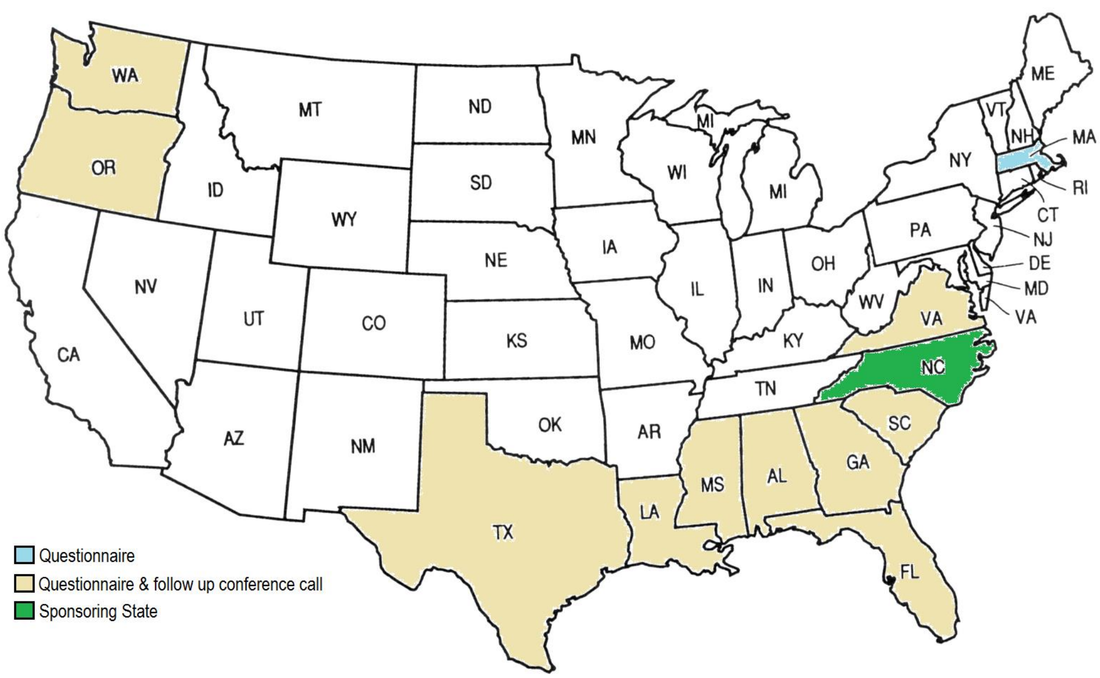


Figure 2-1: Map showing participants of SOP study.

2.3. Methodology

The methodology followed in this SOP study consisted of the following steps:

a. Review of online information (manuals, design drawings, etc.), as well as review of available online design resources (e.g. spreadsheets, software) of each DOT,

b. Design of a survey questionnaire to collect information not readily available online,

c. Distribution of survey questionnaire to participants,

d. Compilation of survey responses,

e. Progress meeting on July 2018 with members of Steering and Implementation Committee (SIC) of NCDOT to provide an update on the SOP synthesis and survey responses received to date, as well as to receive feedback. This meeting resulted in some modifications to the survey and the addition of follow-up conference calls to respondents,

f. Follow-up conference calls to survey respondents (performed between July to October 2018),

g. Compilation of survey questionnaire results and information compiled during follow-up conference calls,

h. Presentation and delivery of SOP Report (Draft version presented to NCDOT on January 2019).

2.4. Review of resources at each coastal DOT

Most SOP participants have design drawings, guidelines, and design aids that are publicly accessible on the internet. A summary of the websites addresses that were used in this SOP study are listed in Appendix A. A summary of the different design standards can be found in Appendix C.

2.5. Mast arm structures

A schematic of a representative mast arm is shown in Figure 2-2. The loading demand on the foundation systems used to support coastal mast arm traffic signal structures is affected not only by the wind speed, but also the dimensions of the mast arm structure. Therefore, the SOP study included compilation of dimensions for these structures (e.g. height, length, base diameter, etc.). For the purposes of this research project, the key dimensions examined were the mast arm length and the pole height as they were considered to have the most influence on the resulting loads transmitted to the foundation.

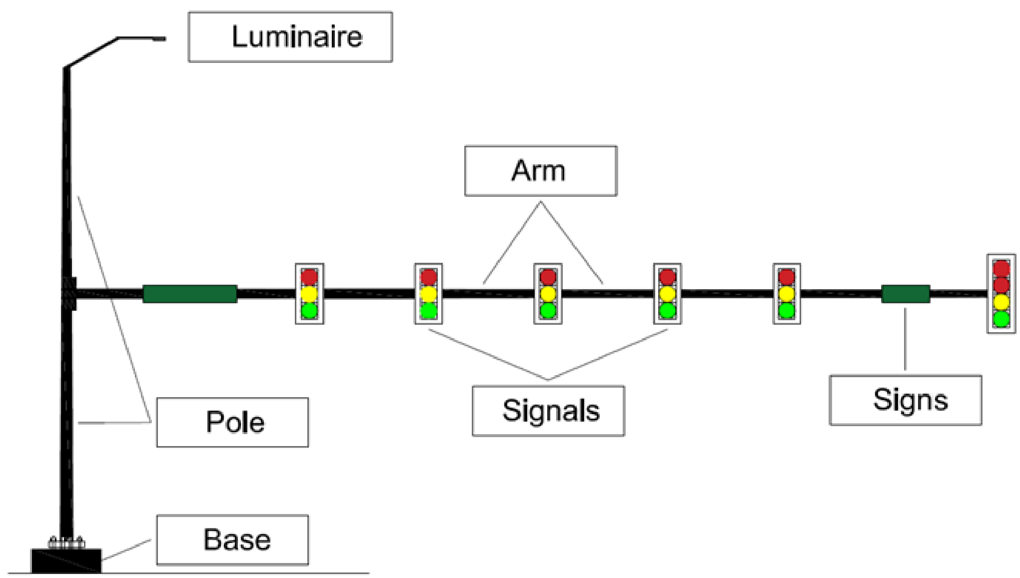
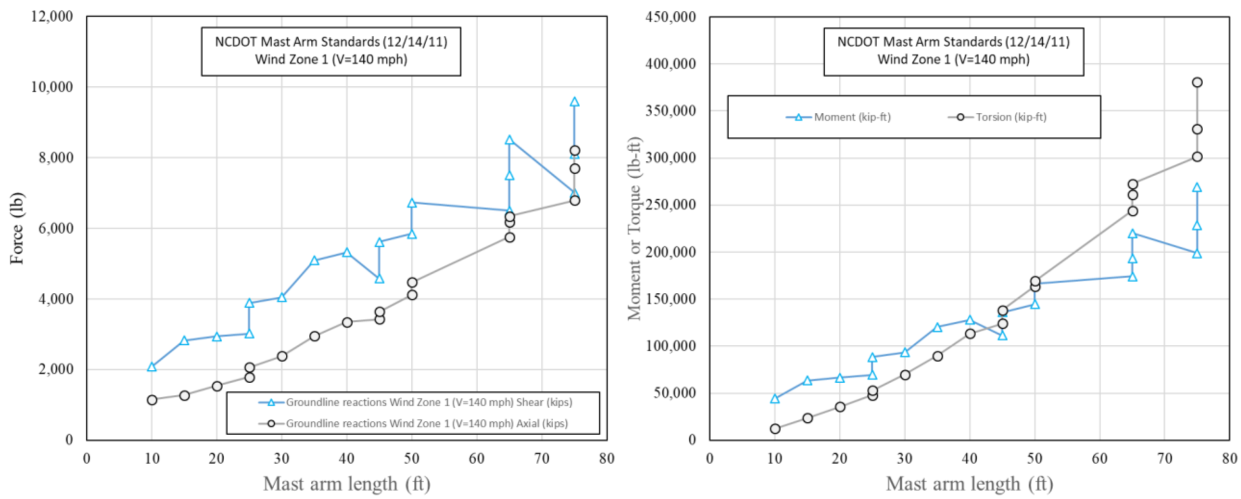


Figure 2-2: Schematic of a typical mast arm structure.

The dimensions for commonly-used mast arms vary greatly from state to state. For example, in North Carolina, based on the NCDOT Mast Arm Standards (NCDOT ITS document dated 12/14/11), the maximum pole height is 26 feet, the mast arm lengths range from 10 to 75 feet, and the diameter of the pole base ranges from 12 to 26 inches. The range of reaction loads (shear load, moment, and torque) reported by this NCDOT standard for a mast arm traffic signal structure built within NCDOT Wind Zone No. 1 (i.e. a design wind speed of V=140 mph) is shown in Figure 2-3. This figure illustrates the influence of the mast arm length on the loading demand for the foundation system.



Note: Reaction values based on NCDOT Mast Arm Standard (12/14/11).

Figure 2-3: Groundline loading demand for drilled shafts as a function of mast arm length.

The range of mast arm lengths reported by the SOP survey participants are summarized in Figure 2-4.

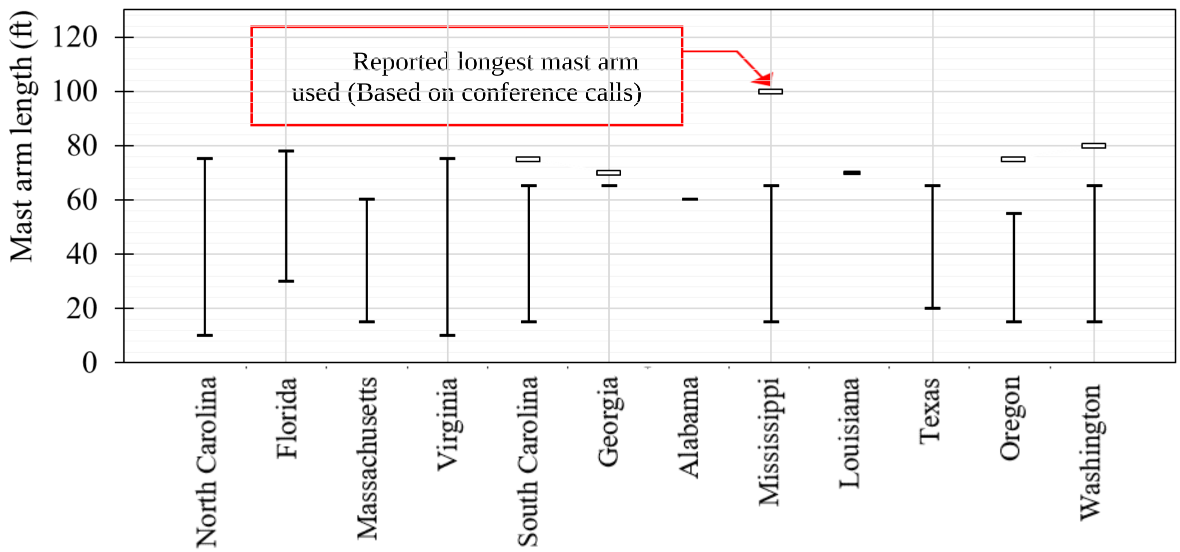
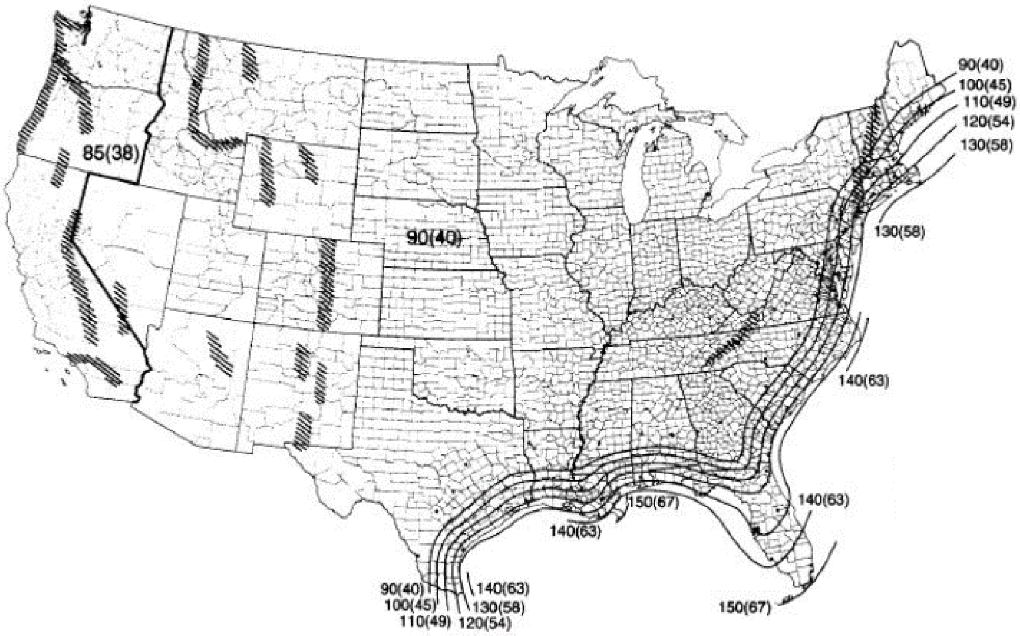


Figure 2-4: Range of mast arm lengths reported by SOP participants.

2.6. Design wind speeds

The loading demand on the foundation system is greatly influenced by the design wind speed. A review of design wind speeds is not part of the scope of this study, but a summary of the design wind speeds used by the different state DOTs was included as part of the SOP study. Therefore, the SOP requested participants to indicate the version of the wind speed maps currently being used as well as the edition of the ASCE 7 guidelines that are related to Minimum Design Loads and Associated Criteria for Buildings and Other Structures. Most state DOTs obtain design wind speeds from isotach wind zone maps, such as the one shown in Figure 2-5. This figure shows that the design wind speed values vary based on the geographic location of the structure. Wind speed maps like this one have been periodically updated by ASCE such as ASCE 7-93, 7-98, 7-05, 7-10, and 7-16. The wind speed maps included in these different ASCE versions look similar but have important differences. One important difference is that ASCE 7-05 and earlier versions were ASD-based maps and in 2010, starting with ASCE 7-10, the load factors changed, and the wind speed maps were based on risk category. The periodic updating of wind maps is a challenge for many state DOT agencies, since this requires consistent revision and updating of design standards, often with limited personnel or resources.



Note: Contours are labeled with wind speed values in mph.

Figure 2-5: Isotach wind speed map for continental USA by ASCE 7-05 (2009).

A summary of the AASHTO specifications, design wind speed source, and design philosophy, used by the SOP participants for design of mast arm structures is presented in Table 2-1.

Table 2-1: Standards used for selection of design wind speeds for mast arm traffic signal structures

AASHTO Standard	Year (Edition)	Wind Map Source	Comments
LTS 3	1994 (3rd Ed)	ASCE 7-93	ASD. Wind map based on wind speed at 10m elevation. 3-s gust.
LTS 4	2001 (4th Ed)	ASCE 7-98	ASD. Wind map based on wind speed at 10m elevation. 3-s gust.
LTS 5	2009 (5th Ed)	ASCE 7-05	ASD. Wind map based on wind speed at 10m elevation. 3-s gust.
LTS 6	2013 (6th Ed)	ASCE 7-10	ASD. Wind map based on wind speed at 10m elevation. 3-s gust.
LRFDLTS 1	2015 (1st Ed)	ASCE 7-10	LRFD. Design wind map depends on risk level defined by MRI. Wind maps based on 3-s gust at 10m elevation

Notes: LTS: AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals. ASD: Allowable stress design; LRFD: Load and Resistance Factor Design; MRI: Mean Recurrence Interval; LRFDLTS: AASHTO LRFD Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals.

The standards used by each state considered in this report are summarized in Table 2-2.

Table 2-2: Standards use by coastal states in the SOP

AASHTO LTS	State
LTS 3-1994	Texas, Alabama, Georgia
LTS 4-2001	Oregon, Mississippi,
LTS 5-2009	Louisiana, North Carolina
LTS 6-2013	South Carolina, Virginia, and Massachusetts
LRFDLTS 1-2015	Florida and Washington

Figure 2-6 shows a map summarizing the maximum coastal wind speed reported by the SOP participants. This figure also reports the current design standard being used by the participants for the design of coastal mast arm structures. Several participants indicated that foundation design for mast arm traffic signal structures had not yet been updated to the latest AASHTO standards due to personnel or other limitations. By contrast, most SOP participants reported having structural design standards updated to comply with the latest AASHTO edition. Figure 2-6 also shows the maximum mast arm length used by each DOT.

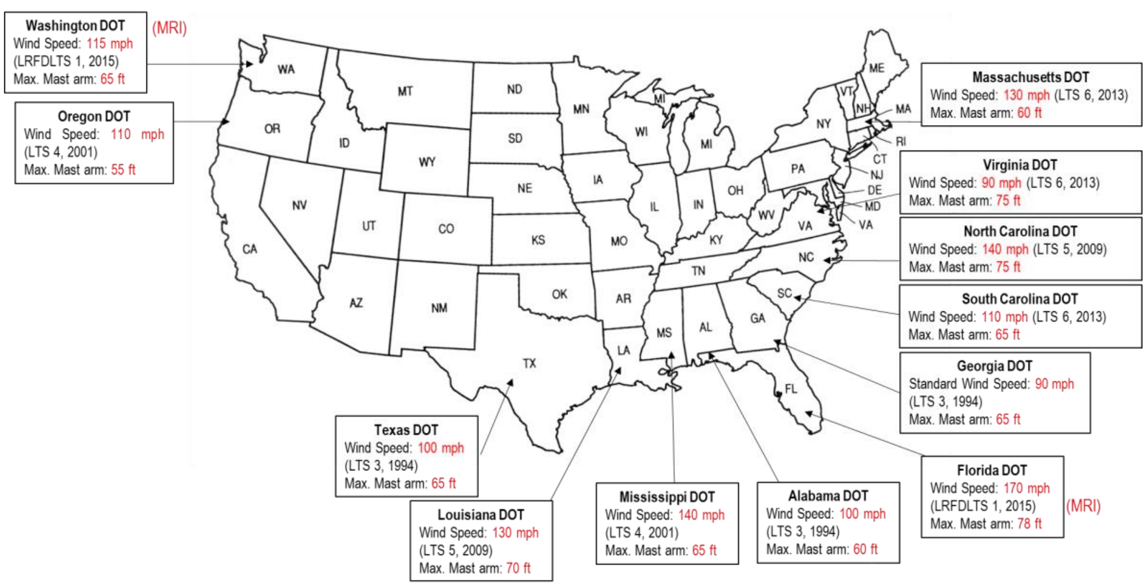


Figure 2-6: Summary map of maximum coastal wind speeds.

2.7. Foundation types used for coastal traffic signal structures

The most popular foundation system used by coastal DOTs for supporting coastal mast arm traffic signal structures is the drilled shaft. All 12 SOP respondents indicated that drilled shafts are the main foundation system used to support these structures. Occasional use of spread footings was also reported by Massachusetts, South Carolina, Oregon, Texas, and Alabama. Spread footings were used only for projects with small mast arms located at sites with competent soil conditions.

For sites with poor geotechnical conditions (e.g. low SPT blow counts and high water table), the states of North Carolina, Virginia and Louisiana reported using drilled shafts with wingwalls. This foundation system features a conventional drilled shaft integrated with two reinforced concrete walls, were the steel reinforcement in the wingwalls is tied to the drilled shaft, as shown in Figure 2-7. The wingwalls are typically installed in the upper 3 to 6 feet of the drilled shaft, with the main purpose being to increase the torsional capacity of the foundation. Virginia and Louisiana indicated they are abandoning use of wingwalls due to constructability issues.

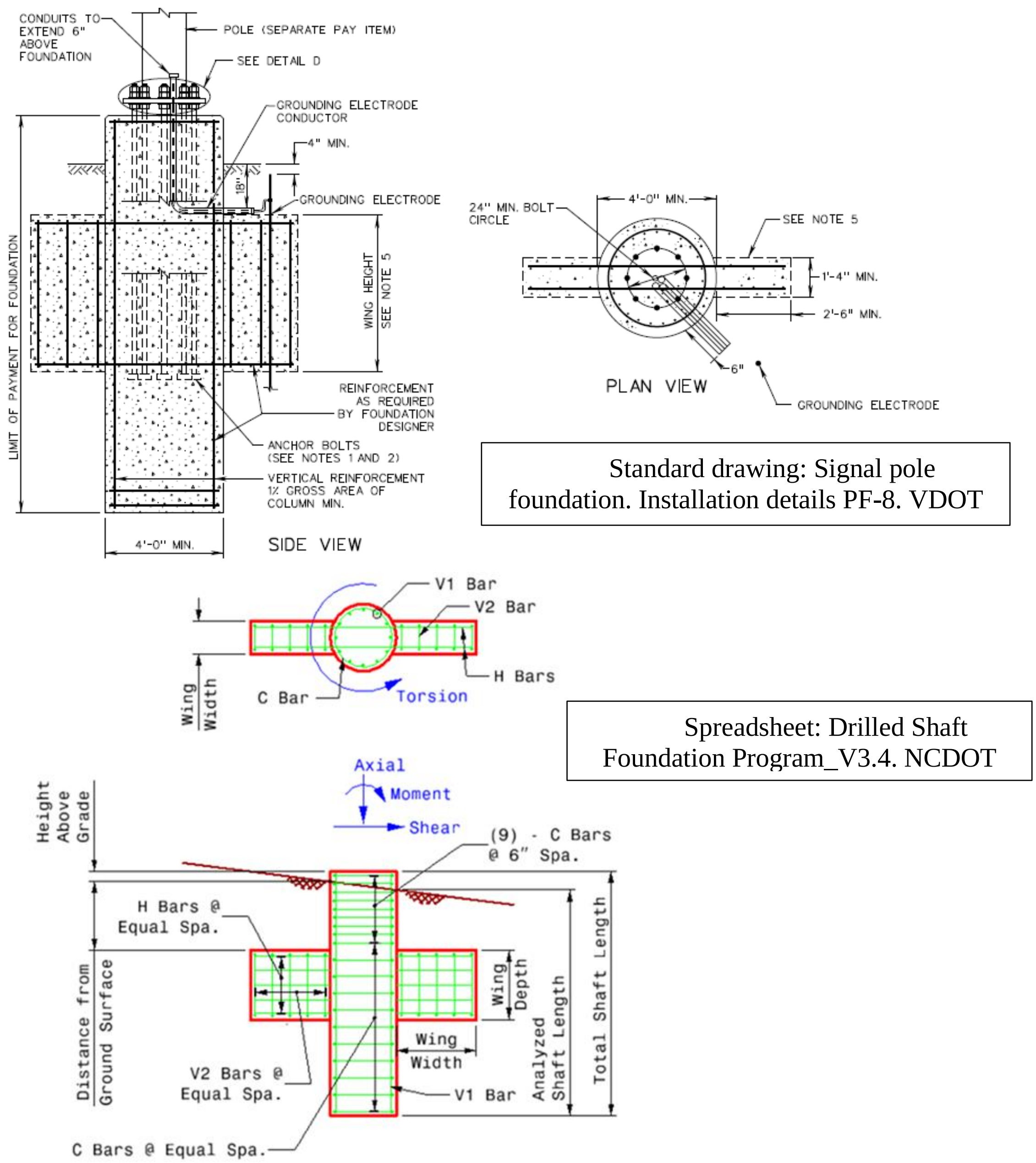


Figure 2-7: Example design drawings for a drilled shaft with wingwalls.

NCDOT and WSDOT reported using a foundation system consisting of a group of micropiles with a pile cap for sites with very poor geotechnical conditions (e.g., SPT N $\leq$ 4). However, this type of solution usually requires a project-specific design. Figure 2-8 shows design drawings used by NCDOT for a specific coastal project.

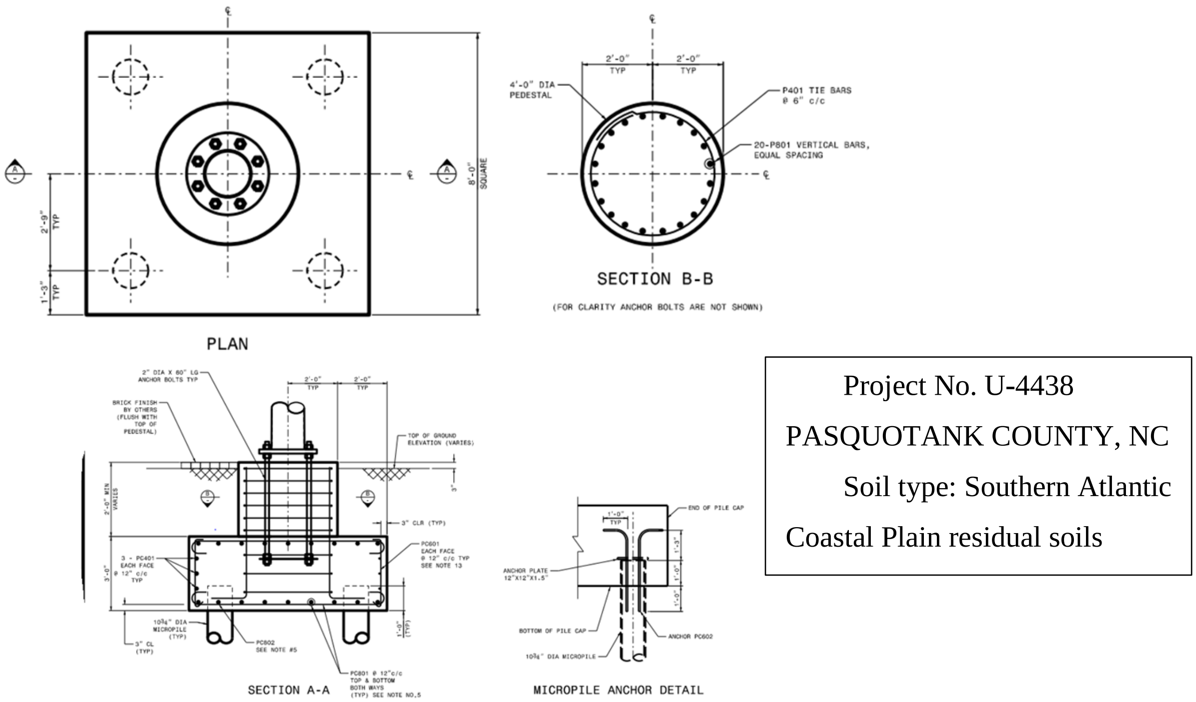


Figure 2-8: Micropiles and cap adapted from (NCDOT 2012)

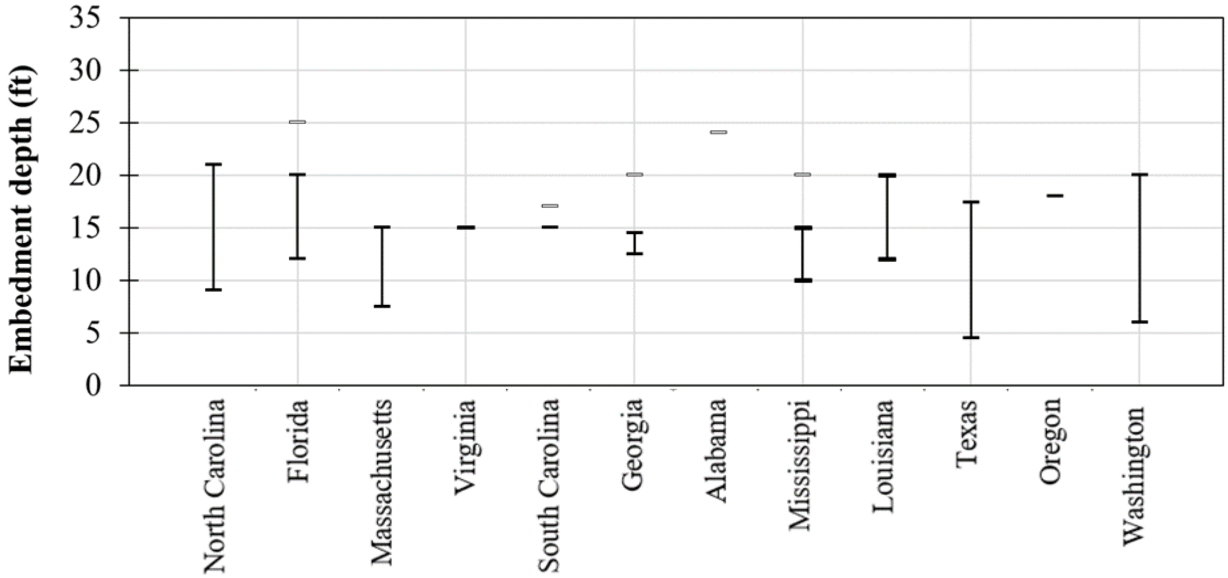
2.8. Drilled shafts

Again, SOP survey responses confirmed that drilled shafts are the most common foundation system used by participants for supporting mast arm traffic signal structures. This section summarizes dimensions and design procedures used across the states included in this study.

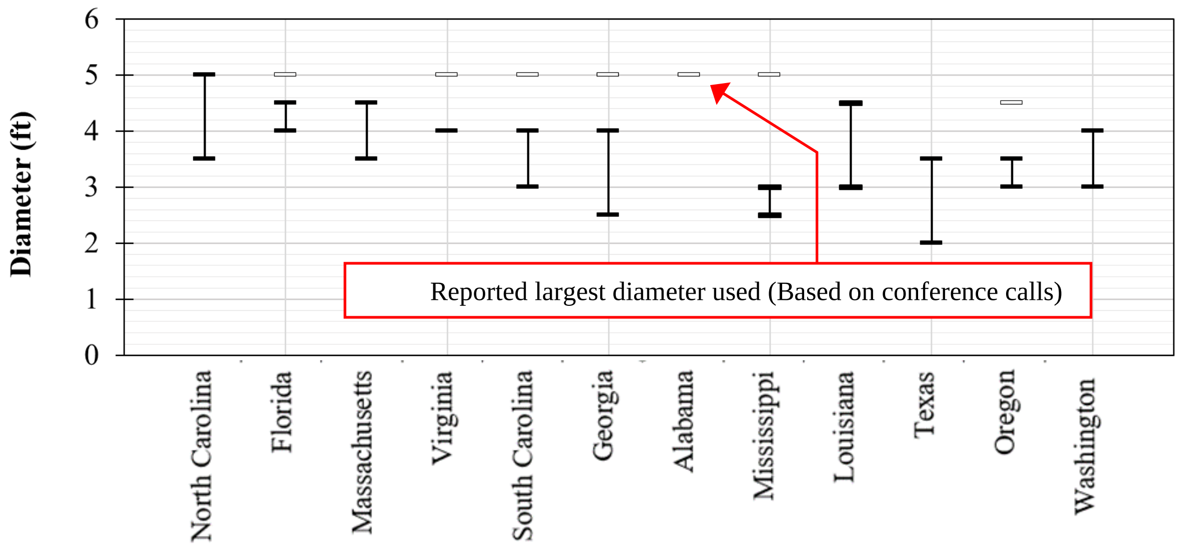
2.8.1. Range of dimensions reported by SOP participants

As discussed earlier, the dimensions of drilled shaft foundations depend on the loading demand dictated by mast arm dimensions (primarily mast arm length), pole height and design wind speed. The dimensions will also greatly depend on the geotechnical conditions of the site. Most DOTs use the Standard Penetration Test (SPT) as the primary field test to characterize geotechnical conditions at sites of mast arm traffic signal structures. The range of embedment depths and diameters reported by the SOP participants are summarized in Figure 2-9.

From this figure, it can be seen that the embedment depth of drilled shafts used in NCDOT projects ranges from 9 to 21 ft. and of diameters range from 3.5 to 5 ft. These values are similar to those reported by FDOT, which uses mast arms of similar dimensions and has a similar design wind speed. FDOT reported embedment lengths between 12 and 20 ft. (with the deepest installation being 25 ft) and drilled shaft dimeters typically between 4 and 4.5 ft.



a) Embedment depth



b) Diameter

Figure 2-9: Range of dimensions of drilled shafts reported by SOP participants.

2.8.2. Design procedures used by SOP participants

As mentioned before, the loading demand on foundation systems of mast arm traffic signal structures involves combined lateral loading (producing shear and bending moment) and torsion. However, all SOP participants reported analyzing the problem using a decoupled approach where the effects of the lateral loading are considered separately from the torsional loading. Table 2-3shows a summary of the design procedures used by the different DOTs to analyze the two loading conditions. For lateral loading the ultimate load calculated by Broms (1964a, 1964b, 1965) is used by many DOTs. The other approach is to analyze the drilled shaft using non-linear p-y curves and a software such as L-Pile (Ensoft, 2016).

Table 2-3: Summary of design procedures for drilled shaft foundations.

STATE	**Lateral Loading and Bending**			**Torsion Loading**		**Torsion is considered coupled with bending or separately**
	Broms	**L-Pile**	**Other**	**Skin**	**Other**	
WSDOT	x				(1)	Separately
ODOT		x		(2)		Separately
TxDOT	x	x	(3)			Separately
LA DOT		x	Ensoft Shaft	(2)		Separately
MDOT	x	x		(2)		Separately
ALDOT		x		(2)		Separately
FDOT	x			(4)		Separately
GDOT	x	x		(2)		Separately
SCDOT		x		(2)		Separately
NCDOT		x		(2)		Separately
VDOT	x	x	COM624P	(2)		Separately
MADOT	x					Separately

Notes: (1): Washington Bridge design manual. (2): β-method or α-method (FHWA, 2010).
(3): Texas cone penetrometer (FHWA, 2010). (4): FDOT uses a modified β-method that removes depth dependency.

3. Failures or poor performance of coastal traffic signal mast arm structures

3.1. Introduction

This section presents a summary of reported failures or poor performance of coastal traffic signal mast arms. This information is presented separately in its own chapter to highlight the relative low percentage of reported failures, or poor performance, of these structures and their foundations. This low rate of reported failures is despite the generally high prevalence of hurricanes in the geographical areas of the SOP participants.

3.2. Recent hurricanes in Southeast US

Since 2000, 32 hurricanes have affected the jurisdictions of the coastal DOT participants of the SOP study. This time span includes hurricane Lili in 2002 that affected LaDOT to Michael in 2018 that affected Florida and Georgia. The wind speed intensities reported for the different hurricanes ranged from Category 2 to 5, so in most states the demand on the coastal traffic signal structures may not have corresponded to the full design wind loads.

3.3. Reported failures or poor performance

All SOP participants have indicated that performance of coastal traffic signal mast arm structures (and foundations) has been satisfactory. Only Mississippi (MDOT) reported one failure of the foundation of a coastal traffic signal mast arm, located at an intersection in the city of Biloxi, Mississippi, that happened during hurricane Katrina in 2005. This failure involved a mast arm with a length of 65 feet failing in torsion by rotating approximately 90 degrees. Based on available information for hurricane Katrina (Babour, 2006), the wind speed is estimated to have been approximately 120 mph at the site of the traffic signal. The MDOT personnel interviewed as part of the SOP study indicated that the mast arm structure was simply rotated to its original orientation to rerun it to service without any major repairs required.

Even though the Puerto Rico DOT was not part of this SOP study, it is reported that Hurricane Maria caused a large mast arm rotation in the area of Fajardo. The mast arm was located in the intersection of PR-194 with PR-53 and experienced a rotation of almost 180°. Figure 3-1 contains pictures provided by Dr. Losif Szabo on September 27, 2017. Hurricane Maria (September 2017), a Category 5 storm, had maximum sustained winds of 175 mph.

Mast arm before Hurricane

Elevation of mast arm rotation

Plan view: estimated rotation

Figure 3-1: Mast arm failure in Fajardo, Puerto Rico – Hurricane Maria 2017

4. Comparative design examples

4.1. Introduction

This chapter presents a series of comparison design examples involving a fictitious mast arm traffic signal structure. This task was added to the original scope of the research project at the request of members of the Steering and Implementation Committee (SIC) from the NCDOT Geotechnical Engineering Unit. These analyses were requested after the findings of the SOP study for this research project were reported. It is our understanding that the request for these analyses was motivated by the observed or perceived differences in drilled shaft dimensions for similar mast arm coastal structures used in other states relative to those used in North Carolina. The members of the SIC from the Geotechnical Engineering Unit were specifically interested in comparing the dimensions of the supporting drilled shaft foundations to the same fictitious support mast arm traffic signal structures designed using the procedures reported to be used by FDOT and NCDOT. Initially, the fictitious example assumed the same structural geometry, geotechnical soil conditions, and wind exposure. The scope was later expanded to include two additional loading conditions for the NCDOT design cases.

The mast arm geometry and soil conditions assumed for the fictitious example, as requested by SIC members of the research project, are shown in Figure 4-1. The mast arm height and length are 21 and 70 feet, respectively. As shown in this figure, the mast arm includes 6 traffic signals and several signs. Additionally, the SIC members requested that the analyses be performed for a site with poor geotechnical conditions consisting of a homogeneous, loose, saturated sand with the groundwater table at the ground surface and the unit weight and average SPT blow count shown in Figure 4-1. The objective of the initial analysis requested by the SIC was to compare required embedment lengths for drilled shafts with diameters of 4, 4.5, and 5 ft for a wind speed of 170 mph. The UNC Charlotte researchers agreed to this request, noting however that the nature of the requested analysis did not account for differences in wind speed maps and design philosophies used by FDOT and NCDOT at the time of the SOP. At the time of the SOP report, NCDOT was using the 5th edition AASHTO-LTS specifications, which utilize the ASD design philosophy and wind speeds sourced from ASCE 7-05. In contrast, FDOT was using the 1st edition of the AASHTO LRFDLTS specifications, which utilize the LRFD design philosophy and wind speed sourced from ASCE 7-10. The ASCE 7-10 release introduced significant changes in how wind loads are calculated. The load factors for wind were significantly revised and, correspondingly, the wind speed maps were updated to reflect this change as well as introduce separate wind speeds for different risk categories. For the initial comparative analysis, it was requested that the same basic wind speed of 170 mph be used in designing the foundation according to both the NCDOT and FDOT procedures. This simplification may be useful for initial comparison purposes, but it is important to point out that the equivalent nominal wind speed for ASD-based design using the 5th Edition AASHTO LTS would be about 22% lower than the LRFD-based ultimate wind speed. The selected design wind speeds for the comparison examples were provided by the SIC members from the NCDOT Geotechnical Engineering Unit. Furthermore, a detailed evaluation or discussion on the differences of wind speed selection was not part of the scope of this study, although it is evident that it is a key factor in the design process for foundation systems of coastal mast arm traffic signal structures.

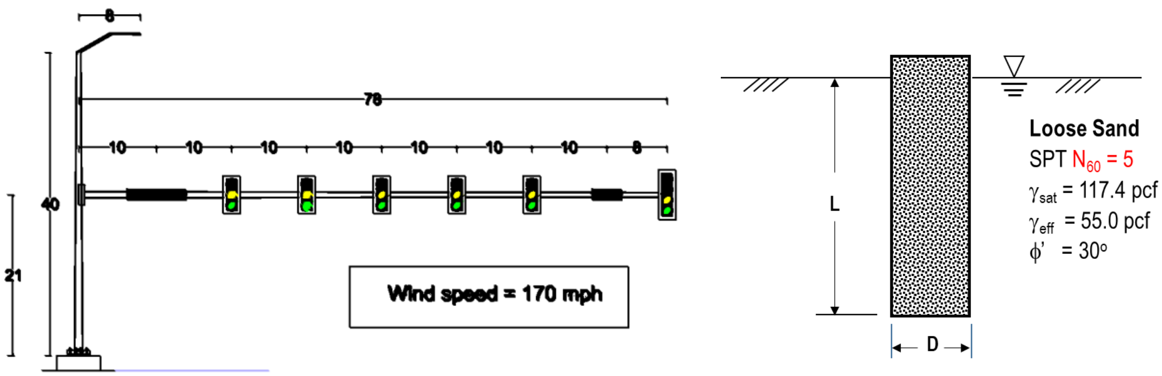


Figure 4-1: Mast arm structure and drilled shaft with soil profile used in comparison examples.

After a draft report was submitted to the NCDOT SIC, a request was received to expand the comparison problem to include two additional analyses with the NCDOT design procedures at a reduced wind speed. Table 4-1 summarizes the three comparison examples requested by NCDOT. This table provides information on the geometry of the mast arm structure, the geotechnical condition considered when estimating the load capacity of the drilled shaft, the loading demand for the different cases, and other information as per instructions provided by the SIC. It should be noted that the loading demand for the examples using the NCDOT design procedures were provided by Mr. Kevin Durigon, P.E. from the NCDOT ITS and Signals Unit.

Table 4-1: Comparison examples requested by SIC members of NCDOT RP2018-17

DOT	Element	ID of Comparison Example Case		
		Load Case No. 1	**Load Case No. 2**	**Load Case No. 3**
Information common for all design example cases (i.e., to FDOT and NCDOT)	Mast arm geometry	Figure 4-1	Figure 4-1	Figure 4-1
	Mast arm length	70 ft	70 ft	70 ft
	Mast arm height	21 ft	21 ft	21 ft
	Drilled shaft diameters	D = 4, 4.5, and 5 ft	D = 4, 4.5, and 5 ft	D = 4, 4.5, and 5 ft
	Soil conditions	Saturated, loose sand (Figure 4-1)	Saturated, loose sand (Figure 4-1)	Saturated, loose sand (Figure 4-1)
FDOT	Wind speed	170 MPH		
	Design Specification for loads	AASHTO-LRFD LRFDLTS-1 (3)		
	Type of analysis	LRFD		
	Axial load	Neglected		
	Lateral load (shear) (1)	18.1		
	Bending moment (1)	436.6		
	Torsion (factored)	496.9 kip-ft		
NCDOT (Loads provided by Kevin Durigon, PE (2) of NCDOT)	Wind Speed	170 MPH	100 MPH	100 MPH
	Design Specification	AASHTO LTS-5 (2009)	AASHTO LTS-5 (2009) (4)	AASHTO LTS-4 (1994) (6)
	Type of analysis	ASD	ASD	ASD
	Axial load	5.26 kip	5.3 kip	3.8 kip
	Lateral load (Shear) (1)	12.3 kip	4.4 kip	8.7 kip
	Bending moment (1)	307.6 kip-ft	172.3 kip-ft	224.3 kip-ft
	Torsion	468.9 kip-ft	165.7 kip-ft (5)	302..4 kip-ft

Notes: (1): Lateral shear load and bending moment are factored groundline reactions, i.e., at top of drilled shaft.
(2): Loads for NCDOT provided by Mr. Kevin Durigon, PE (Cases 2 & 3 via email on August 23, 2019).
(3): Loads for FDOT cases based on AASHTO- LRFDLTS-1 and FDOT's spreadsheet Mastarm-Index17743-v1.1.
(4): Loads based on Method 3-second gust wind speed (100 mph wind speed from ASCE 7-05).
(5): Torsion loads based on ASCE 7-05.
(6): Loads based on fastest-mile wind speed (100 mph wind speed from ASCE 7-93, Group II).

4.2. Drilled shaft embedment depths for design example using FDOT procedures

4.2.1. Embedment length requirements to resist lateral loading moment demand

For the lateral load and bending moment loading demand, FDOT reported in the SOP that they use the Broms (1964a and b) ultimate load method for single piles. The assumed soil reaction along a single pile installed in a uniform sand deposit at geotechnical failure (i.e., Broms' short pile type failure) is shown in Figure 4-2.

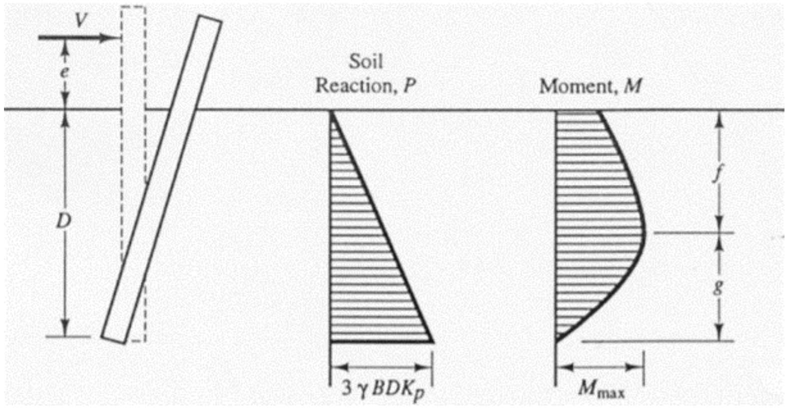


Figure 4-2: Soil reaction assumed by Broms (1964) for short single piles in sands.

Based on the Broms methodology used by FDOT, the resisting moment for a given drilled shaft diameter can be computed for different drilled shaft embedment depths until the factored resisting moment at the groundline (using a resistance load factor ϕ=0.5) is found to be equal to, or just greater, than the factored bending moment demand listed in Table 4-1 (Note FDOT methodology was only performed for Case 1). To resist the lateral load and bending moment demands listed in Table 4-1, the computed required embedment lengths for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft using the FDOT design process were 15.1 ft, 14.5 ft, and 14 ft for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively.

4.2.2. Embedment length requirements to resist torsion loading demand

The design approach used by FDOT that was reported to the SOP is described in their structural manual (Section 13 of Volume 3) that is a based on AASHTO LRFDLTS-1 (2015), but with their unique modifications as described in FDOT (2017, 2018, and 2019). One important modification is that the methodology used by FDOT to compute the torsional capacity of a single drilled shaft, as reported in the SOP, is based on computing the side friction (f_s) using a modified beta method as follows:

$$f_s = \omega_{FDOT} \cdot \sigma'_v \quad (4.1)$$

where σ'_v is the effective vertical stress at the depth of interest for computing f_s, and ω_{FDOT} is equivalent to the β coefficient used in the beta static method that is commonly utilized for estimating the vertical capacity of drilled shafts. For drilled shafts under axial loading, the FHWA (2010) drilled shaft manual recommends using a beta method as follows:

$$f_s = \beta \cdot \sigma'_v \quad (4.2)$$

Where β is an empirical coefficient that can be estimated using empirical correlations with geotechnical information obtained from field tests, such as the SPT. Empirical correlations for static methods are based on well characterized axial load tests. The correlation reported by FHWA (2010) for the beta coefficient is sourced from load test data interpreted and analyzed by Reese and O'Neill (1988). The expression for dimensionless coefficient β is:

$$\beta = \frac{N_{60}}{15} \cdot \left(1.5 - 0.135\sqrt{z(ft)}\right) \qquad (4.3)$$

where N_{60} is the SPT blow count corrected for hammer energy to be equivalent to a 60% efficiency (above equation applies only to $N_{60} < 15$), and z is the depth of the SPT blow count in feet.

The ω coefficient used by FDOT is estimated using a modified equation from the one developed by Reese and O'Neill (1988) where the dependency with depth (z) has been removed, as follows:

$$\omega_{FDOT} = 1.5.\frac{N_{field}}{15} = \frac{N_{field}}{10} \qquad (4.4)$$

where N_{field} is the field, or uncorrected, SPT blow count. According to the FDOT design guidance, the above equation is valid for sands and field SPT values between 5 and 15. For field SPT values equal to or greater than 15, FDOT recommends using $\omega_{FDOT} = 1.5$.

Based on the reported FDOT design procedures, the factored torsional resistance for a drilled shaft installed in a homogeneous sand site can be computed as follows:

$$\emptyset \cdot T_n = \emptyset_{Tor} \cdot \omega_{FDOT} \cdot \sigma_v'\left(z = \frac{L}{2}\right) \cdot (\pi D L) \cdot \frac{D}{2} \qquad (4.5)$$

where:

- ϕ_{Tor} = Resistance factor for torsion (=1.0 for mast arm traffic signal structures),
- ω_{FDOT}= side friction coefficient as per above equation correlation with SPT N_{field} ($\approx N_{60}$),
- $\sigma_v'\left(z = \frac{L}{2}\right)$= effective stress level at the mid-depth of the drilled shaft (embedment depth),
- D = drilled shaft diameter,
- L = embedded depth of drilled shaft.

FDOT uses an LRFD based methodology, thus the factored torsional resistance (Eq. 4.5) must be equal to or greater than the factored torsional loading demand. For the comparison example, the factored torsional loading demand is listed in Table 4-1.

Using the above approach, the minimum embedment depths obtained for the comparison example (Figure 4-1) were found to be 38 ft. 33.5 ft, and 30.5 ft for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively.

4.2.3. Summary of FDOT embedment depth results for comparison example

The computed required embedment depths for the comparison example in Figure 4-1, and Case 1 loading in Table 4-1, obtained using the FDOT procedures reported in the SOP, are summarized in Figure 4-3.

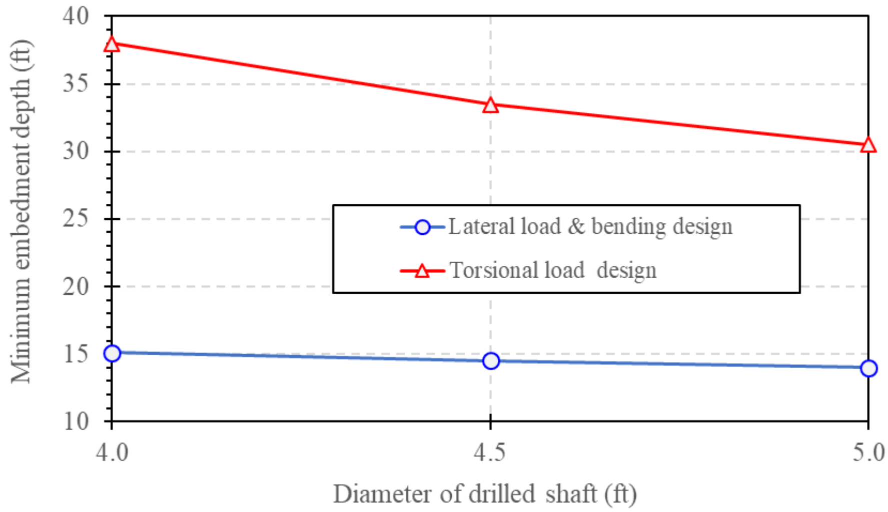


Figure 4-3: Summary FDOT embedment depth results for comparison example (Case No. 1 Only).

This figure presents two curves corresponding to the required embedment depths for the 3 drilled shaft diameters considered for the two geotechnical limit states of lateral loading and bending and torsional loading that were described and presented above. A comparison of the two curves show that torsional loading design controls the embedment depth requirement based on the current FDOT design procedures considered (i.e., using the codes listed in Table 4-1).

4.3. Drilled shaft embedment depths for design example using NCDOT procedures

The comparison example solved using the NCDOT design procedures reported in the SOP are presented for the three loading demand scenarios requested by the SIC of the NCDOT research project SIC. These three cases are listed in Table 4-1and correspond to a design wind speed of 170 mph (Case No. 1 used for direct comparison with the FDOT analyzed case), and a design wind speed of 100 mph that corresponds to Cases No. 2 and No. 3 with demand loads computed based on different design codes (See Table 4-1).

4.3.1. NCDOT embedment length requirements to resist lateral loading moment

The embedment length requirement to resist lateral load and bending is computed by NCDOT using lateral load analyses based on the p-y curve formulation. The design uses ASD with a global factor of safety of 1.5 for the loading demand listed in Table 4-1.

The p-y methodology models the pile behavior with a series of discrete elements and the soil reaction resultant (p) through non-linear springs, as shown schematically in Figure 4-4. The NCDOT ITS and Signals Unit indicated in the SOP survey for this project that the p-y analyses for drilled shafts supporting mast arm traffic signals are performed using the commercial software LPILE (Ensoft, 2016).

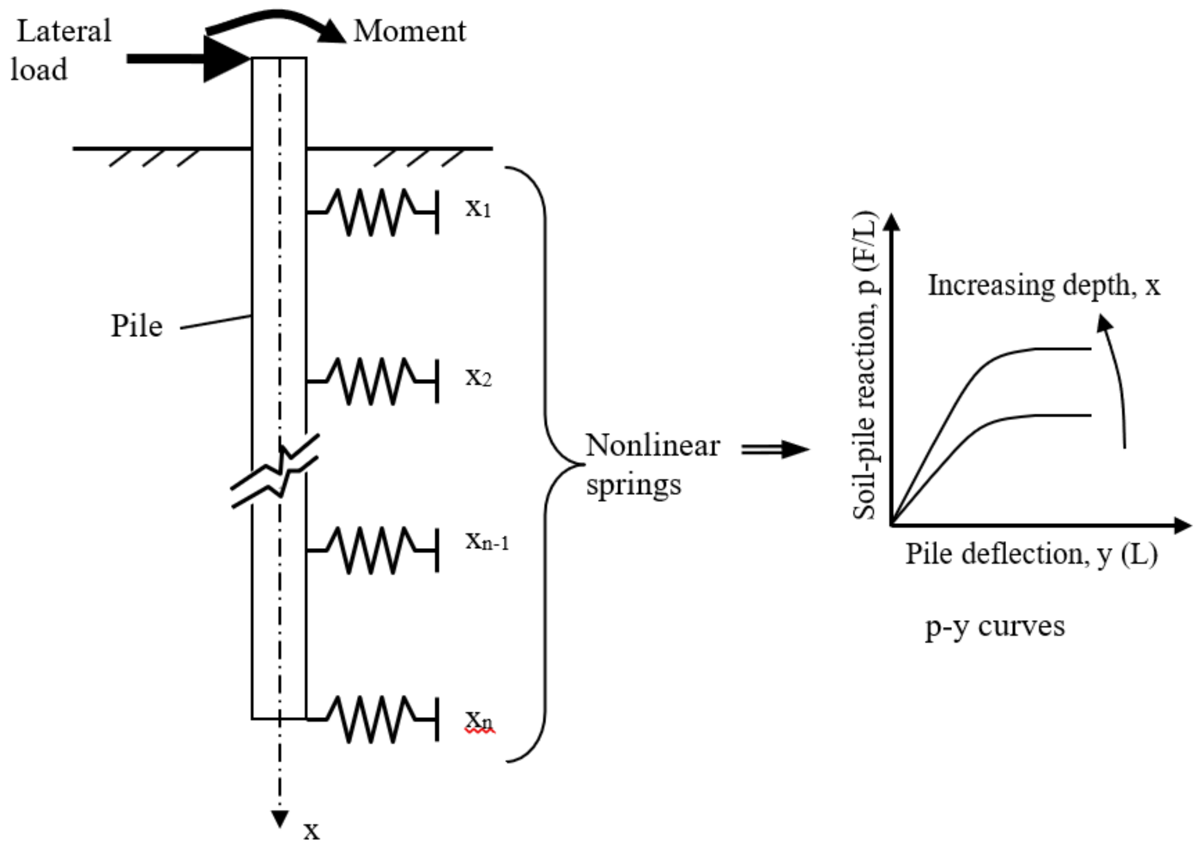


Figure 4-4: Schematic showing pile model used in P-Y curve analyses of laterally loaded piles.

NCDOT reported in the SOP that the p-y curve formulation by Reese et al. (1974) is typically used for mast arm sites involving sands with a high-water table. The typical shape of this p-y curve proposed by Reese et al. (1974) is shown in Figure 4-5. In this figure, important elements of the p-y curve can be identified, including: the initial slope, E_{py-max}, and the ultimate soil resistance value, p_u. At any point along the p-y curve, the resultant soil reaction, p, acting on the pile is a force per unit length of pile that is related to the pile deflection, y, at the location of the non-linear spring. Additional background on the p-y analyses can be found in Reese and Van Impe (2011).

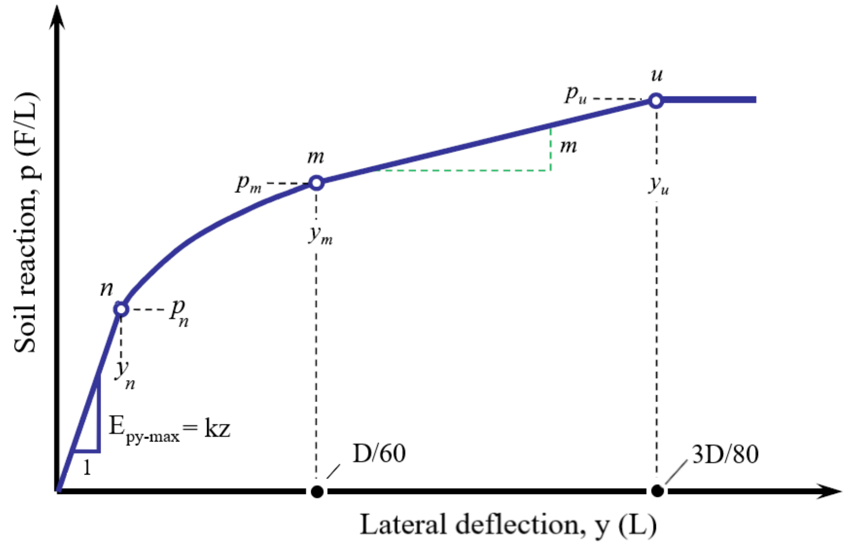


Figure 4-5: Typical Reese et al. (1974) p-y curve for laterally loaded piles in sands.

Specific to the p-y curve proposed by Reese et al. (1974), the curve is formed by an initial straight line with a slope equal to E_{py-max} that extends to Point n (coordinates p_n, y_n). Then the p-y curve has a curved transition segment that connects Points n and m. Point m corresponds to a pile lateral deflection, at the depth of the nonlinear spring, equal to $D/60$ (where D is the diameter of the drilled shaft). The transition segment is followed by a straight segment that connects Points m and u. Point u is where the ultimate soil reaction (p_u) is mobilized. The value of p_u is a function of the vertical effective stress value at the depth of interest, the friction angle (ϕ'), and the diameter of the drilled shaft (D) and is computed by LPILE following the procedure established by Reese et al. (1974). For this p-y curve formulation, the ultimate soil reaction is considered to be mobilized at a lateral deflection equal to $3D/80$. The parameters required to define the p-y curves for a pile modeled using the Reese et al. (1974) formulation are listed in Table 4-2. This table also lists the values selected for the analyses for the comparison example. The k parameter is used to define the variation of the E_{py-max} with depth. The E_{py-max} is the slope of the initial portion of the p-y curve and although has units of F/L^2 it should not be confused with the soil modulus (E_s). For loose, saturated sands like in the comparison example, a value of 20 lb/in^3 is typical for k and so that value was assumed for the following analysis.

Table 4-2: Input Parameters for p-y curves for comparison example

Input parameter	Description/Comments	Values used for Comparison Example
p-y curve formulation	Reese et al. (1974) for sands	See Fig. 4-1
Friction angle (ϕ')	Typically selected based on SPT correlations	30°, as per Figure 4-1
Effective unit weight (γ')	Used to define vertical effective stress profile	55 pcf, as per Figure 4-1
E_{py-max} parameter (k)	Used to define variation of E_{py-max} with depth	20 lb/in^3
Drilled shaft info	Diameter, embedment length, structural parameters for nonlinear EI	D = 4, 4.5, 5 ft L varied until drilled shaft was able to resist loading demand.

Using the NCDOT design approach described above and the LPILE software to perform the nonlinear p-y analysis, the minimum embedment depths required to resist lateral loading and associated bending moment were computed for the three loading demand cases listed in Table 4-1. The results are summarized below.

Results for Loading Case No. 1 (Wind speed = 170 MPH):

As indicated in Table 4-1, this loading demand case involves a wind speed of 170 mph that produces a lateral load of 12.3 kips and corresponding a bending moment of 307.6 kip-ft. As mentioned before, the loading demand prescribed for Case No. 1 was provided by NCDOT, while the analysis followed the specifications in AASHTO LTS-5 (2009).

Using the approach and model described above, the computed embedment lengths required to resist the lateral load and associated bending moment were computed for Case No. 1. The minimum required lengths for this loading case, using an ASD safety factor of 1.5, were computed as 15.2 ft, 14.4 ft, and 13.8 ft for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively.

Results for Loading Case No. 2 (Wind speed = 100 MPH):

As indicated in Table 4-1, this loading case corresponds to a wind speed of 100 mph and uses the specifications in AASHTO LTS-5 (2009) to compute the loading actions and available strengths. As previously mentioned, the loading demand listed in this table for Case No. 2 was provided by NCDOT.

Using a similar approach as for Case No. 1, the computed embedment lengths required to resist the lateral load and associated bending moment were computed for Case No. 2. The minimum required lengths for this loading case, using an ASD safety factor of 1.5, were computed as 12 ft, 11.7 ft, and 10.9 ft for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively.

Results for Loading Case No. 3 (Wind speed = 100 MPH):

As indicated in Table 4-1 this loading demand case corresponds to a wind speed of 100 mph and the AASHTO LTS-4 (1994) code. The loading demand for Case No. 3 was provided by NCDOT and is listed in Table 4-1. As can be seen in this table, the loading demand in terms of lateral load and bending moment is higher for Case 3 than for Case 2 despite both being based on a wind speed of 100 MPH. This difference in loading demand is related to different code editions (See Table 4-1) and that Case 3 is based on fastest mile wind speed, versus Case 2 that uses the 3-second gust wind velocity.

Using the approach and model described above, the computed embedment lengths required to resist the lateral load and associated bending moment were computed for Case No. 1. The minimum required lengths for this loading case, using an ASD safety factor of 1.5, were computed as 13.6 ft, 13.4 ft, and 12.6 ft for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively.

4.3.2. NCDOT embedment length requirements to resist torsion loading

The design approach that was reported in the SOP to be used by NCDOT to resist torsion loading demand is based on AASHTO LTS-5 (2009), which uses an ASD approach for the design against torsional load. It should be noted that the NCDOT ITS & Signal Unit indicated being in the transition to adopt the LRFD based design according to LRFDLTS-1 in AASHTO (2015). The methodology described below is based on the ASD approach as it was still in place at the time of the SOP study.

The methodology used by NCDOT to compute the torsional capacity of a single drilled shaft, as reported in the SOP, is based on computing the side friction (f_s) using a modified beta method as follows:

$$f_s = \beta \cdot \sigma_v' \tag{4.6}$$

where σ'_v is the effective vertical stress at the depth of interest for computing f_s, and β is the coefficient used in the beta effective stress static method that is commonly utilized for estimating vertical capacity of drilled shafts (FHWA 2010). As mentioned earlier (See Eq. 4.3), the β empirical coefficient that can be estimated using empirical correlations with field tests like the SPT. The empirical correlation (Equation 4.3), based on a well characterized axial load tests, interpreted and analyzed by Reese and O’Neill (1988), involves a term dependent on depth. For convenience, Eq. 4.3 is repeated below:

$$\beta = \frac{N_{60}}{15} \cdot \left(1.5 - 0.135\sqrt{z(ft)}\right) \tag{4.7}$$

where terms were as defined before.

The side friction for drilled shafts in sand deposits is computed by NCDOT and FDOT using the same effective stress static method based on multiplying the vertical effective stress by an empirical coefficient. The main differences between the two approaches lies on the empirical coefficient used, as NCDOT uses the FHWA recommended β coefficient (Eq. 4.7), and FDOT uses a modified coefficient with respect to the original FHWA coefficient called the ω_{FDOT} coefficient (Eq. 4.4). From Eq. 4.7 and 4.4, the ratio of these two coefficients, for the same site and SPT values, is as follows:

$$\frac{\beta}{\omega_{FDOT}} = 1.0 - 0.09 \cdot \sqrt{z(ft)} \qquad (4.8)$$

The above equation assumes that the SPT N_{field} values, used by FDOT, are equal to N_{60} values that are used to compute β (Eq. 4.7) as per FHWA (2010). Equation 4.8 shows that the side friction required for torsion capacity using the β coefficient as per FHWA (2010) will be lower than the capacity computed using the FDOT approach based on the ω_{FDOT} coefficient, and that this difference increases for longer drilled shaft due to the depth dependency of the β coefficient. For example, based on Eq. 4.8, the average side friction computed using NCDOT approach (β coefficient) will be 71.5%, 59.8%, and 50.7% of the average side friction computed using the approach by FDOT (ω_{FDOT} coefficient) for drilled shaft lengths of 10 ft, 20 ft, and 30 ft, respectively. This difference in design side friction for torsion is discussed further in the comparison section of this chapter.

Using the static method described above, the NCDOT design procedure using AASHTO LTS-5, would result in the following expression to compute the ultimate torsional resistance for a drilled shaft installed in a *homogeneous sand* site:

$$T_{ult} = \cdot \overline{f_s} \cdot (\pi \cdot D \cdot L) \cdot \frac{D}{2} \qquad (4.9)$$

Where $\overline{f_s}$ corresponds to the average interface friction between drilled shaft and surrounding foundation soil that can be replaced by expression in Eq. (4.5), and simplified to:

$$T_{ult} = \beta \cdot \overline{\sigma_v'} \cdot (\pi D L) \cdot \frac{D}{2} \qquad (4.10)$$

where:

- β = side friction coefficient as per above correlation with SPT N_{60} (Eq. 4.3 or 4.7),
- $\overline{\sigma_v'}$ = average effective stress level along the embedment depth of the drilled shaft,
- D = drilled shaft diameter,
- L = embedded depth of drilled shaft.

The minimum embedment depth using the ASD approach is based on ensuring that the torsional loading demand is equal or greater than the ultimate torsional divided by a global factor of safety. Based on input obtained from NCDOT during the SOP study, a global factor of safety against torsional loading of unity is currently being used for design ($FS_{Torsion}$ =1.0) (NCDOT, 2010).

Using the NCDOT design approach described above, the minimum embedment depths required to resist torsional loading were computed for the three loading demand cases listed in Table 4-1. The results are summarized below for the drilled shaft diameters considered of 4 ft, 4.5 ft, and 5 ft.

Results for Loading Case No. 1 (Wind speed 170 MPH):

As indicated in Table 4-1 the torsional loading demand of 468.9 kip-ft corresponds to a wind speed of 170 mph and the AASHTO 2009 LTS-5. As mentioned previously, the loading demand listed in this table for Case No. 1 was provided by NCDOT. For this loading demand, the geotechnical conditions of this simplified example, and the approach described above, the computed required minimum embedment lengths were **49.6 ft**, **42.9 ft**, and **37.8 ft** for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively. If an ASD factor of safety of 1.5 were to be used for design, the required minimum embedment lengths would increase to 64.6 ft, 55.25 ft, and 48.33 ft for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively. However, as mentioned earlier NCDOT uses a FS=1.0 for this design approach (AASHTO 2009 LTS-5).

Results for Loading Case No. 2 (Wind speed 100 MPH):

Loading Case No. 2, as indicated in Table 4-1, has a torsional loading demand of 165.7 kip-ft based on a wind speed of 100 mph and the AASHTO 2009 LTS-5. The computed required minimum embedment lengths were **26.75 ft**, **23.4 ft**, and **20.8 ft** for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively. These minimum required embedment depths increase to 33.8 ft, 29.5 ft, and 26.1 ft for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively, if the ASD factor of safety is increased from 1.0 to 1.5.

Results for Loading Case No. 3 (Wind speed 100 MPH):

Loading Case No. 3, as indicated in Table 4-1, has a torsional loading demand of 302.4 kip-ft based on a wind speed of 100 mph and the AASHTO 1994 LTS-4. Using this loading demand, the computed required minimum embedment lengths were **37.95 ft**, **33.03 ft**, and **29.23 ft** for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively. These minimum required embedment depths increase to 48.95 ft, 42.03 ft, and 37.04 ft for drilled shaft diameters of 4 ft, 4.5 ft, and 5 ft, respectively if the ASD factor of safety is increased from 1.0 to 1.5.

4.3.3. Summary of NCDOT embedment depth results for comparison example

This subsection summarizes the computed required minimum embedment depths for the comparison example in Figure 4-1, based on NCDOT procedures reported in the SOP for the Load Cases No. 1 through 3 as listed in Table 4-1.

<u>Summary of Results for Loading Case No. 1 (Wind speed 170 MPH)</u>:

The minimum required embedment depths computed for Loading Case No. 1 (Wind speed = 170 mph) as per information in Table 4-1are summarized in Figure 4-6. This figure presents two curves corresponding to the required minimum embedment depths for the 3 drilled shaft diameters considered for the two geotechnical design considerations of: i) lateral loading and bending moment, and ii) torsional loading using methodologies that were described and presented above. A comparison of the two curves show that the torsional loading design controls the minimum embedment depth requirement based on the NCDOT design procedure reported in the SOP study (i.e., using the codes listed in Table 4-1 for Load Case No. 1).

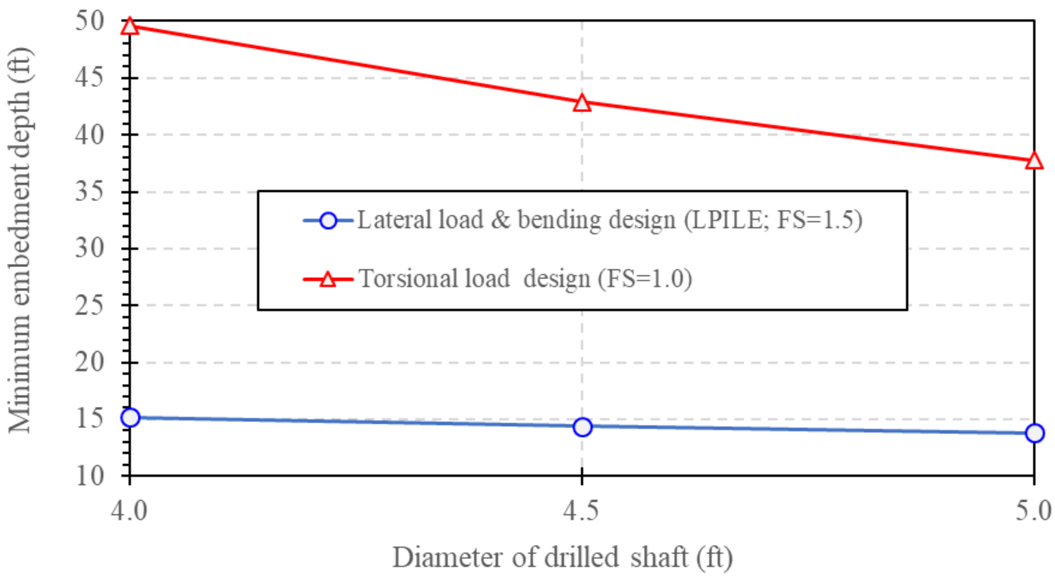


Figure 4-6: Summary NCDOT embedment depths for comparison example – Load Case No. 1.

<u>Summary of Results for Loading Case No. 2 (Wind speed 100 MPH)</u>:

The minimum required embedment depths computed for Loading Case No. 2, using a wind speed of 100 mph and the additional information provided in Table 4-1, are summarized in Figure 4-7.

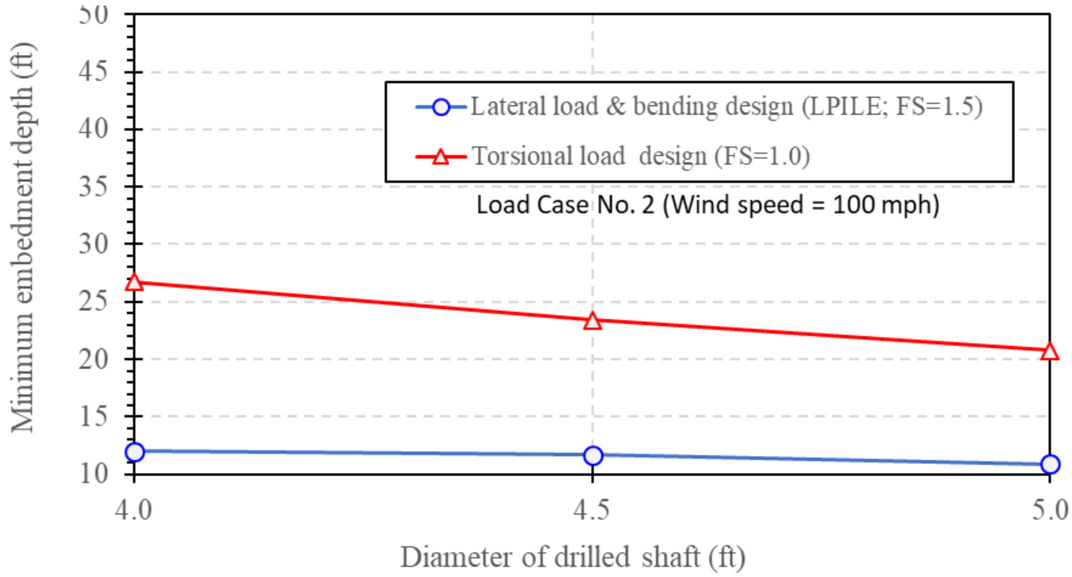


Figure 4-7: Summary NCDOT embedment depths for comparison example – Load Case No. 2.

This figure presents two curves corresponding to the required minimum embedment depths for the 3 drilled shaft diameters considered for the two geotechnical design considerations of: i) lateral loading and bending moment, and ii) torsional loading using methodologies that were described and presented above. A comparison of the two curves show that the torsional loading design controls the minimum embedment depth requirement based on the NCDOT design procedure reported in the SOP study (i.e., using the codes listed in Table 4-1for Load Case No. 2).

Summary of Results for Loading Case No. 3 (Wind speed 100 MPH):

The minimum required embedment depths computed for Loading Case No. 3, using a wind speed of 100 mph and the additional information provided in Table 4-1, are summarized in Figure 4-8.

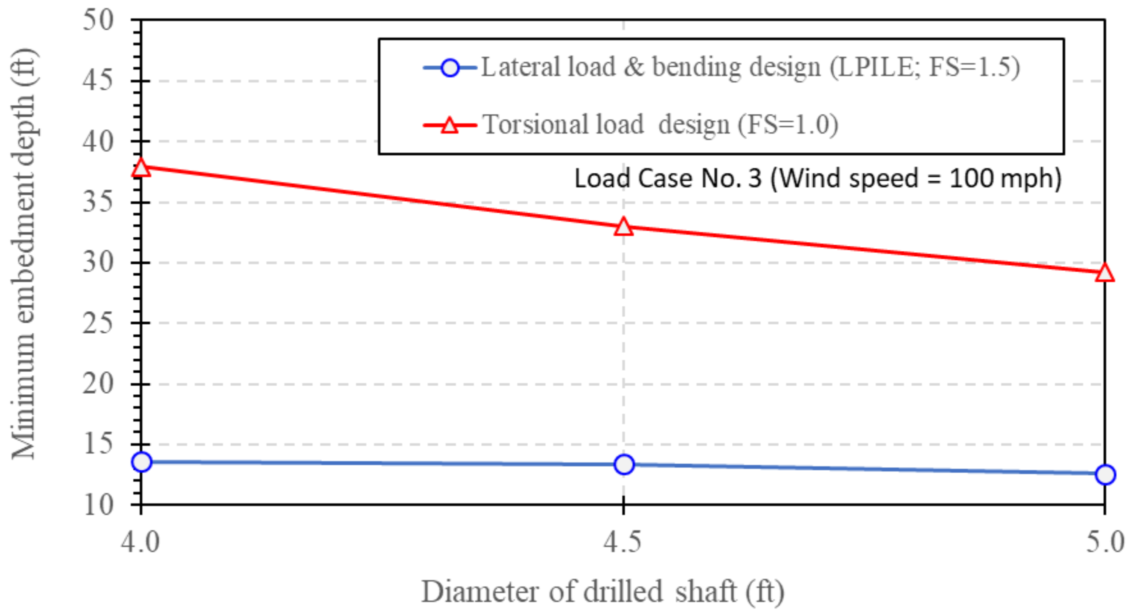


Figure 4-8: Summary NCDOT embedment depths for comparison example – Load Case No. 3.

This figure presents two curves corresponding to the required minimum embedment depths for the 3 drilled shaft diameters considered for the two geotechnical design considerations of: i) lateral loading and bending moment, and ii) torsional loading using methodologies that were described and presented above. A comparison of the two curves show that the torsional loading design controls the minimum embedment depth requirement based on an older NCDOT design code as indicated Table 4-1 for NCDOT Load Case No. 3.

4.4. Comparison of minimum required embedment lengths for Comparison Example

The comparison example designed using current design procedures used by FDOT and NCDOT showed that torsion loading controls the minimum required drilled shaft embedment depths for the three diameters considered and the conditions of the example summarized in Figure 4-1.

4.4.1. Comparison of required lengths based on lateral loading

A comparison of the required minimum embedment depths required to withstand the lateral load and bending moment demand for the comparison example using procedures for both DOTs is provided in Table 4-3. The comparison corresponds to values computed for loading demand Case No. 1 (Table 4-1) that corresponds to a wind speed of 170 mph. As pointed out earlier, despite both DOT examples have the same wind speed, the differences computed are related to variations in loading demand related to the different codes used by both agencies and related to differences in design procedures as described above.

Table 4-3 shows that the minimum embedment depth requirements computed using the FDOT design approach (i.e., based on the Broms ultimate load procedure and the LRFD methodology with a resistance ϕ factor of 0.5) yielded results that are similar or slightly longer than the values computed using the design methodology used by NCDOT (i.e., based on p-y formulation, LPILE, and an ASD approach with a global FS=1.5).

Table 4-3: Comparison of minimum embedment depths required to carry lateral load demand.

Drilled Shaft Diameter (ft)	Minimum Embedment Depth Required (ft)		Ratio L_{NCDOT}/L_{FDOT}
	FDOT Load Case No. 1 (Broms, LRFD w/ϕ factor = 0.5)	**NCDOT** Load Case No. 1 (LPILE, ASD and FS=1.5)	
4	15.1	15.2	100.7 %
4.5	14.5	14.4	99.3 %
5	14.0	13.8	98.6 %

4.4.2. Comparison of required lengths based on torsion loading

A summary comparison of the minimum embedment depths required to withstand the torsional loading demand for the comparison example using the procedures reported by FDOT and NCDOT are provided in Table 4- below.

Table 4-4: Comparison of minimum embedment depths required to carry torsional load demand.

Drilled Shaft Diameter (ft)	Minimum Embedment Depth Required (ft)		Ratio L_{NCDOT}/L_{FDOT}
	FDOT Load Case No. 1 (ω coefficient, and LRFD w/ ϕ factor = 1.0)	**NCDOT** Load Case No. 1 (β coefficient, and ASD w/ FS=1.0)	
4	38	49.6	130.5 %
4.5	33.5	42.9	128.1 %
5	30.5	37.8	123.9 %

The results in Table 4-4 show that the minimum embedment lengths required to withstand torsional loading are considerably higher than the values required to resist lateral loading reported in Table 4-3. Therefore, as mentioned before, design to resist torsion loading controls the drilled shaft design since it requires considerably deeper embedment depths compared to requirements to resist axial load or bending/lateral load demands.

Additionally, Table 4- also shows that the embedment depth requirements using the current NCDOT design procedures, for the same design wind speed of 170 mph, are between 24 and 31% longer than the values obtained using the current FDOT procedures. This difference is attributed to the differences in the design approach described earlier, i.e., the difference in skin friction coefficient where FDOT has opted to use a less conservative omega (ω_{FDOT}) coefficient that is a modification of the original beta (β) coefficient proposed by Reese and O'Neill (1988). A comparison of the side friction coefficients used by NCDOT (i.e., based on the 2010 FHWA drilled shaft manual) and FDOT is shown in Figure 4-9 based on the expression in Eq. 4.8, and assuming homogeneous sand site conditions (i.e., a constant SPT with depth and $N_{60} \approx N_{field}$). This figure serves to illustrate how the FDOT side friction coefficients (ω_{FDOT}) is higher than the corresponding NCDOT β values for a given average SPT (N_{60} value). The difference between the side friction computed using the FDOT procedure increases with increasing drilled shaft embedment depth. Figure 4-9 shows the FDOT design side friction for torsion is about 40% and 100% higher than the corresponding value using the NCDOT (FHWA, 2010) procedure for drilled shaft embedment depths of 10 ft and 30 ft, respectively.

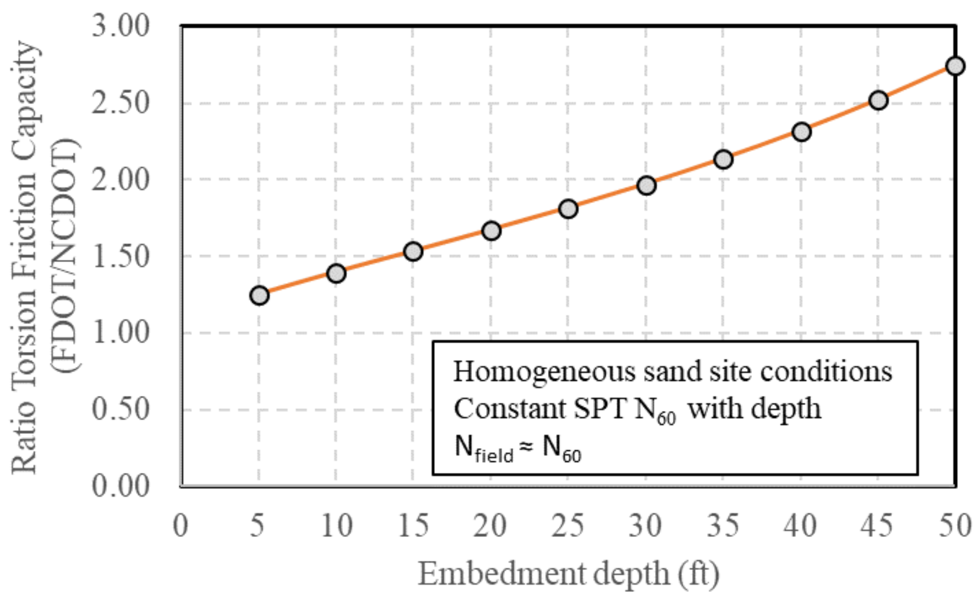


Figure 4-9: Ratio of FDOT to NCDOT torsion side friction capacity as a function of depth.

During the SOP phone interviews, FDOT personnel explained that the agency had decided to modify the torsional side friction coefficient to intentionally result in higher torsional capacities compared to those obtained using the original beta coefficients proposed by O'Neill and Reese (1988). As mentioned above, the main difference is that FDOT has eliminated the factor related to depth dependency. Another reason that influences the different torsional minimum required embedment depths computed when using

FDOT and NCDOT design procedures for the comparison example is associated to code and design approach differences. As indicated in Table 4-1, FDOT uses AASHTO- LRFDLTS-1 which involves an LRFD methodology that results in larger factored loads and currently uses a resistance factor $\phi = 0.5$ for the geotechnical torsion capacity. In contrast, NCDOT in the SOP study reported using code AASHTO LTS-5 (2009) that is based on ASD methodology and uses a global factor of safety equal to 1.0. However, it is the writer's opinion that the main factor that makes the FDOT embedment lengths lower than the NCDOT values for the comparison example considered is related to the higher torsional side friction coefficients intentionally used by FDOT.

5. Literature Review

5.1. Introduction

The literature review summarized in this chapter focused on research in the following three main areas:

- Performance of drilled shafts under combined lateral and torsion loading.
- Alternative foundation systems for combined lateral and torsion loading

The above three topics are based on the initial scope of this research project involved experiments and computational efforts to better understand the behavior (performance and capacity) of drilled shafts under combined lateral and torsional loading. Additionally, the research scope included identification of alternative foundation systems that showed promise as possible foundations to support mast arm traffic signal structures. The original research project involved experiments and analyses on a selected alternative foundation system. As mentioned earlier, the original scope was modified early in the project to focus on the SOP and the comparison of design procedures of conventional drilled shafts. Nevertheless, this literature review chapter is presented to summary some key findings as they relate to the revised scope of the project.

5.2. Performance of drilled shafts under combined lateral and torsional loading

Most of the identified research that involved study of drilled shafts under combined lateral and torsional loading demand has been from the University of Florida (UF) and from with funding from FDOT. A timeline summarizing the most relevant research from these institutions in Florida is presented in Figure 5-1.

Most of the research in summarized in this figure has involved scaled model tests using the UF centrifuge that can be approximated to full-scale field conditions using scaling laws. Independent of any advantages and possible limitations associated to centrifuge based research, which is outside the scope of this study, the research by the UF research group is very valuable to gain insight on the behavior of drilled shafts under combined lateral and torsional loading. Other relevant research from other research groups include Li (2017) and Li et al. (2017) from the University of Oregon that investigated load transfer mechanisms of drilled shafts under combined lateral and torsion loading and performed full-scale field tests. The following subsections summarizes the most relevant studies shown in Figure 5-1.

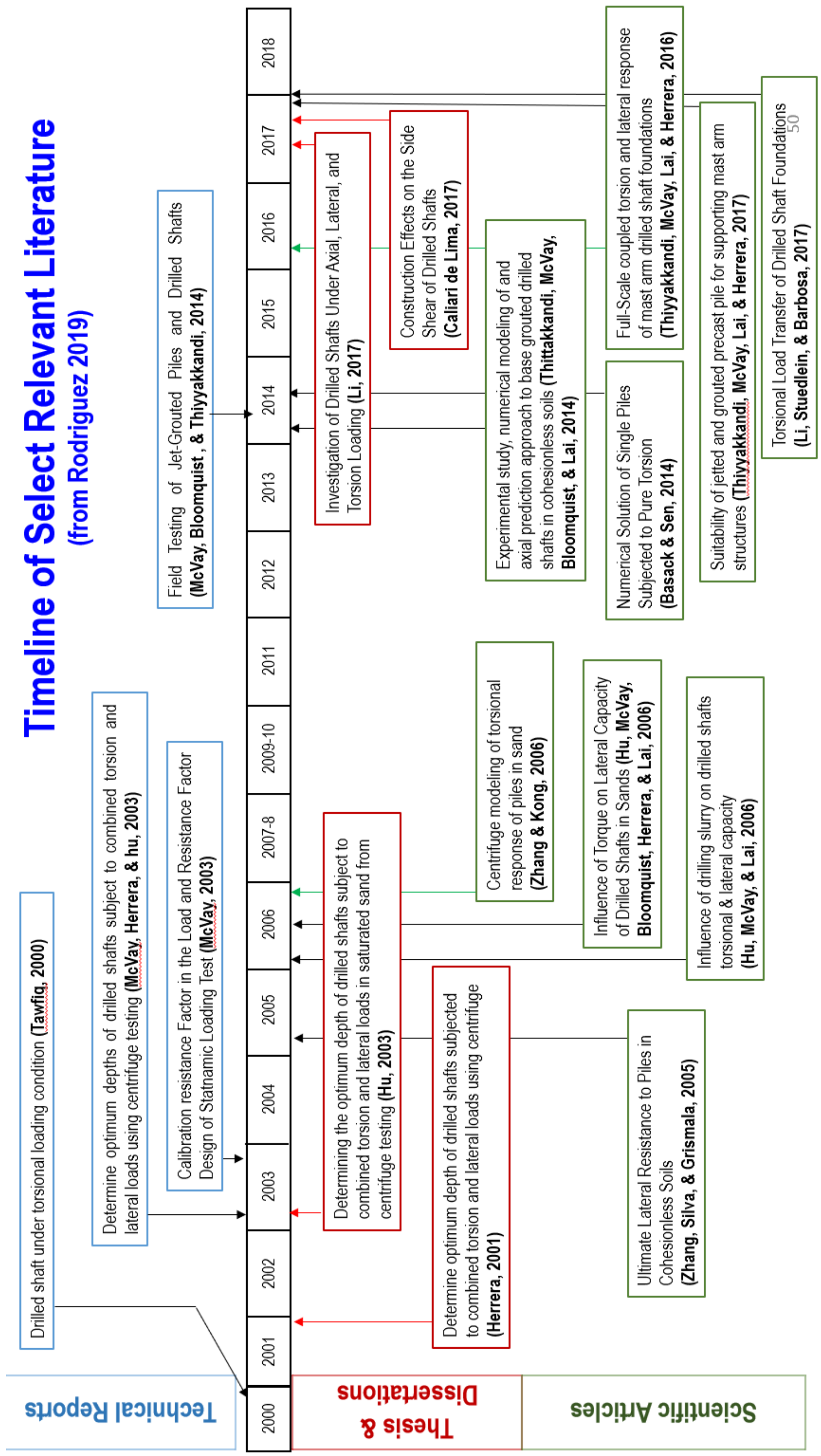


Figure 5-1: Timeline showing selected research on drilled shafts under lateral and torsional loading.

5.2.1. Centrifuge tests at UF reported by Hu et al. (2006)

Initial research by UF includes the MS thesis by Herrera (2001) and the doctoral dissertation by Hu (2003). These studies involved performing a series of centrifuge tests of drilled shafts in homogeneous saturated sand deposits under combined lateral and torsional loading. A summary of the results from this study can also be found in McVay et al. (2003) and Hu et al. (2006).

Hu et al. (2006) performed 91 centrifuge tests involving model drilled shafts like the one shown in Figure 5-2. The study involved uniform sand conditions with 3 levels of relative density, and under both dry and saturated conditions, three embedment depth to diameter (L/D) ratios (L/D = 3, 5, and 7), and loading conditions involving pure lateral loading and combined lateral and torsion achieved by varying the location of the applied point load along the mast arm shown in Figure 5-2. Table 5-1 summarizes the main test conditions considered by Hu et al. (2006).

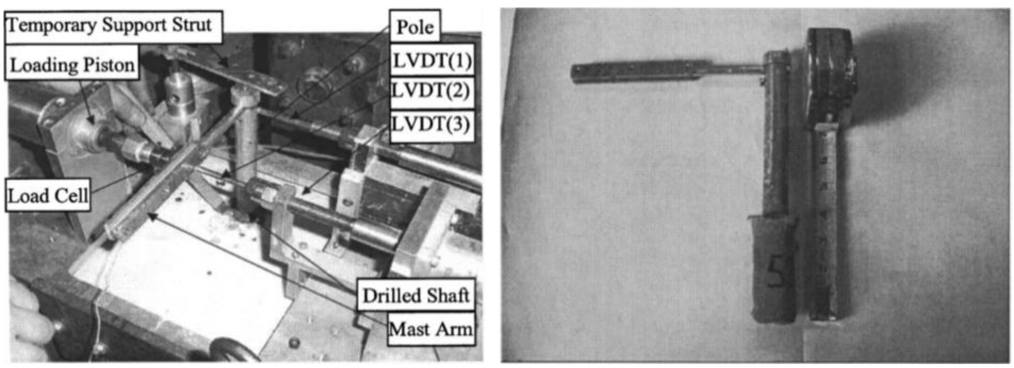


Figure 5-2: Details of centrifuge model testing by Hu et al. (2006).

Table 5-1: Summary of test conditions considered by Hu et al. (2006).

Type of tests	Number of tests	Conditions	Embedment depth L/D	Load Application
Centrifuge	54	Loose, medium and dense dry sand	3, 5 and 7	At Pole (No torsion). At mid mast (T>0) At end of mast (T>0)
Centrifuge	37	Loose and dense saturated Sand	5 and 7	

The initial set of tests by Hu (2003) involved experiments under lateral loading only. These tests results are useful to compare the predicted failure lateral load obtained using the ultimate load method by Broms (1964) with the measured failure loads in the centrifuge experiments with no torsional loading. As mentioned in Chapter 3, the Broms (1964) method is the one used by FDOT for lateral load design. Rodriguez (2019) compared predicted ultimate lateral loads using Broms (1964) with the measured failure lateral loads reported by Hu (2003) and the summary is presented in Figure 5-3. The experimental results presented involve three L/D ratios and three relative densities. This figure shows that in general Broms (1964) overpredicted the measured failure loads by about 35 % for L/D ratios of 3 and 5. In contrast, the predictions for L/D = 7 were found show good agreement with measured failure values.

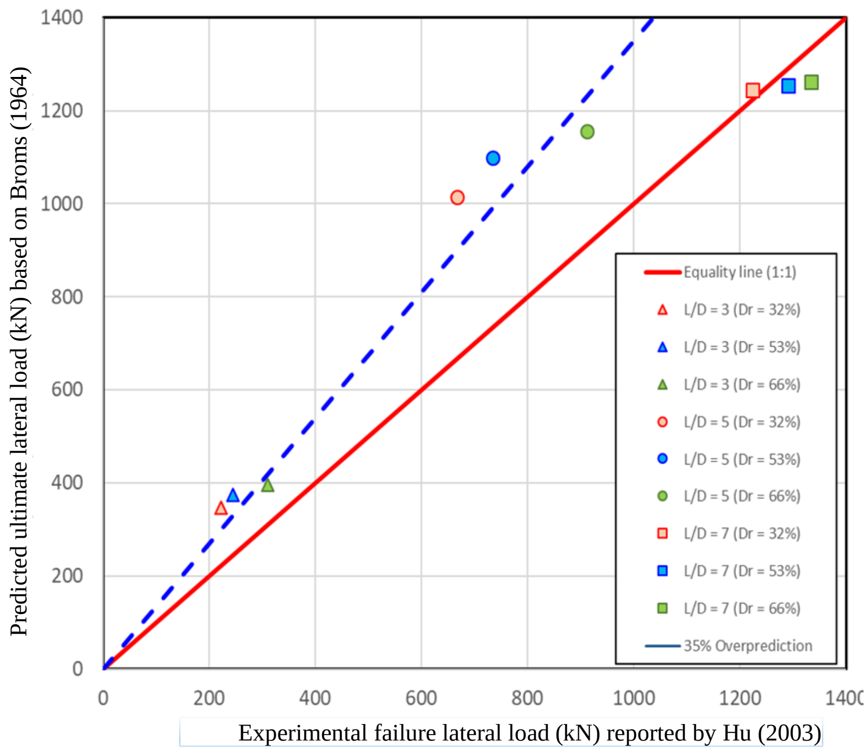


Figure 5-3: Predicted lateral Load based on Broms (1964) versus Experimental loads by Hu (2003).

Centrifuge tests with combined lateral and torsional loading by Hu (2003) revealed that the presence of torsion loading has a significant impact on the lateral load capacity of the deep foundation. This can be seen in results presented in Figure 5-4 where Hu et al. (2006) reports a significant loss of lateral load capacity when torsion loading is present. The above figure presents three plots of lateral load versus lateral deflection for three levels of torsion: i) no torsion, ii) torsion when the point load is applied at the center of mast arm, and iii) torsion when the point load is applied at the end of the mast arm. The test results correspond to centrifuge tests by Hu (2003) with sand at a medium dense relative density (D_r = 53%). The three plots shown correspond to embedment ratios (L/D) of 3, 5 and 7. For all three L/D ratios the results show that the lateral load capacity decreases significantly and is the capacity decrease is the highest (as much as about 50 %) for the experiments with the highest level of torsional loading level (i.e., when the point load was located at the end of the mast arm). In summary, the results shown in Figure 5-4 show that the presence of torsion loading can decrease considerably the lateral load capacity of the drilled shaft.

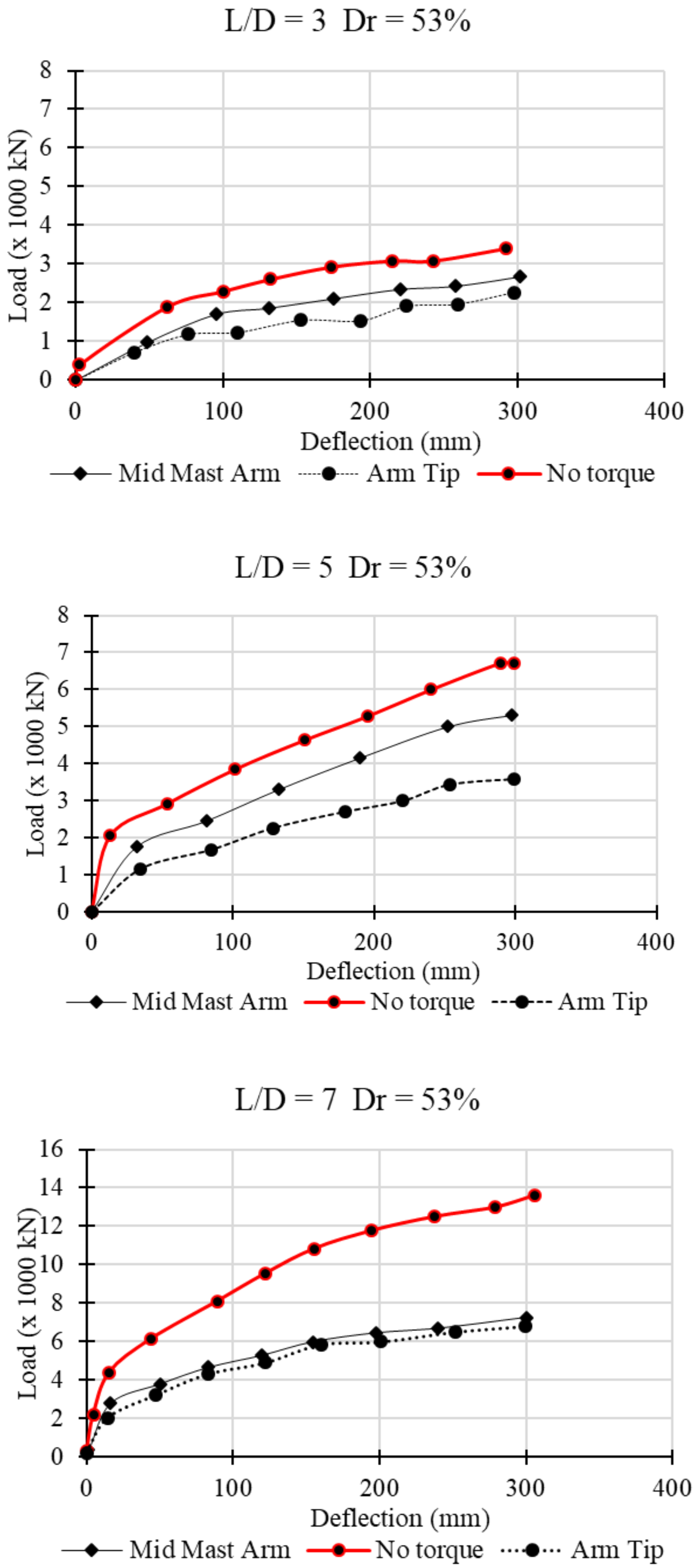


Figure 5-4: Influence of torsion on lateral load capacity of drilled shafts (Hu et al., 2006).

The above research underlines the importance of developing design procedures that consider the coupled effects of lateral and torsional loading. This is an important as the SOP study, reported in Chapter 2, showed that all US DOT participants currently use a decoupled methodology to predict the capacities of the drilled shaft under lateral and torsion loading. This highlights the need for more research to better understand the performance of deep foundations under combined lateral and torsional loading and towards development of coupled approaches that adequately capture this important decrease in lateral load capacity reported in the literature (e.g., Hu, 2003; Hu et al., 2006).

5.2.2. Full-scale torsion tests at silty clay test site Oregon State University

Li (2017) and Li et al. (2017) reported results for a full-scale field torsional load test program involving two instrumented test drilled shafts. The torsional field tests were performed at the geotechnical field research site at the Corvallis campus of Oregon State University. These drilled shafts were installed predominantly in stiff to very stiff silty clay to clayey silt as shown in Figure 5-5. There were two test sites ate this location TDS and TDSFB with the latter installed with a free base condition. Figure 5-5 shows a photo of an exhumed drilled shaft after completion of testing and the loading arm used to apply the torque loading.

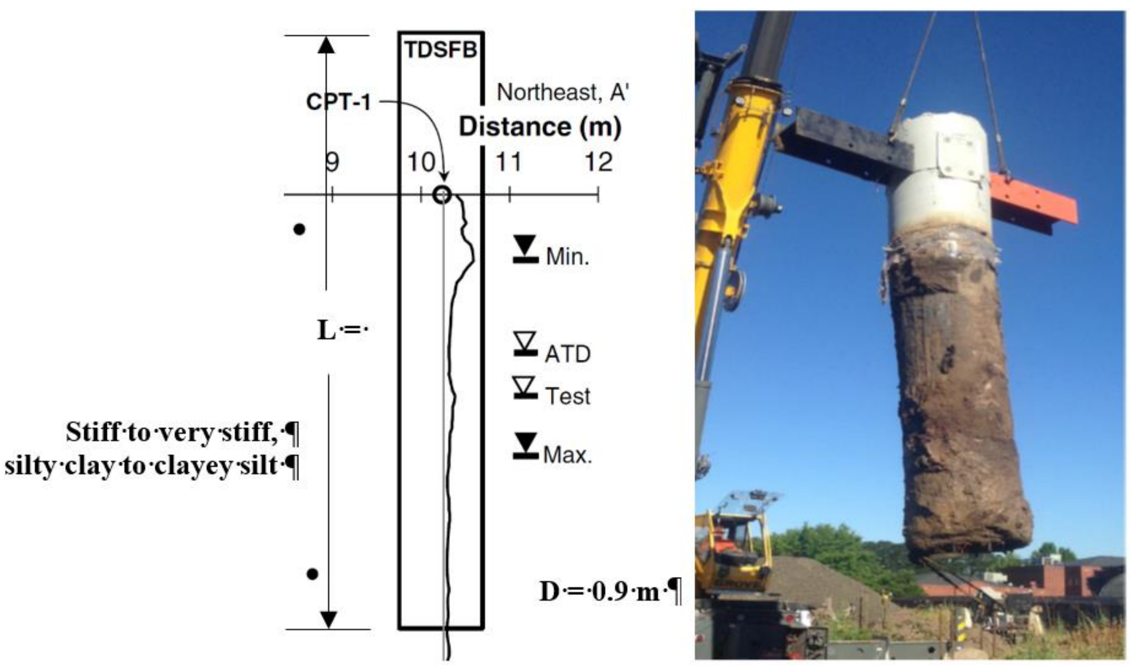


Figure 5-5: Details of torsional load testing at the OSU site by Li et al. (2017).

The details of the torsional load test are described by Li (2017) and Li et al. (2017). The measured ultimate torsional load were 180 kN-m and 250 kN-m for the test drilled shafts TDSFB (free base) and TDS, respectively. The larger torsional capacity of test drilled shaft TDS was due to the contribution of the base of the drilled shaft and also related to differences in soil conditions including a dense silty sand layer that was present near the bottom of the TDS shaft. The authors showed that the torsion load versus was well approximated by a hyperbolic model and peak load was reached after relatively small rotations of no more than 2 degrees. The predicted maximum load using the total stress α–method for drilled shafts proposed by Reese and O'Neil (1988), were reasonably close with differences not greater than 25% (Li, 2017).

5.2.3. Full-scale load tests of drilled shaft supported mast arms by UF research group

Thiyyakkandi et al. (2016) extend past centrifuge studies by the UF research group performed to investigate performance of drilled shaft foundations subjected to combined torsion and lateral loading. In this study authors present results of a full-scale tests on mast-arm-drilled shaft assemblies as the one shown in Figure 5-16. One of the main objectives of the study was to investigate the coupled lateral and torsion load behavior of drilled shafts. The study reports a significant reduction in lateral resistance due to the influence of torque that is in line with observations reported from their previous centrifuge studies. The field tests showed torsional resistance was reduced by approximately 20% by the impact of lateral load when compared with the anticipated torsional resistance predicted using static methods of the unit skin friction values like the α (clay) and β (sand) methods.

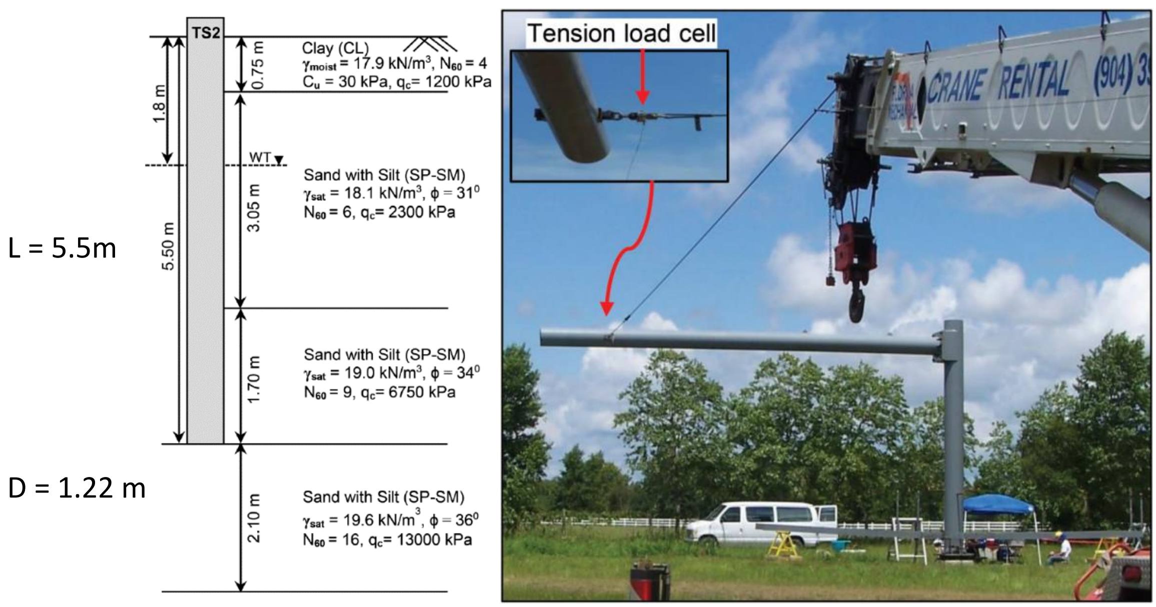
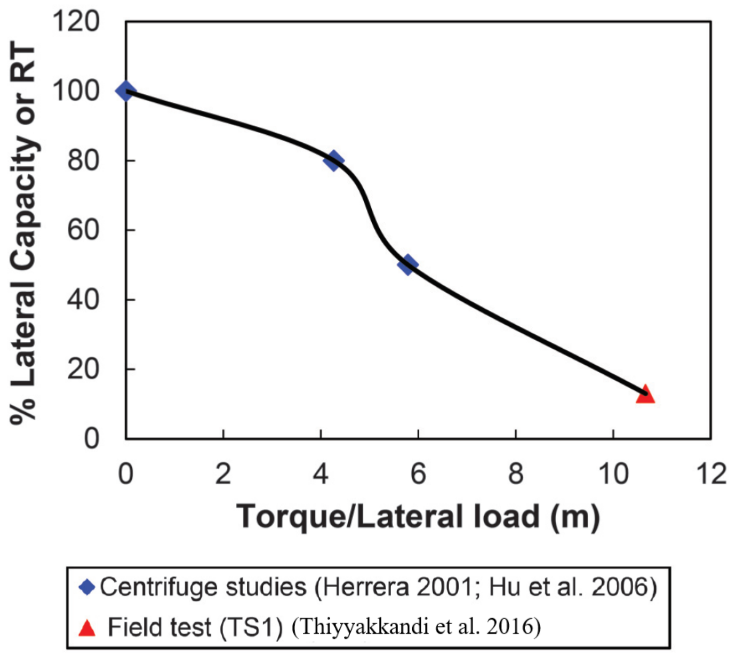


Figure 5-6: Subsurface profile and field testing setup used by Thiyyakkandi et al. (2016).

The reduction of lateral load capacity due to torsional loading measured in these field tests is shown in Figure 5-7. This figure also includes results from the UF centrifuge studies by Hu (2003) and Hu et al. (2006) that were summarized earlier. As can be seen the field test with the higher level of torsion loading resulted in a lateral load capacity drop in excess of 80%. This valuable field study further highlights the importance of considering the large reduced lateral load resistance due to the coupled effect with torsion.



[for L/D=3 and sites with predominantly sandy soils]

Figure 5-7: Reduction of lateral capacity versus torsion loading level (Thiyyakkandi et al., 2016).

5.2.4. Unit skin friction for torsion capacity

Many of the studies summarized in the previous sections, as well as SOP participants, reported use of a decoupled approach to estimate the torsional resistance of drilled shafts. The most common approach used was to compute the torsional capacity using static methods, developed from axial load tests, to estimate the unit side resistance (e.g., skin friction) that would develop along the skin surface of the drilled shaft. If we consider that the skin friction in general varies along the drilled shaft with depth, the contribution towards the torsional capacity of this side resistance for an idealized drilled shaft with a cylindrical geometry can be computed as follows:

$$T_s = \pi . D . \int_o^L f_s(z) \cdot dz \qquad (5.1)$$

where:

- T_s = torsional capacity associated to unit side resistance (skin friction),
- D = drilled shaft diameter,
- L = embedded depth of drilled shaft,
- $f_s(z)$ = unit side friction at depth z.

Based on the field tests reported by Li et al. (2017), that compared torsional capacity of a test drilled shaft with a free base versus a conventional drilled shaft, the contribution from the tip towards the torsional capacity can be significant. The contribution from the base towards the torsion capacity can be computed as the average shear stress times the area, which can be estimated:

$$T_b = (\bar{\sigma}_b \cdot \tan\delta) \cdot \left(\frac{\pi \cdot D^2}{4}\right) \cdot \bar{X} \qquad (5.2)$$

where:

- T_b = torsional capacity associated to friction along the base,
- $\bar{\sigma}_b$ = average normal stress along the base,
- δ = interface friction angle between base and soil at the base,
- $\bar{X}$ = average arm of average shear stress (D/4 for constant distribution to D/3 for triangular distribution),
- D = drilled shaft diameter.

Thiyyakkandi et al. (2017) propose an equation to estimate the contribution of the base towards the torsional capacity of the drilled shaft based on the unit weight of concrete as follows:

$$T_b = (\gamma_{con} \cdot L \cdot \tan\delta) \cdot \left(\frac{\pi \cdot D^2}{4}\right) \cdot \left(\frac{D}{3}\right) \qquad (5.3)$$

where:

- T_b = torsional capacity associated to friction along the base,
- γ_{con} = unit weight of concrete,
- δ = interface friction angle between base and soil at the base,
- L = embedded depth of drilled shaft,
- D = drilled shaft diameter.

The unit side resistance (fs) is estimated in the literature primarily using static methods based on correlations with in-situ tests that were developed from axial load tests. The most commonly used methods are reported in the FHWA drilled shaft manual (FHWA, 2010) and include the β method for sands (e.g., SPT correlation) and the α method for clays (based on undrained shear strength S_u). Use of CPT based static methods like the LCPC by Bustamante and Gianeselli (1982) was also reported by several torsion studies (Li et al. 2017; Thiyyakkandi et al. 2017).

The difference reported in Chapter 3 of empirical coefficient β used by most SOP participants (including NCDOT), versus the depth-independent ω_{FDOT} coefficient used by the FDOT highlighted the importance to further study this important design aspect. In particular, given that the static methods being used in practice were developed from axial load tests and not from actual torsional tests.

5.3. Alternative foundation systems

Although the SOP study identified the drilled shaft as the most used foundation system for traffic signal mast arm structures a few alternative systems have been reported in the literature.

Thiyyakkandi et al. (2017) reported good performance of a precast driven pile that is post-grouted along the skin area and tip. Photos of this post-grouted precast driven pile are shown in Figure 5-8. The authors report that the post-installation grouted pile had similar or higher lateral and torsion load capacities compared to a drilled shaft of similar dimensions (Thiyyakkandi et al. 2017)). This study did not comment on possible issues associated to vibrations induced during pile driving that could be a consideration at sites located in urban environments.

Figure 5-8: Photos of grouted precast pile reported by Thiyyakkandi et al. (2017).

Another possible alternative foundation system identified as having good potential to support the large loading demand of coastal mast arm traffic signals, are large diameter open ended driven steel pipe piles that were the focus of a relatively recent NCHRP study by Brown and Thompson (2015). However, mast-arm traffic signal structures often have a limited footprint right-of-way available for the installation of the foundations, thus this may limit the use of this alternative for projects with limited area.

The use of steel pipe piles with helical plate fins, as shown in Figure 5-9, has been recently reported by PND Engineers Inc. These piles, marketed under the trade name SPIN FIN™ piles, are proprietary deep foundation system by PND Engineers (2018). This type of pile, or a modified design with different types of the fins, or modified fin layout, may be a feasible foundation system alternative. In particular as the fins may help withstand the large torsional loads that as discussed are the controlling design load in the coastal mast arm comparison examples presented in Chapter 4.

Figure 5-9: Photo of SPINFIN finned pipe pile (Image from PND Engineers).

5.4. Summary

The literature review study shows that there is a need for more research to better understand the behavior of drilled shafts under combined lateral and torsion loading. The few large-scale field studies available showed that the presence of torsional loading significantly decreases the lateral capacity of the drilled shaft. There is a need for additional full-scale field tests that involved combined lateral and torsion loading. Additionally, there is a need to develop analysis and design procedures that considered the combined torsion and lateral loading in a coupled fashion.

The literature review also revealed an important gap related to the need for static methods for predicting unit skin friction for torsion loading, or preferably combined torsion with axial and bending loading. The current approach is to use static methods reported in drilled shaft manuals (e.g., FHWA 2010) that are based on axial load testing, thus their applicability to the complex loading involved in traffic signal mast arms is questionable.

In terms of alternative foundation systems that could be used for supporting mast arm coastal traffic signal structures at sites with poor geotechnical conditions three alternative systems were identified, but additional research is needed to assess their feasibility.

6. Summary and conclusions

This report presented the results of a state of practice (SOP) study performed as part of NCDOT Research Project RP 2018-17 on foundations for coastal traffic signal mast arm structures. The SOP study involved an email survey questionnaire, review of design documentation for different participants, and follow-up phone interviews to the 12 coastal U.S Departments of Transportation that participated. The main objective of the survey was to find out their construction and design practice related to foundation systems used to support traffic signal mast arm structures in coastal environments where they are often exposed to high wind loads and poor geotechnical conditions. The focus was to document information such as type of foundations used, design methodologies and procedures, design wind loading, and scope of geotechnical investigation typically used for these structures in coastal environments.

The SOP study revealed that the most commonly used foundation system to support coastal mast arm traffic signal structures was a single conventional drilled shaft. Occasional use of a drilled shaft with wing walls was reported by NCDOT, VDOT, and ALDOT for structures with high torsional loading demand on the foundation. However, VDOT and ALDOT reported that in recent years their practice was moving towards eliminating the use of wing walls due to construction and installation difficulties. The SOP study also revealed large differences in the procedure for selecting wind speed and the associated foundation loading demand. These differences are attributed to variations in timelines for transitioning from allowable stress design (ASD) to load and resistance factor design (LRFD) as well as significant changes in the load factors and wind speed maps used in the design of mast arm traffic signal structures. These differences make the comparison of design practices between coastal DOTs challenging.

At the request of the SIC, design practices between FDOT and NCDOT were compared. Personnel from the geotechnical unit of NCDOT were interested in identifying why current NCDOT design practice often requires the use of a drilled shaft with wing walls when a similar mast arm structure designed according to current FDOT practices in coastal Florida, with similar wind loading demand and mast arm dimensions used by NCDOT, would consist of a single drilled shaft without wingwalls. Therefore, this report also included comparison examples suggested by the project SIC members from the NCDOT geotechnical unit. These comparison examples considered n a fictitious mast arm traffic signal structure in a coastal site designed using current NCDOT and FDOT procedures. The comparison is challenging due to the fact that, at the time of the study, NCDOT was still using ASD design practice and ASCE 7-05 wind speed maps, while FDOT had already fully adopted LRFD based design and ASCE 7-10 wind speed maps. Therefore, recognizing inherent differences between ASD and LRFD and the significant changes in the wind speed maps and associated load factors that occurred during the transition to ASCE 7-10, the comparison problems assumed that the same design wind speed of 170 mph (Case 1) applied to both agencies. However, it was pointed out that the ASD nominal design wind speed appropriate for use with the 5th Edition AASHTO LTS would be lower than the LRFD ultimate wind speed by about 22%. The comparison problems revealed important differences in the design approach used by both agencies, particularly with respect to the mobilized unit side friction during torsion. NCDOT estimates the mobilized side friction based on the current 2010 FHWA drilled shaft manual, while FDOT uses a modified expression that is depth independent and yields unit side friction values than are 40% to 100% higher than those predicted using the FHWA drilled shaft manual (FHWA, 2010) for embedment depths of 10 ft to 30 ft, respectively. Therefore, this difference alone results in shallower drilled shaft embedment depth requirements for FDOT designs.

This report also included a literature review that summarized research on drilled shafts under the complex, multi-directional loading present in mast arm traffic signal structures. Specifically, the combined eccentric lateral and gravity loads on mast arm traffic signal structures lead to axial, shear, flexural, and torsional loads transferred to the mast arm foundation. The literature review and SOP results showed that most current design approaches adopt a decoupled approach for the analysis, where the failure loads are predicted separately for the axial loading, lateral loading, and torsional loading. However, experimental research has revealed that a significant reduction in lateral load capacity occurs when the drilled shaft is simultaneously subjected to torsion. However, the SOP study revealed that all participants use a decoupled approach for the design of drilled shafts supporting mast arm traffic signal structures that do not account for these interaction effects. The literature review also revealed an important gap in terms of static methods for predicting unit skin friction when the foundation is subjected to torsion loading combined with axial and bending forces. The current FHWA drilled shaft manual does not provide guidelines for skin friction for this loading case and the static methods used are based on experimental data from compression axial load tests. Finally, the literature review included a summary of some alternative foundation systems that have been proposed, or were deemed to have some potential, for supporting coastal traffic signal mast arm structures at sites with poor geotechnical conditions. For example, FDOT has reported investigating the feasibility of using driven post-grouted concrete piles, with the intent of the post-grouting along the shaft being able to enhance the torsion capacity. Other alternative foundation systems identified include large driven pipe piles that can be driven open or closed ended, and finned pipe piles. All these alternatives would require additional research to better assess their technical merit and feasibility.

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APPENDIX A WEBSITES USED TO COMPILE DESIGN AND CONSTRUCTION INFORMATION FOR EACH SOP PARTICIPANT

STATES INCLUDED IN THIS APPENDIX
ALDOT
FDOT
GDOT
LaDOT
MDOT
NCDOT
ODOT
SCDOT
TxDOT
VDOT
WSDOT

State DOT	Website address	Description
Alabama	https://www.dot.state.al.us/conweb/specifications.html	2018 standard specifications
	https://alletting.dot.state.al.us/Docs/Standard_Drawings/2017%20English/STDUS17_1000.pdf	Standard drawings
	https://alletting.dot.state.al.us/Docs/Standard_Drawings/2016%20English/STDUS16_1200.pdf	Standard drawings wind speed
Florida	http://www.fdot.gov/structures/StructuresManual/CurrentRelease/Vol3LTS.pdf	FDOT modifications to LRFD specifications for structural supports for highway signs, luminaires and traffic signals (lrfdlts-1)
	http://www.fdot.gov/structures/proglib.shtm	Excel Spreadsheet Mastarm-Index17743-v1.1
	http://www.fdot.gov/roadway/DS/18/IDx/17743.pdf	Standard mast arm assemblies 17743
	http://www.fdot.gov/roadway/ds/12/ids/ids-17743.pdf	Index 17743 standard mast arm "d" & "e" assemblies
	http://www.fdot.gov/structures/ProgLib.shtm	Mathcad Drilled Shaft- LRFD v1.0
	http://www.fdot.gov/roadway/DS/16/IDx/17745.pdf	Mast arms drawings
Georgia	http://mydocs.dot.ga.gov/info/gdotpubs/ConstructionStandardsAndDetails/Forms/AllItems.aspx	Standard drawings
	http://www.dot.ga.gov/PartnerSmart/Business/Source/specs/2001StandardSpecifications.pdf	Standard Specifications Construction of Transportation Systems
	http://www.dot.ga.gov/PartnerSmart/DesignManuals/SignalDesignManual/Traffic%20Signal%20Design%20Guidelines-2016.pdf	Traffic signal design guidelines
Louisiana	http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Standard_Plans/Pages/default.aspx	Standard plans / special details
	http://wwwsp.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Design-Build/AmiteBridge_Juban/RFP/I-12%20PS-08%20Geotechnical%20PS%20(11-20-09).pdf	Geotechnical performance specification

State DOT	Website address	Description
Mississippi	http://sp.mdot.ms.gov/Construction/Standard%20Specifications/2017%20Standard%20Specifications.pdf	Mississippi Standard Specifications for Road and bridge construction
	http://mdot.ms.gov/documents/lpa/checklist/722-1.pdf	Materials for Traffic Signal Installation
	http://mdot.ms.gov/bidsystem_data/20180123/PLANDATA/107241302.pdf	Standard drawings
North Carolina	https://connect.ncdot.gov/resources/safety/Pages/ITS-Design-Resources.aspx	ITS and Signals Unit Design Resources
	https://connect.ncdot.gov/resources/Geological/Documents/16-03-29_Geotechnical%20Investigation%20and%20Recommendations%20Manual.pdf	Geotechnical investigation and recommendations manual
	https://www.scdot.org/business/standard-specifications.aspx	Standard specifications for highway construction
Oregon	https://www.oregon.gov/ODOT/Engineering/Pages/Drawings-Traffic.aspx	Standard drawings - Traffic
	ftp://ftp.odot.state.or.us/techserv/roadway/web_drawings/2018_STD_July_2017_Update.pdf	Oregon standard drawings 2018 numbers and revision dates
	http://library.state.or.us/repository/2015/201512030819134/ODOT_HWY_GEOENVIRONMENTAL_docs_Geology_Geology_GDM_Chptr16.pdf	Foundation Design for Signs Signals, Luminaires, Sound Walls and Buildings
	https://www.iccsafe.org/	Https://www.iccsafe.org/
South Carolina	https://www.scdot.org/business/standard-specifications.aspx	Standard specifications for highway construction
	https://www.scdot.org/business/traffic-signals.aspx	Traffic signal design guidelines sc
	https://www.scdot.org/business/geotech.aspx	Geotechnical design manual
Texas	http://www.dot.state.tx.us/insdtdot/orgchart/cmd/cserve/standard/toc.htm	Traffic standards (english)
	https://library.ctr.utexas.edu/digitized/texasarchive/phase1/244-1-ctr.pdf	Analysis of single piles under lateral loading
	http://onlinemanuals.txdot.gov/txdotmanuals/geo/geo.pdf	Geotechnical manual
	ftp://ftp.dot.state.tx.us/pub/txdot-info/dal/specinfo/trfstds/traffic-signal-pole-foundation.pdf	Traffic signal pole foundation standard drawing

State DOT	Website address	Description
Virginia	http://www.extranet.vdot.state.va.us/LocDes/Electronic_Pubs/2008Standards/CSection1300.pdf	Index of sheets section 1300-traffic control
	http://www.virginiadot.org/business/resources/const/VDOT_2016_RB_Specs.pdf	Road and Bridge Specifications
	http://www.virginiadot.org/business/resources/IIM/TE-382_AASHTO_Standard_Specifications.pdf	VDOT Guidelines to AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaries, and Traffic Signals, 6th Edition, 2013 with 2015 interims
Washington	http://www.wsdot.wa.gov/publications/fulltext/Standards/english/PDF/j26.15-01_e.pdf	Standard drawings
	http://www.wsdot.wa.gov/publications/fulltext/Standards/english/PDF/j26.10-03_e.pdf	Standard drawings
	http://www.wsdot.wa.gov/Bridge/Structures/StandardDrawings.htm#10	General standard drawings
	http://www.wsdot.wa.gov/publications/manuals/fulltext/M23-50/BDM.pdf	Bridge design manual
	http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/design.pdf	Design manual

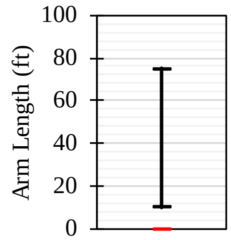
APPENDIX B – TABLES WITH SUMMARY OF SURVEY QUESTIONNAIRE AND FOLLOW-UP CONFERENCE CALLS

STATES INCLUDED IN THIS APPENDIX
NCDOT
FDOT
MassDOT
VDOT
SCDOT
GDOT
ALDOT
MDOT
LaDOT
TxDOT
ODOT
WSDOT

SUMMARY FOR NCDOT

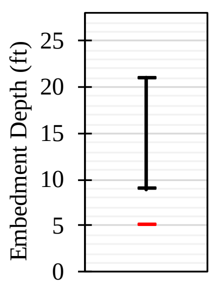
	Yes/No	Date	Contact-Person	
Questionnaire	-	-	Debesh Sarkar	dcsarkar@ncdot.gov
Follow-up conference	-	-		

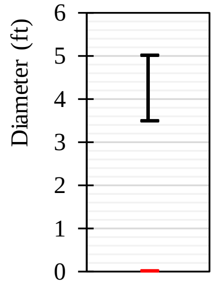
a) **Mast arm length:**



Notes/Comments:
- 10 mast arms with different lengths.

b) **Most commonly used foundation system:** Drilled Shafts





Notes/Comments:
- L-Pile 2016.9.07 for overturning and methods α or ß for torsion and axial loading.
- Spreadsheet Drilled Shaft Foundation Program_V3.4
- One case of pile cap foundation.

c) **Geotechnical exploration:** Min. Number of borings:
Requirements: SPT Yes
Other:

- Standard designs based on soil type, SPT, wind zone, and mast arm length.

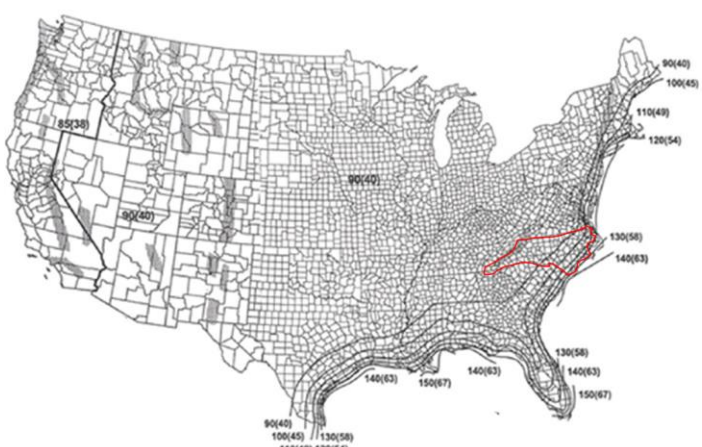
d) **Design standard used:** AASHTO 2009 - LTS 5

Wind speed in the coastal are: 140 mph

MRI: 50

Wind map:

Notes/Comments:
- 5 wind zones



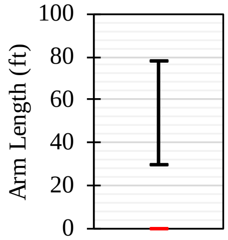
d2) **Foundation Design Standards:** See appendix C-a

e) **Reported Failures:** No Comments:

SUMMARY FOR FDOT

	Yes/No	Date	Contact-Person	
Questionnaire	**Yes**	5/29/2018	Larry Jones	larry.jones@dot.state.fl.us
Follow-up conference	**Yes**	8/22/2018		

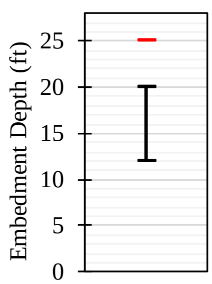
a) Mast arm length:

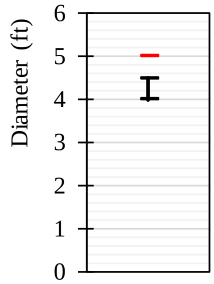


Notes/Comments:
- INDEX 17743 STANDARD MAST ARM "D" & "E" ASSEMBLIES

- See survey questionnaire in Appendix D-a.

b) Most commonly used foundation system: Drilled Shafts





Notes/Comments:
Design tools of FDOT
- Excel Spreadsheet Mastarm-Index17743-v1.1
- Mathcad Drilled Shaft- LRFD v1.0

c) Geotechnical Exploration:
Requirements:

Min. Number of borings: 1*
SPT Yes
Other:

Notes/Comments: One SPT boring to 25 ft in soil or 10 ft in competent rock with 15 ft min.

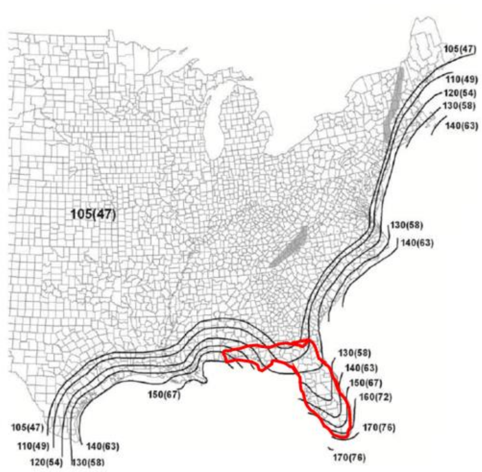
d) Design standard used: AASHTO LRFD, First Edition 2015 – LRFDLTS 1*

Wind Speed in the coastal are: 170 mph

MRI: 300

Wind Map:

Notes/Comments:
* Vol3LTS-19 modifications to LRFDLTS 1



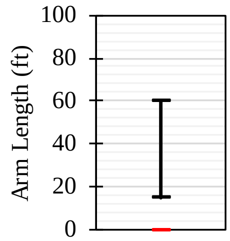
d2) Foundation Design Standards: See appendix C-b

e) Reported Failures: NO Comments:

SUMMARY FOR MassDOT

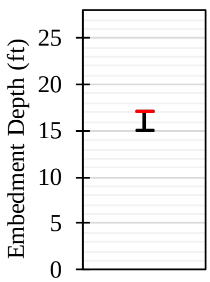
	Yes/No	Date	Contact-Person	
Questionnaire	**Yes**	5/22/2018	Peter Connors	peter.connors@state.ma.us
Follow-up conference	**No**			

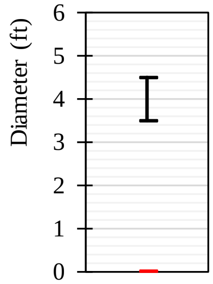
a) Mast arm length:



Notes/Comments:

b) Most commonly used foundation system: Drilled Shafts





Notes/Comments:

c) Geotechnical exploration: Min. Number of borings: 1

Requirements: SPT Yes

Other:

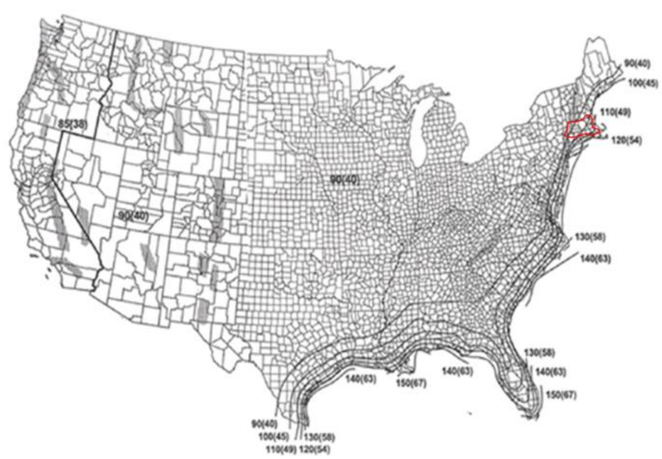
d) Design standard used: AASHTO 2013 - LTS 6

Wind speed in the coastal are 130 mph

MRI: 50

Wind map:

- Wind speed AASHTO 2013 - LTS 6.



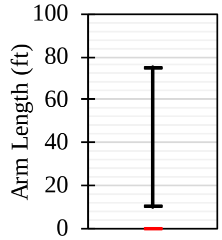
d2) Foundation design standards: See appendix N-A

e) Reported failures: NO Comments:

SUMMARY FOR VDOT

	Yes/No	Date	Contact-Person	
Questionnaire	Yes	6/26/2018	John Hall	john.hall@vdot.virginia.gov
Follow-up conferenc	Yes	9/21/2018		

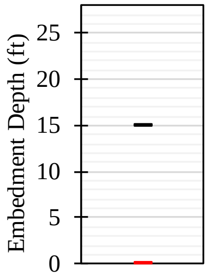
a) **Mast arm length:**

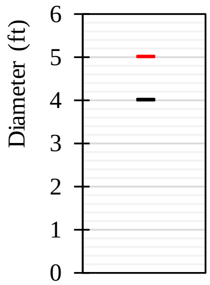


Notes/Comments:

- See survey questionnaire in Appendix D-c.

b) **Most commonly used foundation system:** Drilled Shafts





Notes/Comments:
- Notes/Comments: Drilled Shafts. We used to have a foundation that consisted on drilled shaft with "wings" for torsional resistance, but we no longer use the wings. Brom's for preliminary calculations, COM624P or L-Pile

c) **Geotechnical Exploration:** Min. Number of borings:
Requirements: SPT Yes
Other:

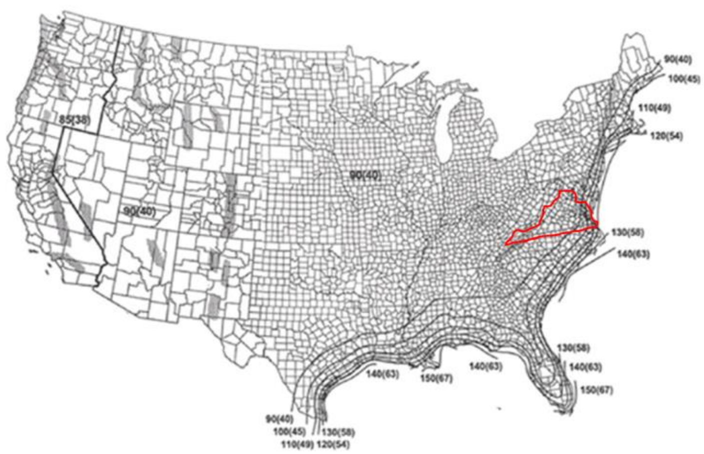
The testing general consists of simple indices tests (gradations, Atterberg limits and moisture contents).

d) **Design standard used:** AASHTO 2013 - LTS 6 - with 2015 interims

Wind Speed in the coastal are 90 mph

MRI: 50

Wind Map:



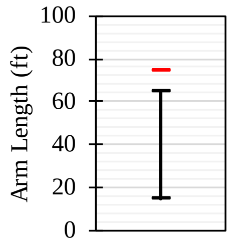
d2) **Foundation Design Standards:** See appendix C-c

e) **Reported Failures:** NO Comments:

SUMMARY FOR SCDOT

	Yes/No	Date	Contact-Person	
Questionnaire	Yes	5/22/2018	Carol Jones	JonesVC@scdot.org
Follow-up conferenc	Yes	9/21/2018		

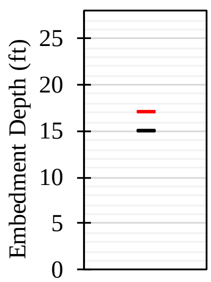
a) **Mast arm length:**

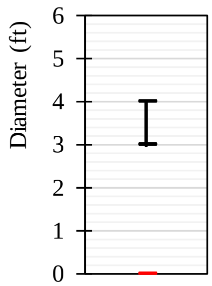


Notes/Comments:

- See survey questionnaire in Appendix D-d.

b) **Most commonly used foundation system:** Drilled Shafts





Notes/Comments:
- Structure & Foundation AASHTO LRFD Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals, 1st Edition (LRFDLTS-1).

c) **Geotechnical exploration:** Min. Number of borings:

Requirements: SPT Yes

Other:

Geotechnical exploration: Borehole of 15 ft minimum required. Undisturbed samples if is possible.

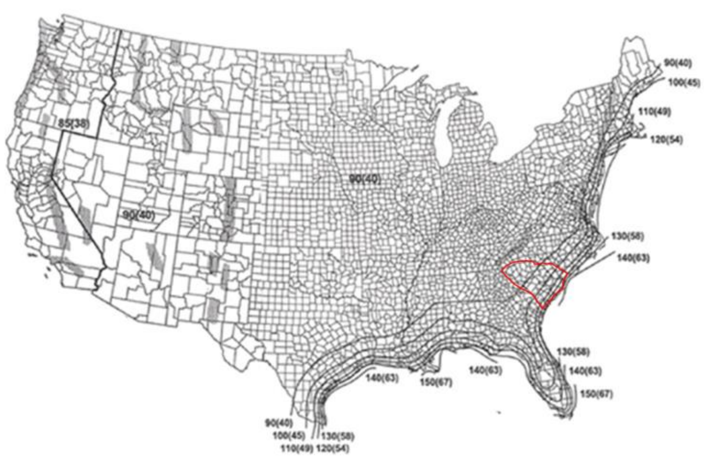
d) **Design standard used:** AASHTO 2013 - LTS 6

Wind speed in the coastal are: 110 mph

MRI: 50

Wind map:

- Wind speed AASHTO 2013 - LTS 6.



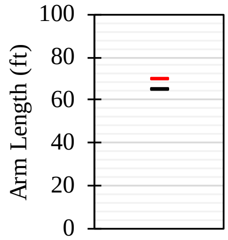
d2) **Foundation design standards:** See appendix N-A

e) **Reported failures:** NO Comments:

SUMMARY FOR GDOT

	Yes/No	Date	Contact-Person	
Questionnaire	**Yes**	5/22/2018	Glen Foster	glon_gfoster@dot.ga.gov
Follow-up conferenc	**Yes**	9/6/2018		

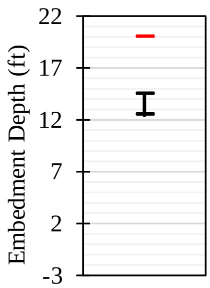
a) Mast arm length:

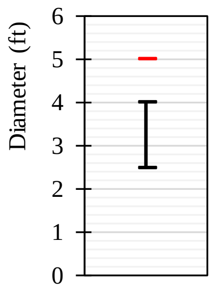


Notes/Comments:

- See survey questionnaire in Appendix D-e.

b) Most commonly used foundation system: Drilled Shafts





Notes/Comments:

c) Geotechnical Exploration:

Requirements:	Min. Number of borings:	1
	SPT	YES
	Other:	

Notes/Comments:

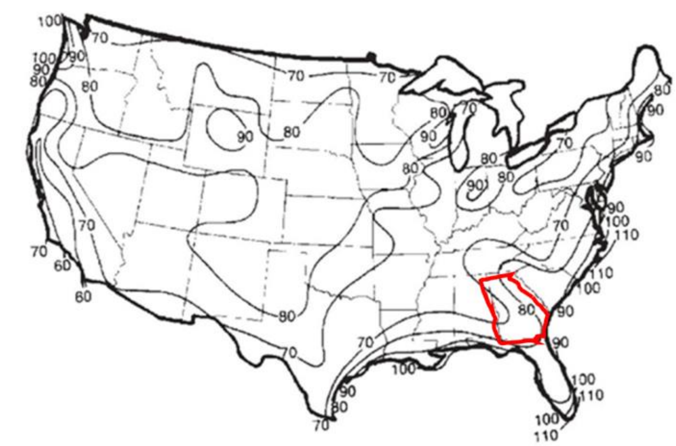
d) Design standard used: AASHTO 1994 - LTS 3

Wind Speed: 90 mph

MRI: 50

Notes/Comments:
Updating from AASHTO 1994 to LRFD 2015

Wind Map:



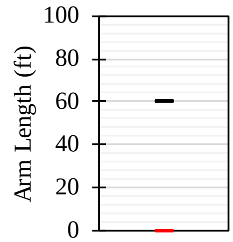
d2) Foundation Design Standards: See appendix C-d

e) Reported Failures: NO Comments:

SUMMARY FOR ALDOT

	Yes/No	Date	Contact-Person	
Questionnaire	**Yes**	6/29/2018	Kate Chancellor	zellers@wsdot.wa.gov
Follow-up conferenc	**Yes**	8/31/2018		

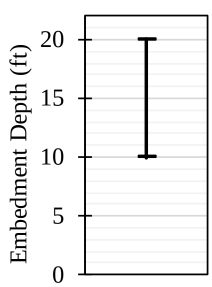
a) **Mast arm length:**

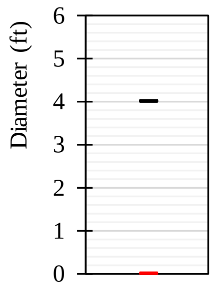


Notes/Comments:
In the past almost exclusively strain poles but now almost exclusively mast arm.

- See survey questionnaire in

b) **Most commonly used foundation system:** Drilled Shafts





Notes/Comments:
- Some units have been required to have **wing walls** attached to the drilled shafts, but we are looking at reevaluating the factor of safety used in our design to eliminate the use of the wings for our pole foundations.

c) **Geotechnical Exploration:** Min. Number of borings: 1*

Requirements: SPT Yes

Other:

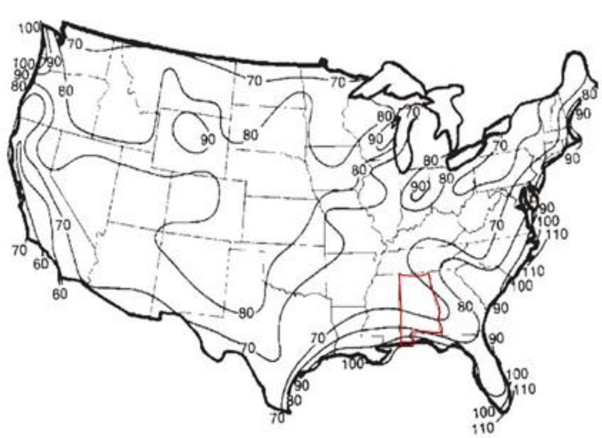
Notes/Comments: borings for each pole location, unless there are a lot of poles in a close area and the geology is such that we can extrapolate information.

d) **Design standard used:** AASHTO 1994 - LTS 3

Wind Speed in the coastal are 100 mph

MRI: 50

Wind Map:



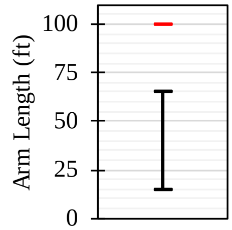
d2) **Foundation Design Standards:** See appendix N-A

e) **Reported Failures:** NO Comments:

SUMMARY FOR MDOT

	Yes/No	Date	Contact-Person	
Questionnaire	**Yes**	10/2/2018	James Sullivan	jssullivan@mdot.ms.gov
Follow-up conferenc	**Yes**	11/6/2018		

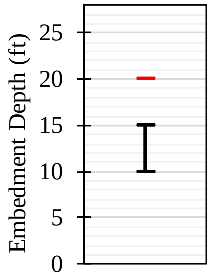
a) Mast arm length:

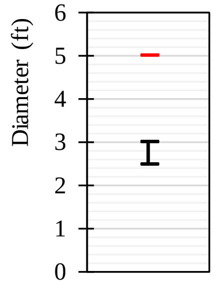


Notes/Comments:
- Longest mast arm mentioned.

- See survey questionnaire in Appendix D-g

b) Most commonly used foundation system: Drilled Shafts





Notes/Comments:
- Design based on Broms for lateral loading and skin friction for torsion loading.

* This will depend on several factors including the type, length, complexity, and scope of the project and whether it's known there are expansive clays in the profile and whether the profile is known to be fairly consistent or varied.

c) Geotechnical Exploration: Min. Number of borings: 1*
Requirements: SPT Depends*
Other:

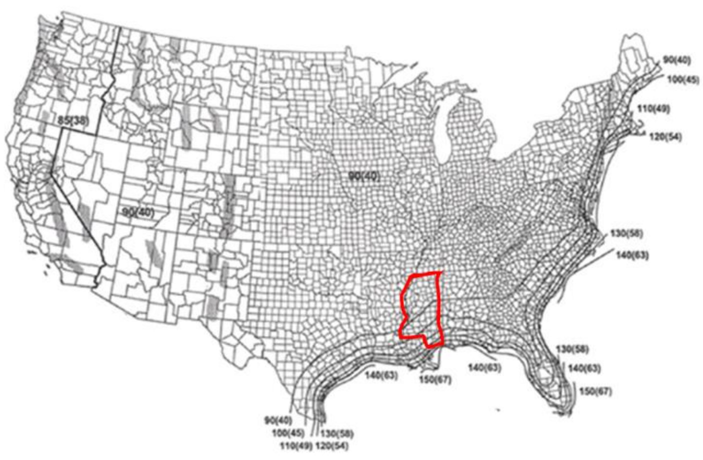
d) Design standard used: AASHTO 2001 - LTS 4

Wind Speed in the coastal are 140 mph

MRI: 50

Wind Map:

Notes/Comments:
* Vol3LTS-19 modifications to LRFDLTS 1



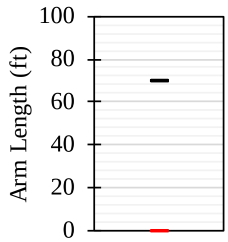
d2) Foundation Design Standards: See appendix C-e

e) Reported Failures: Yes Comments: Mast arm that have rotatet up to 90°

SUMMARY FOR LaDOT

	Yes/No	Date	Contact-Person	
Questionnaire	Yes	9/21/2018	Chris Nickel	Chris.Nickel@la.gov
Follow-up conferenc	Yes	10/4/2018		

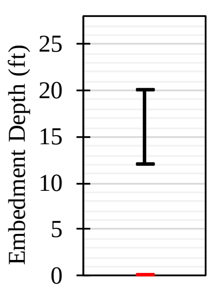
a) Mast arm length:

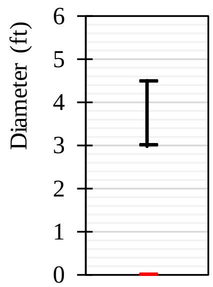


Notes/Comments:

- See survey questionnaire in Appendix D-h

b) Most commonly used foundation system: Drilled Shafts





Notes/Comments:

c) Geotechnical Exploration:
Requirements:

Min. Number of borings:
SPT
Other:

Notes/Comments: Soil maps for Louisiana for types of soils in different areas of the site

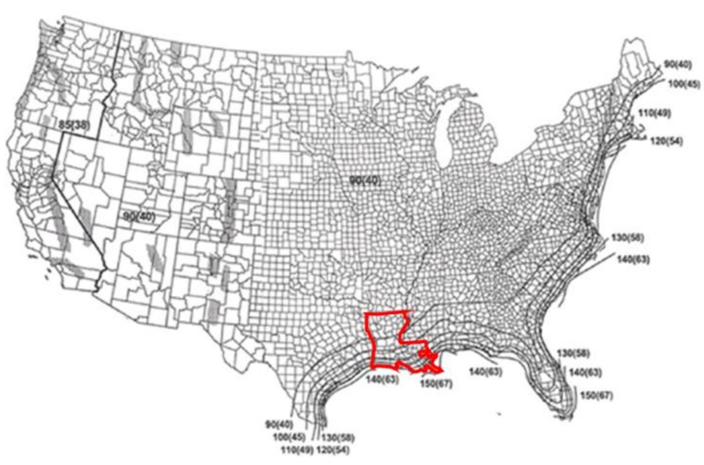
d) Design standard used: AASHTO 2001 - LTS 4

Wind Speed in the coastal are 130 mph

MRI: 50

Wind Map:

Notes/Comments:



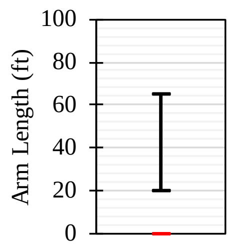
d2) Foundation Design Standards: See appendix C-f

e) Reported Failures: NO Comments:

SUMMARY FOR TxDOT

	Yes/No	Date	Contact-Person	
Questionnaire	**Yes**	6/14/2018	Steven Austin	Steven.Austin@txdot.gov
Follow-up conferenc	**Yes**	8/31/2018		

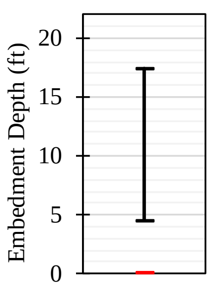
a) **Mast arm length:**

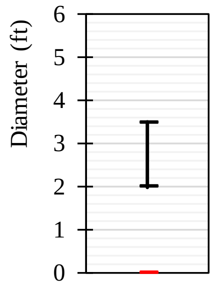


Notes/Comments:

- See survey questionnaire in Appendix D-i

b) **Most commonly used foundation system:** Drilled Shafts





Notes/Comments:

c) **Geotechnical Exploration:** Min. Number of borings: 1

Requirements: SPT -

Other: TCP*

Notes/Comments: Texas Cone Penetrometer is using stead SPT

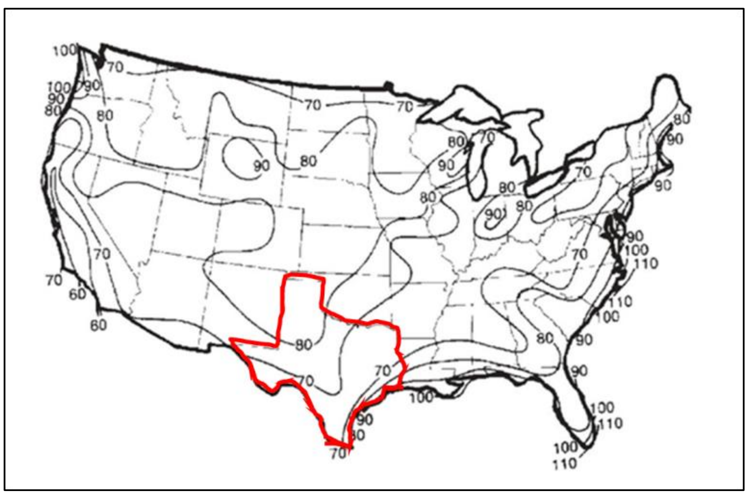
d) **Design standard used:** AASHTO 1994 - LTS 3

Wind Speed in the coastal are 100 mph

MRI: 50

Wind Map:

Notes/Comments:



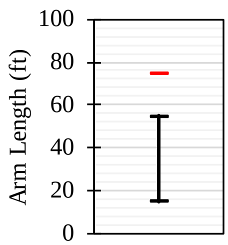
d2) **Foundation Design Standards:** See appendix C-g

e) **Reported Failures:** NO Comments: 0

SUMMARY FOR ODOT

	Yes/No	Date	Contact-Person	
Questionnaire	**Yes**	5/29/2018	Scott JOLLO	Scott.U.JOLLO@odot.state.or.us
Follow-up conferenc	**Yes**	8/22/2018		

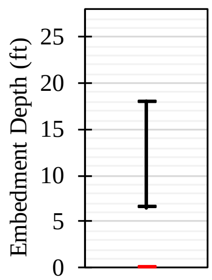
a) Mast arm length:

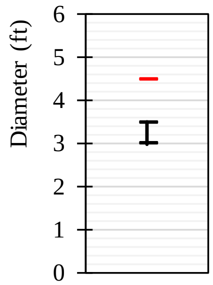


Notes/Comments:

- See questionnaire in Appendix D-j

b) Most commonly used foundation system: Drilled Shafts





Notes/Comments:
- Design is based in LPile and skin friction.
- The foundation conditions at the signal pole site should be investigated and characterized in terms of soil type, soil unit weight, and soil friction angle

c) Geotechnical Exploration: Min. Number of borings: 1*

Requirements: SPT Yes

Other:

Notes/Comments: Foundation within 75' with uniform soil have one boring wit SPT.

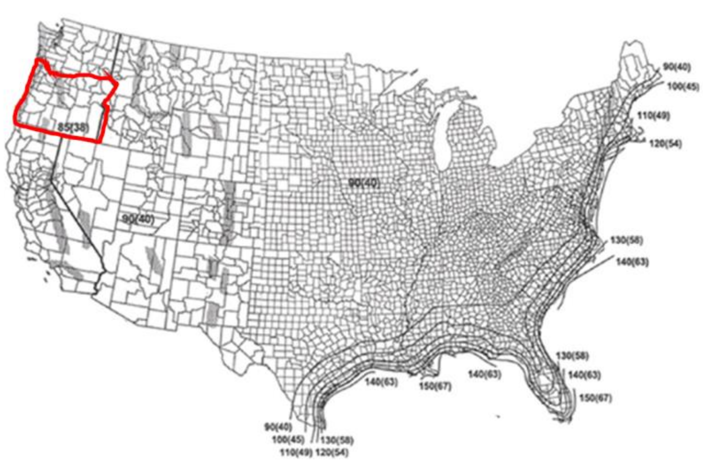
d) Design standard used: AASHTO 2001 - LTS 4 & for wind speed AASHTO 2013 -LTS 6

Wind Speed in the coastal are 110 mph

MRI: 50

Wind Map:

Notes/Comments:



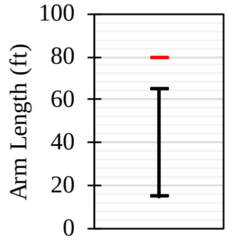
d2) Foundation Design Standards: See appendix

e) Reported Failures: NO Comments:

SUMMARY FOR WSDOT

	Yes/No	Date	Contact-Person	
Questionnaire	**Yes**	6/24/2018	Scot Zeller	zellers@wsdot.wa.gov
Follow-up conferenc	**Yes**	8/28/2018		

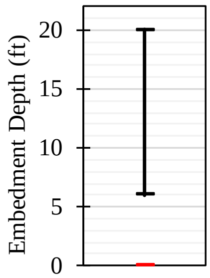
a) Mast arm length:

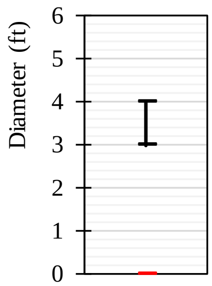


Notes/Comments:

- *See questionnaire in Appendix D-k*

b) Most commonly used foundation system: Drilled Shafts





Notes/Comments:
- Broms approximate method & torsion in WSDOT bridge design manual 10.1.5C
- Foundations that instead of wing have trench.

c) Geotechnical Exploration: Min. Number of borings: 1*

Requirements: SPT Yes

Other:

Notes/Comments: Bore hole or test pit for each location. Some cases consistency in subsurface.

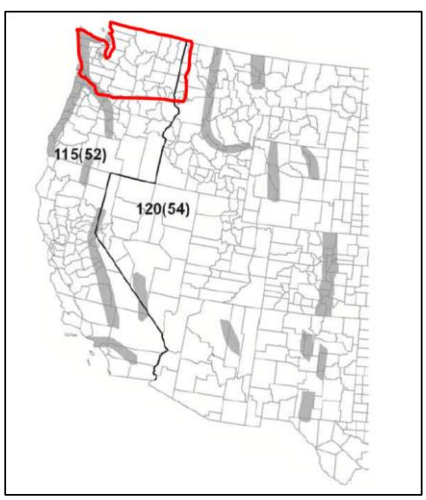
d) Design standard used: AASHTO LRFD, First Edition 2015 – LRFDLTS 1

Wind Speed in the coastal are 115 mph

MRI: 1700

Wind Map:

Notes/Comments:



d2) Foundation Design Standards: See appendix C-h Based in older standard plan

e) Reported Failures: NO Comments:

APPENDIX C- SUMMARY OF STANDARD DESIGNS

STATES INCLUDED IN THIS APPENDIX	
NCDOT	C-a
FDOT	C-b
VDOT	C-c
GDOT	C-d
MDOT	C-e
LaDOT	C-f
TxDOT	C-g
WSDOT	C-d

a) Summary of standard design for North Carolina:

The State of North Carolina is divided into 5 wind zones, **Figure C-1**.

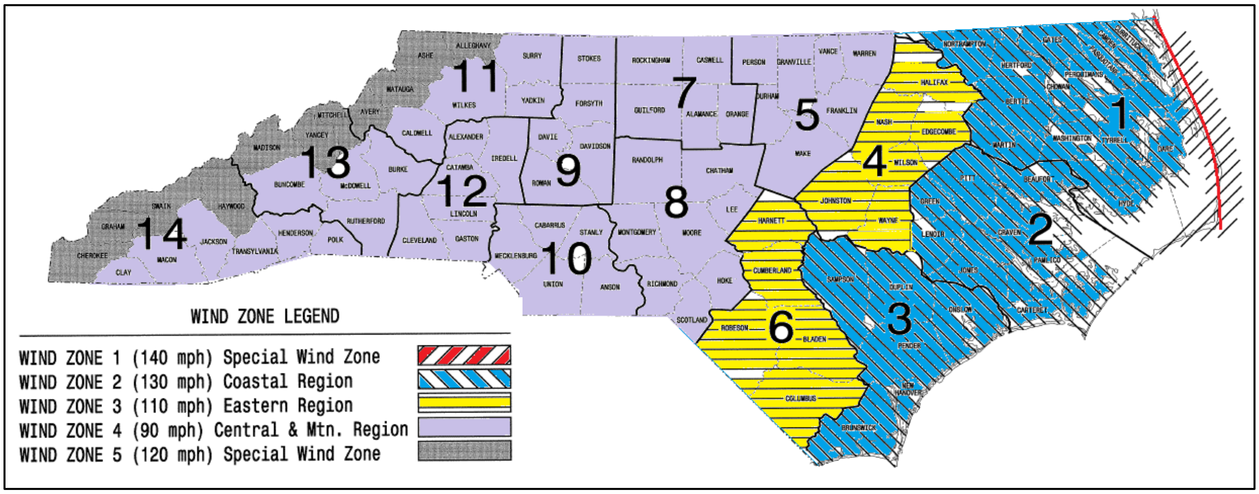


Figure C-1: Wind speed zone in North Carolina (NCDOT)

The procedure to select the drilled shaft embedment depth: first, from Figure C-1, a wind zone is selected; second, from Figure C-2, choose a mast arm number (red square); the third step is to define a type of soil (blue square), where options are cohesive and cohesionless; and finally, a SPT blow count will determine the embedment depth (green square). Each load case is assigned a drilled shaft diameter (purple square).

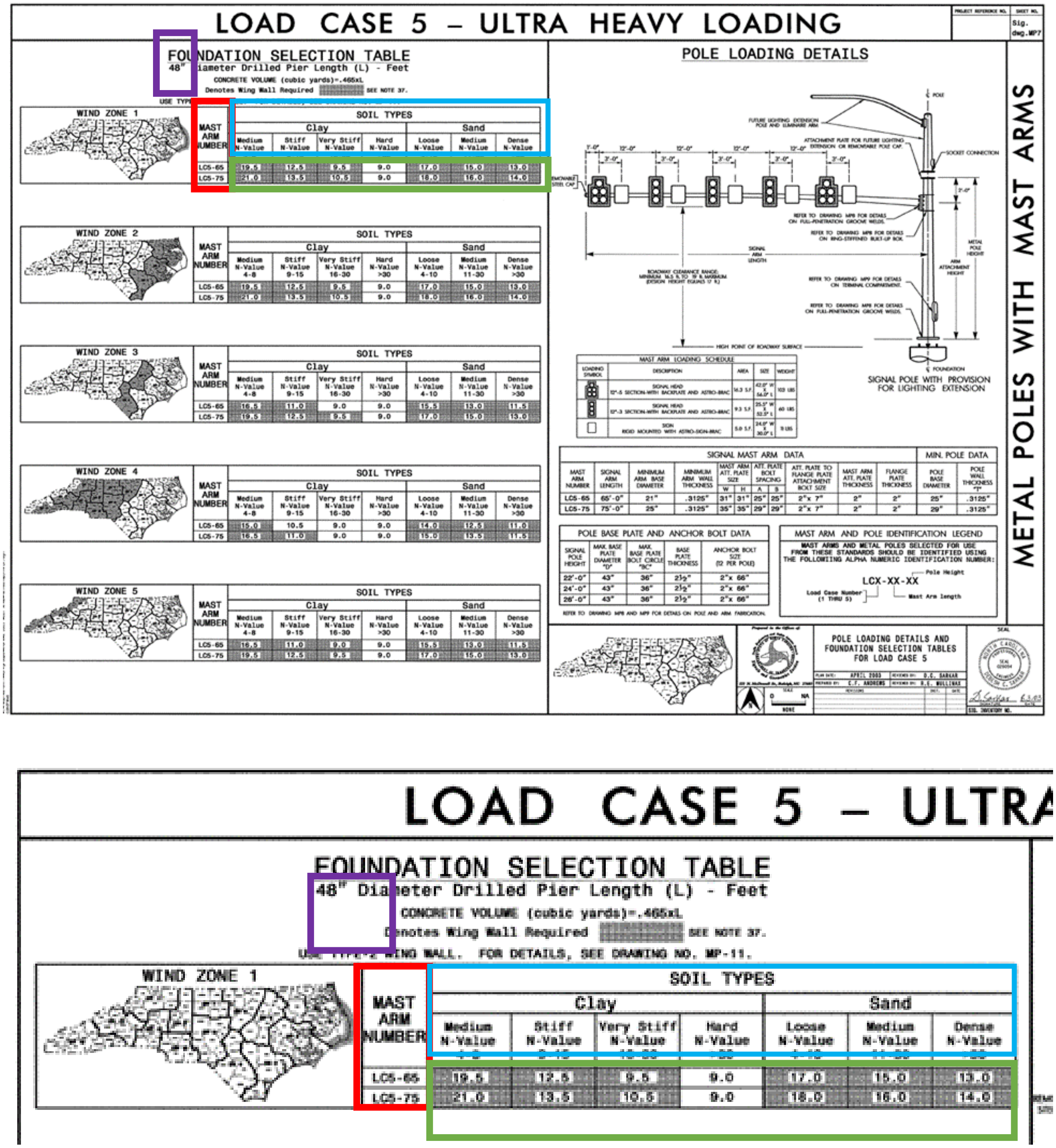


Figure C-2: North Carolina embedment depth and diameter selection (NCDOT)

b) Summary of standard design for Florida:

Below, the mast arm foundation design procedure, found in FDOT's website, is described.

i) The first step corresponds to choosing the mast arm elements (arm and pole). The possible combinations are found in Table 1 and 2 in the STANDARD MAST ARM ASSEMBLIES, Index No. 17743. The arm length depends on the number of lanes, the route configuration and the number of intersections. The arm and pole characteristics are found in Tables 1 and 2 in STANDARD MAST ARM ASSEMBLIES, Index No.17743 and No.17745 as shown in Figure C-3.

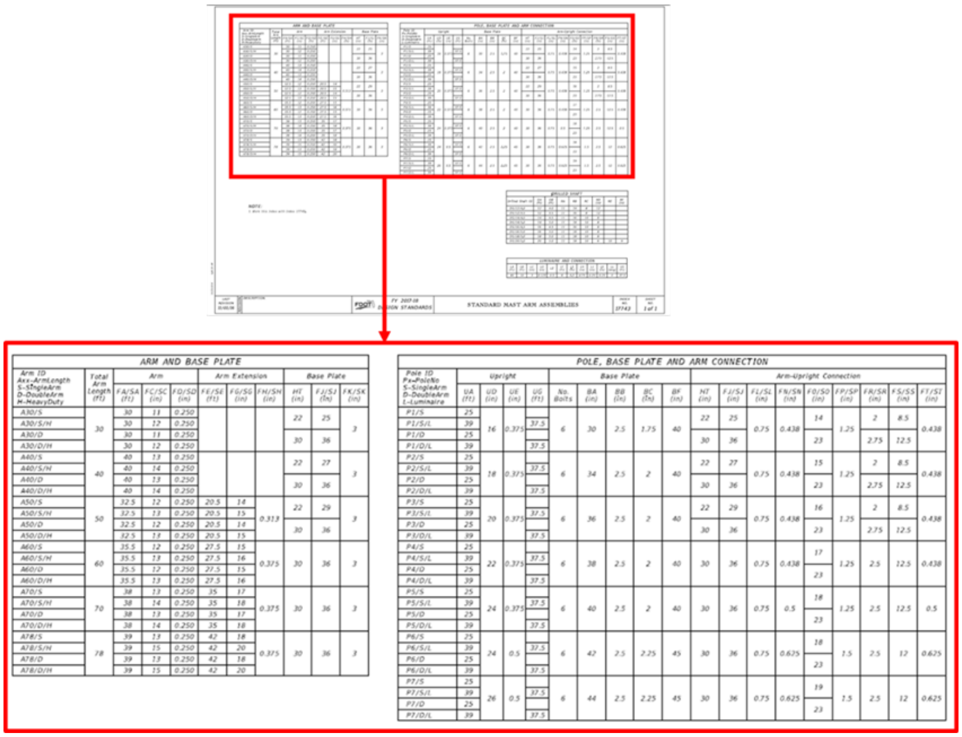


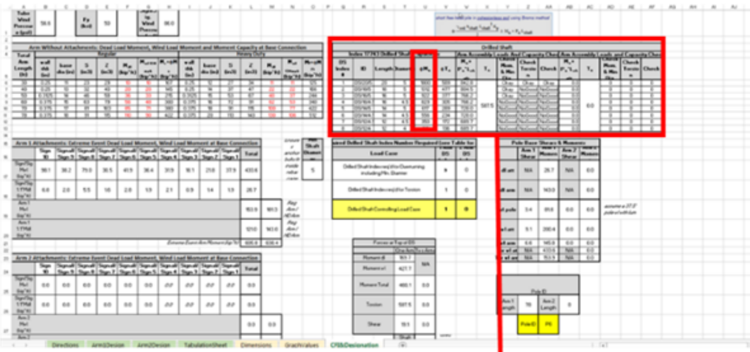
Figure C-3: Standard Mast Arm Assemblies Document (FDOT 2016).

ii) The lateral moment is calculated using the equation given in the spreadsheet; see also Figure C-4.

$$\phi \cdot \frac{\gamma_{soil} \cdot b_{shaft} \cdot L_{shaft}^{3} \cdot K_p}{2} \geq M_u + P_u \cdot L_{shaft}$$

Figure C-4: Lateral Moment Equation (FDOT 2016).

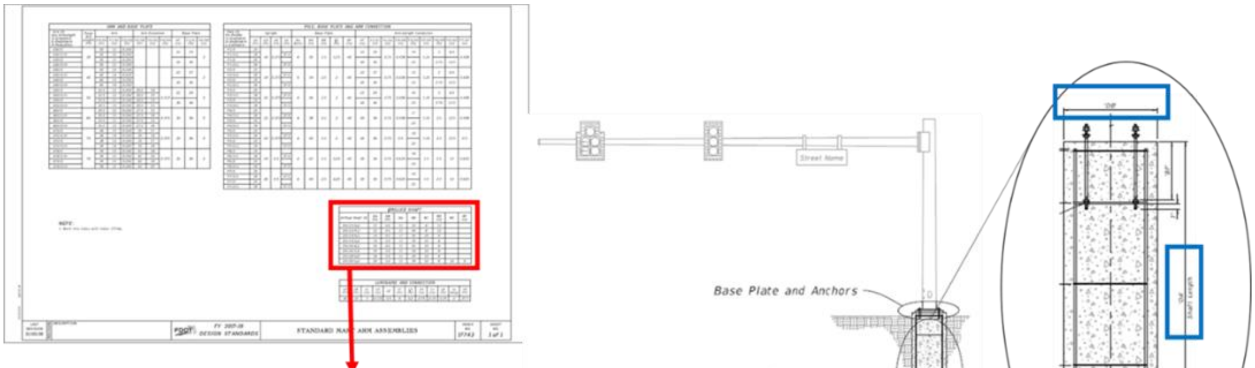
Florida DOT provides eight drilled shafts with different geometries (depth and diameter); for these geometries, the lateral capacity is calculated following Brom's theory (1964). These values are provided by Florida DOT in the spreadsheet Mastarm-Index17743-v1.1 – Sheet CFI&Designation – Table DRILLED SHAFT – Column 7; see Figure C-5.



Drilled Shaft															
Index 17743 Drilled Shaft Capacities						1 Arm Assembly Loads And Capacity Check					2 Arm Assembly Loads and Capacity Check				
DS Index #	ID	Length	Diameter	ϕM_n	ϕT_n	$M_u + P_u{}^*L_{shaft}$	T_u	Check Mom. & Min Dia.	Check Torsion	Check	$M_u + P_u{}^*L_{shaft}$	T_u	Check Mom. & Min Dia.	Check Torsion	Check
1	DS/20/5	20	5	1800	589	842.8	587.5	Okay	Okay	Okay	0.0	0.0	0	0	0
2	DS/18/5	18	5	1312	477	804.5		Okay	NoGood	NoGood	0.0		0	0	0
3	DS/16/5	16	5	922	377	766.2		Okay	NoGood	NoGood	0.0		0	0	0
4	DS/16/4.5	16	4.5	829	305	766.2		NoGood	NoGood	NoGood	0.0		0	0	0
5	DS/14/5	14	5	617	289	728.0		NoGood	NoGood	NoGood	0.0		0	0	0
6	DS/14/4.5	14	4.5	556	234	728.0		NoGood	NoGood	NoGood	0.0		0	0	0
7	DS/12/4.5	12	4.5	350	172	689.7		NoGood	NoGood	NoGood	0.0		0	0	0
8	DS/12/4	12	4	311	136	689.7		NoGood	NoGood	NoGood	0.0		0	0	0

Figure C-5: Spreadsheet of Florida DOT Drilled Shaft Dimensions (FDOT 2016).

The information on drilled shaft geometry used by Florida DOT is provided in spreadsheet Mastarm-Index17743-v1.1 – Sheet CFI & Designation – Table DRILLED SHAFT – Columns 2 and 3; see Figure C-6.

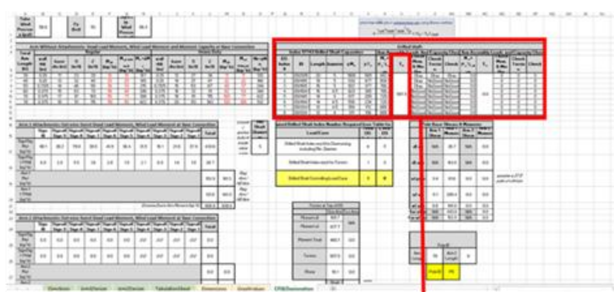


DRILLED SHAFT								
Drilled Shaft ID	DA	DB	RA	RB	RC	RD (in)	RE	RF (in)
DS/12/4.0	12	4.0	11	14	8	12		
DS/12/4.5	12	4.5	11	16	8	12		
DS/14/4.5	14	4.5	11	16	10	8		
DS/14/5.0	14	5.0	11	18	10	8		
DS/16/4.5	16	4.5	11	16	10	8		
DS/16/5.0	16	5.0	11	18	10	8		
DS/18/5.0	18	5.0	11	18	10	8		
DS/20/5.0	20	5.0	11	18	10	6	10	9

Figure C-6: Florida DOT Drilled Shaft Dimensions (FDOT 2016).

iii) Once the lateral moment is verified, the torsion parameter should be calculated using the mast arm geometry and the elements selected.

The torsion moment is compared with the value calculated using the Beta Theory Method. The FDOT spreadsheet provides a set of values calculated with the Beta Theory Method for different drilled shaft geometries; see Figure C-7.



Drilled Shaft															
Index 17743 Drilled Shaft Capacities						1 Arm Assembly Loads And Capacity Check					2 Arm Assembly Loads and Capacity Check				
DS Index #	ID	Length	Diameter	ϕM_n	ϕT_n	$M_u + P_u * L_{shaft}$	T_u	Check Mom. & Min Dia.	Check Torsion	Check	$M_u + P_u * L_{shaft}$	T_u	Check Mom. & Min Dia.	Check Torsion	Check
1	DS/20/5	20	5	1800	589	842.8	587.5	Okay	Okay	Okay	0.0	0.0	0	0	0
2	DS/18/5	18	5	1312	477	804.5		Okay	NoGood	NoGood	0.0		0	0	0
3	DS/16/5	16	5	922	377	766.2		Okay	NoGood	NoGood	0.0		0	0	0
4	DS/16/4.5	16	4.5	829	305	766.2		NoGood	NoGood	NoGood	0.0		0	0	0
5	DS/14/5	14	5	617	289	728.0		NoGood	NoGood	NoGood	0.0		0	0	0
6	DS/14/4.5	14	4.5	556	234	728.0		NoGood	NoGood	NoGood	0.0		0	0	0
7	DS/12/4.5	12	4.5	350	172	689.7		NoGood	NoGood	NoGood	0.0		0	0	0
8	DS/12/4	12	4	311	136	689.7		NoGood	NoGood	NoGood	0.0		0	0	0

Figure C-7: Florida DOT Drilled Shaft Dimensions (FDOT 2016).

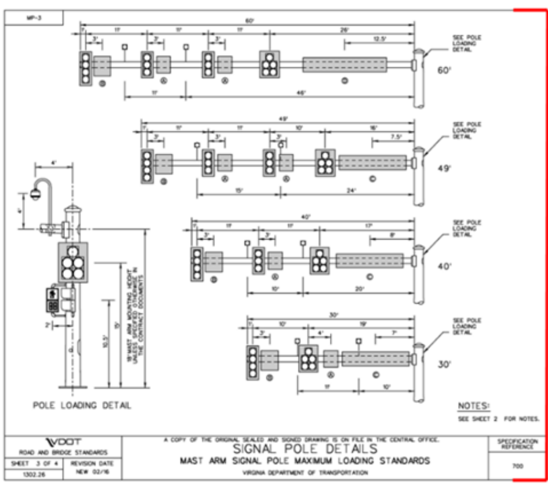
c) Summary of standard design for Virginia:

Bearing pressure:

First, the tip resistance/bearing pressure parameter is calculated using Brom's theory for piles, considering the loads shown in Figure C-8. However, other methods (or software) are used to estimate shaft deflections. In terms of these parameters the following is defined:

For mast arm signals and span wire signals, the maximum total horizontal deflection shall not be greater than 0.75 inches at ground level and 0.25 inches at the pole tip.

For other structures, the maximum total horizontal deflection shall not be greater than 0.5 inches at ground level and 0.15 inches at the pole tip.



DEVICE		SURFACE AREA (SEE NOTES 5 & 6)	DEAD LOAD (SEE NOTE 6)
	3-SECTION SIGNAL HEAD W/ BACKPLATE	8.7 SF	65 LBS
	4-SECTION SIGNAL HEAD W/ BACKPLATE	11.0 SF	80 LBS
	5-SECTION SIGNAL HEAD W/ BACKPLATE (IN-LINE)	13.4 SF	95 LBS
	5-SECTION SIGNAL HEAD W/ BACKPLATE (DOGHOUSE/CLUSTER)	13.75 SF	105 LBS
	SP-9 PEDESTRIAN SIGNAL HEAD	2.4 SF	30 LBS
A	30" x 36" SIGN	7.5 SF	22.5 LBS
B	36" x 42" SIGN	10.5 SF	26.7 LBS
C	12' x 2.5' STREET NAME SIGN	30 SF	66 LBS
D	15' x 2.5' STREET NAME SIGN	37.5 SF	88.5 LBS
	VIDEO CAMERA	1.00 SF	22 LBS

Figure C-8: Virginia Plan MP-3 Document (VDOT 2016a).

Torsion moment:

The second parameter corresponds to torsion/sliding/skin friction and is to be evaluated following the *ASSHTO LRFD Bridge Design Specifications* (AASHTO, 2015). Section 10.8.3.5- Nominal Axial Compression Resistance of Single Drilled Shafts,

Drilled shaft characteristics are defined in standard drawings, *Signal Pole Foundation Installation Details,* plan PF-8. VDOT does not define a range of drilled shaft diameters and depths, but defines minimum values instead. Nevertheless, the use of wing walls are specified when required. Drawings of a typical wing wall is shown in Figure C-9 (VDOT, 2016a).

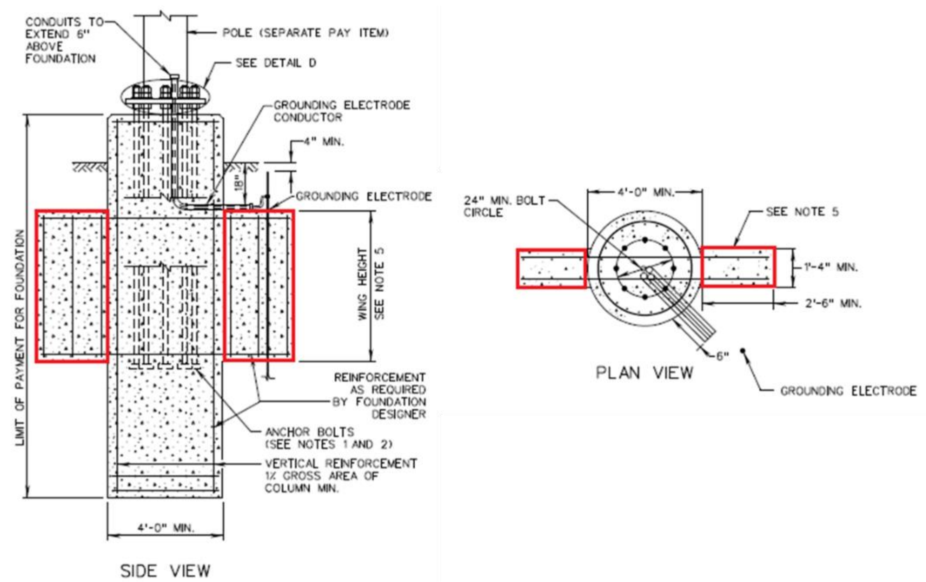


Figure C-9: Virginia Plan PF-8 Document (VDOT 2016a)

d) Summary of standard design for Georgia:

Each mast arm and traffic signal support require, at a minimum, a drawing indicating the location and the foundation design. Georgia DOT (and other DOTs) provides a standard drawing, where guidelines for specified foundations can be found. The current SOP recommends drilled shaft foundations.

The traffic signal detail, DETAILS OF STRAIN POLE AND MAST ARM FOUNDATIONS TS-06, of GDOT shows the conditions, geometries and specifications for their drilled shafts. The drawing is divided into three charts providing three geotechnical parameters (unit weight, friction angle and cohesion) for different types of soils: Piedmont, Valley & Ridge and Coastal Plain; see Figure C-10 (GDOT, 2010).

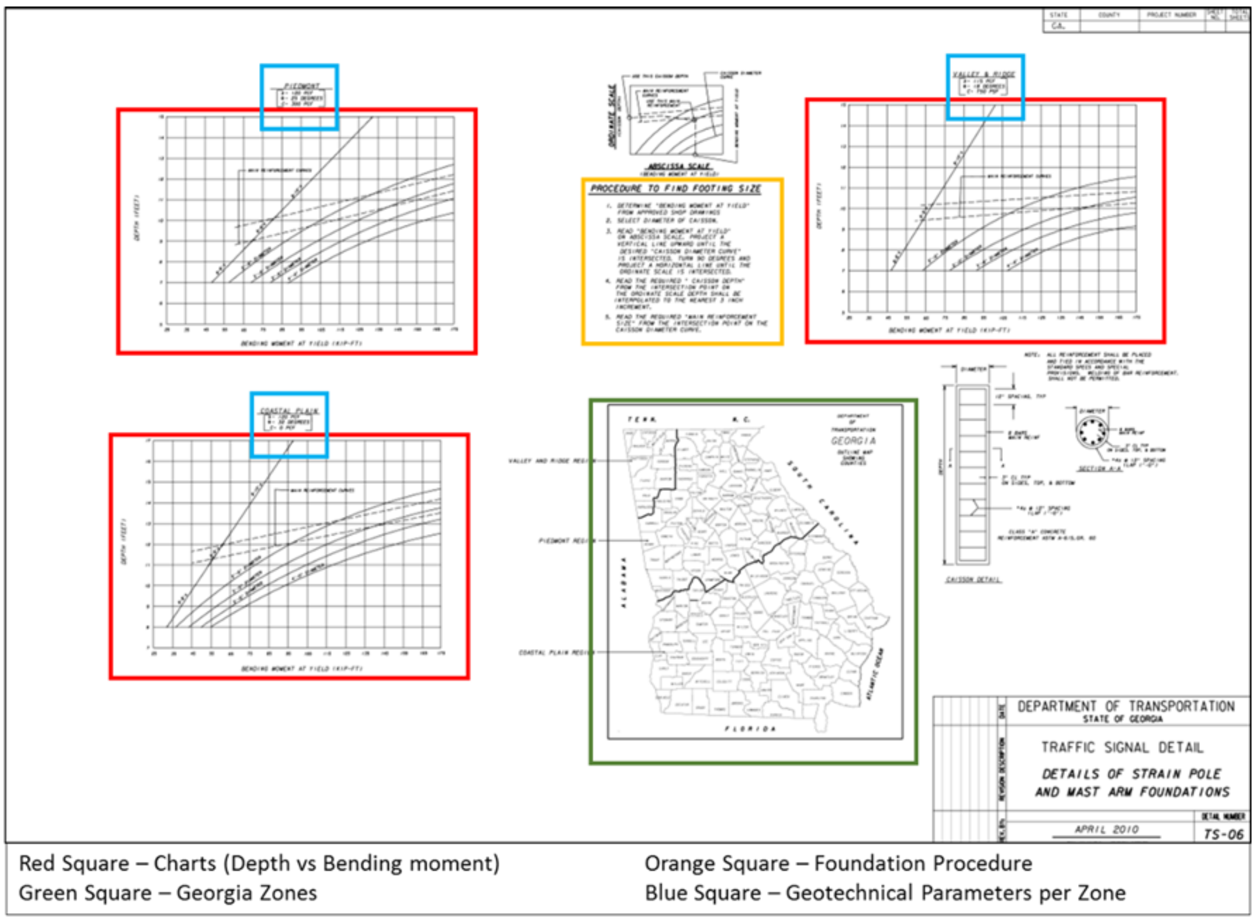


Figure C-10: TS-06 Standard Drawing , Modified from (GDOT 2010).

The charts in Figure C-10 correspond to different drilled shaft dimensions (depth, diameter) and in the y-axis different h/d ratios. The squares shown represents the minimum and maximum limits for a specific drilled shaft condition. In some cases, two vertical lines displays the maximum and minimum geometries when all the conditions are considered. Figure C-11 displays the variation of drilled shaft depth with bending moment at yield for a family of shaft diameters.

Once the standard drawing has been identified, GDOT specifies the procedure below to determine the most accurate drilled shaft in terms of depth and diameter.

- Identify the zone where the traffic signal or highway signs will be located; this is shown in the green box in Figure C-10.
- Determine the maximum bending moment at yield using an approved theoretical method.
- Select the desired shaft diameter, curves 1 to 4 identified in Figure C-11.

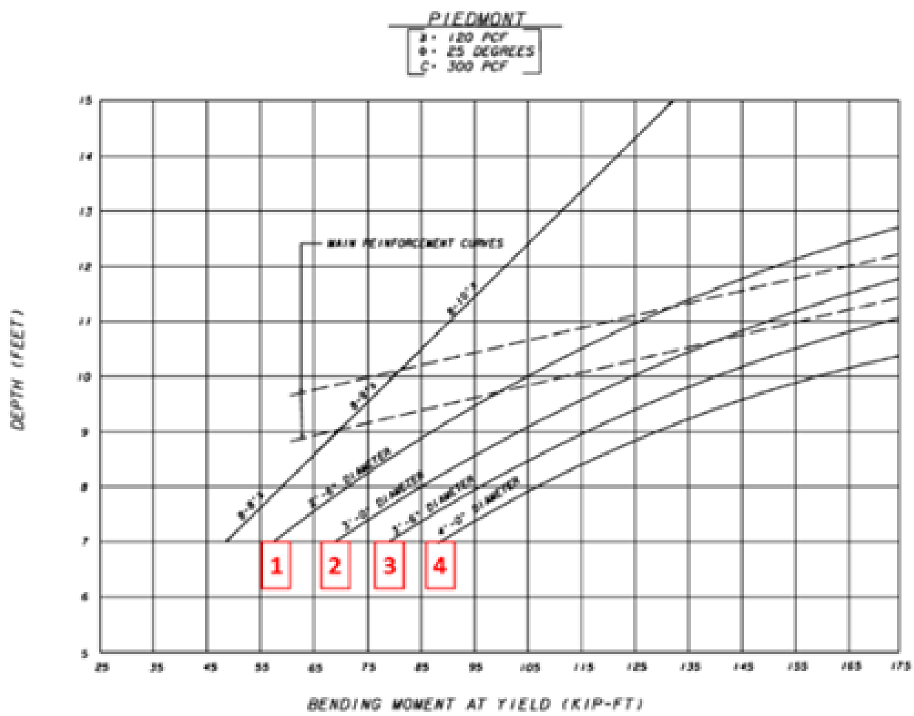


Figure C-11: Georgia Drilled Shafts Diameters (GDOT 2010).

- Use the bending moment found above and draw a vertical line up to intersect the curve for the desired diameter of the shaft.

- Read off the corresponding depth of the shaft by drawing a horizontal line from the point of intersection (from the step above) to the vertical axis. The main reinforcement size is taken at the point where the vertical line intersects the Main Reinforcement Curves, dashed blue lines in Figure C-12.

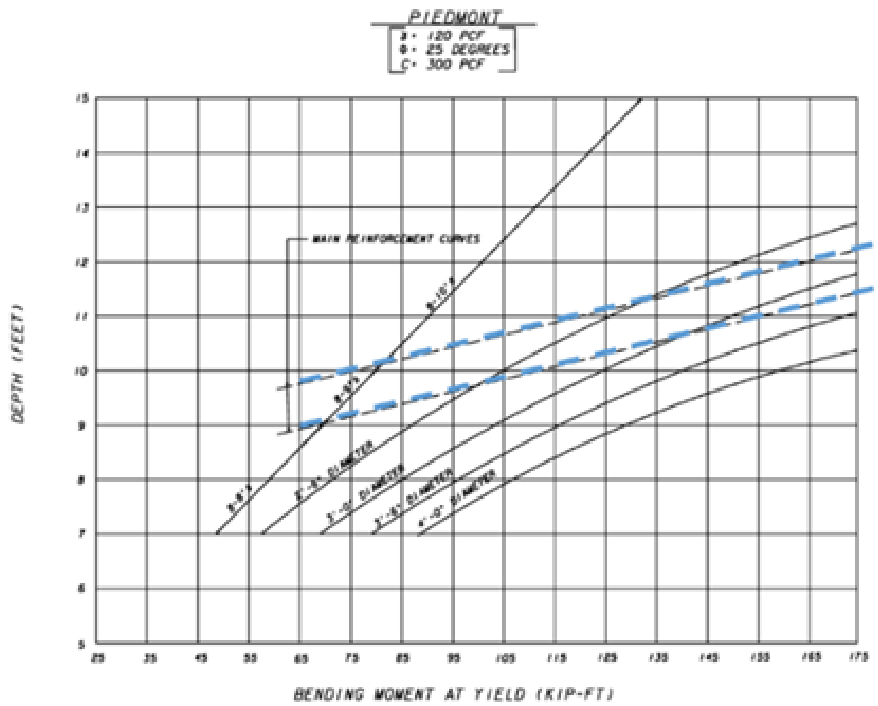


Figure C-12: Georgia reinforcement drilled shafts. (GDOT 2010).

The three soil parameters were used to calculate drilled shaft depths for the three soil types using Brom's assumptions for cohesive and non-cohesive soils, as shown in Figure C-13.

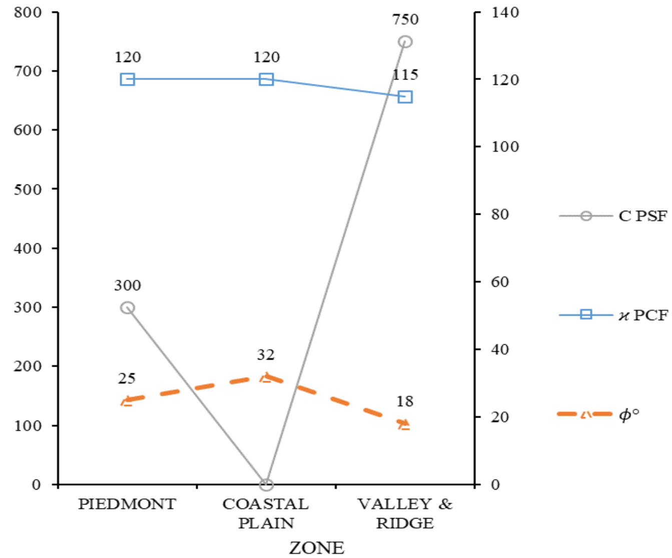


Figure C-13: Zones of Georgia Corresponding to geotechnical parameters (GDOT 2010).

e) Summary of standard design for Mississippi:

MDOT has assigned two standard foundations that depend on location in its TSD-6.DGN standard drawing. There are two location options: coastal areas (blue square) and other areas (red square), as shown in Figure C-14.

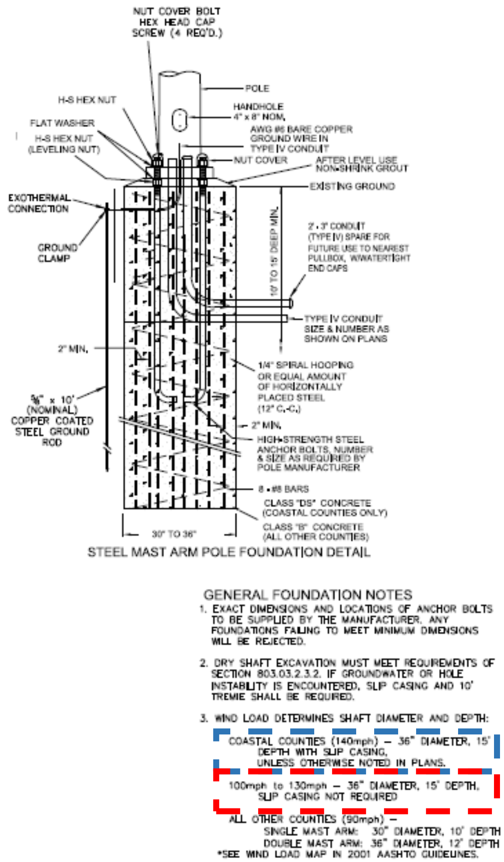


Figure C-14: MDOT Drilled Shaft Dimensions.

f) Summary of standard design for Louisiana:

i) Identify the mast arm location, zones 1 to 4 in Figure C-15.

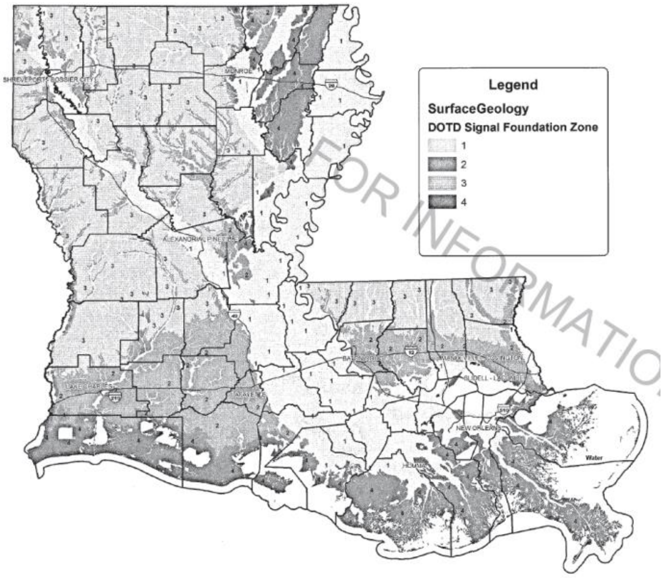


Figure C-15: LaDOT signal foundation zone.

ii) In Figure C-16, identify the length in feet for a single or double mast arm (red square); select the foundation design (diameter and depth) for a given zone (green square).

FOUNDATION SIZE SELECTION TABLE												
Mast Arm Length(s) (ft)	Bending Moment (ft-lb)	Torsion (ft-lb)	Shear (lb)	Axial Force (lb)	*Foundation Size Selection (diameter in inches, depth in feet)*							
					Zone 1 (Diameter/Depth)		*Zone 2+ (Diameter/Depth)*		*Zone 3+ (Diameter/Depth)*		*Zone 4 (Diameter/Depth)*	
55	125,120	121,100	5,500	5,862	*	*	42	18	36	14	*	*
60	141,805	128,940	5,930	6,561	*	*	42	19	36	15	*	*
65	161,259	150,480	6,130	6,965	*	*	48	17	36	16	*	*
70	182,103	169,590	6,620	7,377	*	*	48	19	36	17	*	*
50 & 35	142,210	101,630	5,860	7,572	54	18	36	20	36	13	*	*
50 & 40	147,540	101,610	5,860	7,798	54	18	36	20	36	13	*	*
55 & 40	159,408	119,900	5,910	8,195	*	*	42	18	36	14	*	*
55 & 45	165,981	119,870	5,910	8,425	*	*	42	18	36	14	*	*
**: Special Design Foundation Required*												

Figure C-16: Foundation size selection table.

g) Summary of standard design for Texas:

The design table for drilled shaft foundations is shown in Figure C-17. Five types of drilled shafts are defined: 24-A, 30-A, 36-A, 36-B and 40-A. The geometries, design loads and embedded lengths for each type are define in the drawing TS-FD-12. The colored boxes highlight the following information:

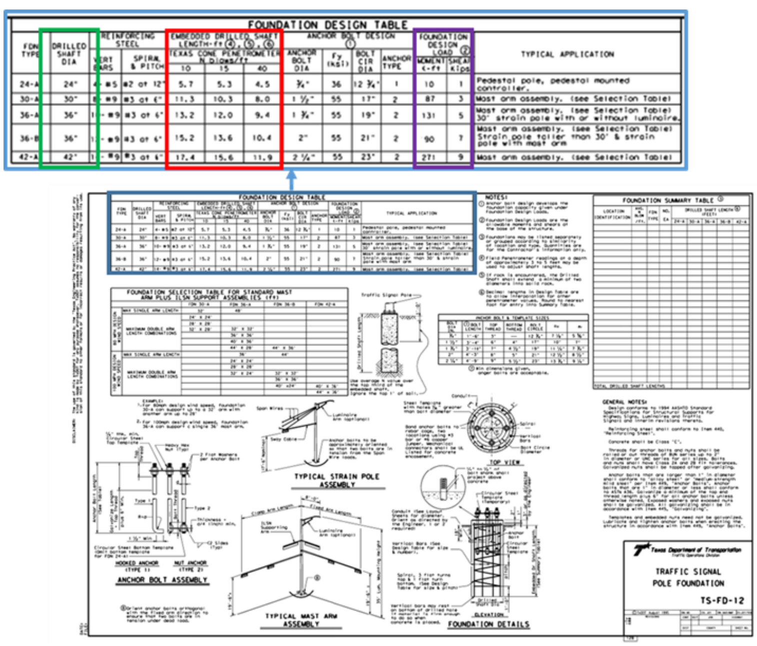
Blue – aggregate drilled shaft information

Green – available shaft diameters

Red – shaft length for a number of Texas penetrometer blows per ft

Purple – foundation design load

Figure C-17 also shows details of the several components comprising a mast arm pole system.



FOUNDATION DESIGN TABLE

FDN TYPE	DRILLED SHAFT DIA	REINFORCING STEEL VERT BARS	REINFORCING STEEL SPIRAL & PITCH	EMBEDDED DRILLED SHAFT LENGTH-ft ④, ⑤, ⑥ TEXAS CONE PENETROMETER N blows/ft 10	15	40	ANCHOR BOLT DESIGN ① ANCHOR BOLT DIA	Fy (ksi)	BOLT CIR DIA	ANCHOR TYPE	FOUNDATION DESIGN LOAD ② MOMENT k-ft	SHEAR Kips	TYPICAL APPLICATION
24-A	24"	4-#5	#2 at 12"	5.7	5.3	4.5	¾"	36	12 ¾"	1	10	1	Pedestal pole, pedestal mounted controller.
30-A	30"	8-#9	#3 at 6"	11.3	10.3	8.0	1 ½"	55	17"	2	87	3	Mast arm assembly. (see Selection Table)
36-A	36"	10-#9	#3 at 6"	13.2	12.0	9.4	1 ¾"	55	19"	2	131	5	Mast arm assembly. (see Selection Table) 30' strain pole with or without luminaire.
36-B	36"	12-#9	#3 at 6"	15.2	13.6	10.4	2"	55	21"	2	90	7	Mast arm assembly. (see Selection Table) Strain pole taller than 30' & strain pole with mast arm
42-A	42"	[illegible]-#9	#3 at 6"	17.4	15.6	11.9	2 ¼"	55	23"	2	271	9	Mast arm assembly. (see Selection Table)

Figure C-17: Texas Plan TS-FD-12 Document (TxDOT 2012).

In Figure C-17, the drilled shaft selection (design) could be based on one of two methods: *(i)* consider the number of blows/ft from the Texas Penetrometer Test (red square); the required depth (ft) for 10, 15 and 20 blows is provided; and *(ii)* use the design load with the drilled shaft diameter; for each standard diameter the moment and shear are shown within the square purple. ***Note: "If rock is encountered, the Drilled Shaft shall extend a minimum of two diameters into solid rock"***

h) Summary of standard design for Washington:

WSDOT defines eight load cases, which depend of the sign area supported by the mast arm. The load cases are named 700, 900, 1350, 1500, 1900, 2300, 2600 and 3000, which correspond to the product of XY (sign area) and Z (distance from the centerlines of the pole and sign). (WSDOT, 2018).

Once the XYZ value is been calculated, the drilled shaft foundation design is determined considering the following variables:

Friction angle - this value should be determined by geotechnical lab tests or correlated to the N-value of the Standard Penetration Test.

Allowable lateral bearing pressure - this value should be correlated to the N-value of the Standard Penetration Test.

Cross-sectional shape of the drilled shaft (round or square) and its length.

Figure C-18 shows the flow diagram that corresponds to Standard Plan J-26.10-03, Figure C-19, which are used to select the most appropriate drilled shaft depth (WSDOT, 2017b).

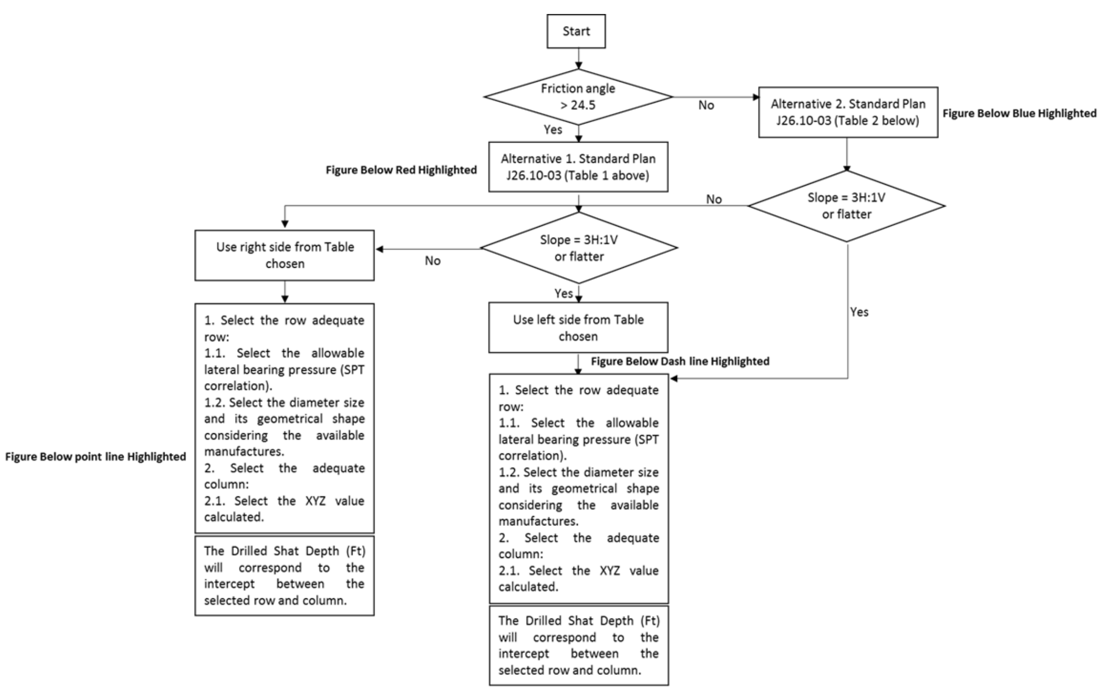


Figure C-18: Washington Plan J-26 Document (WSDOT 2018).

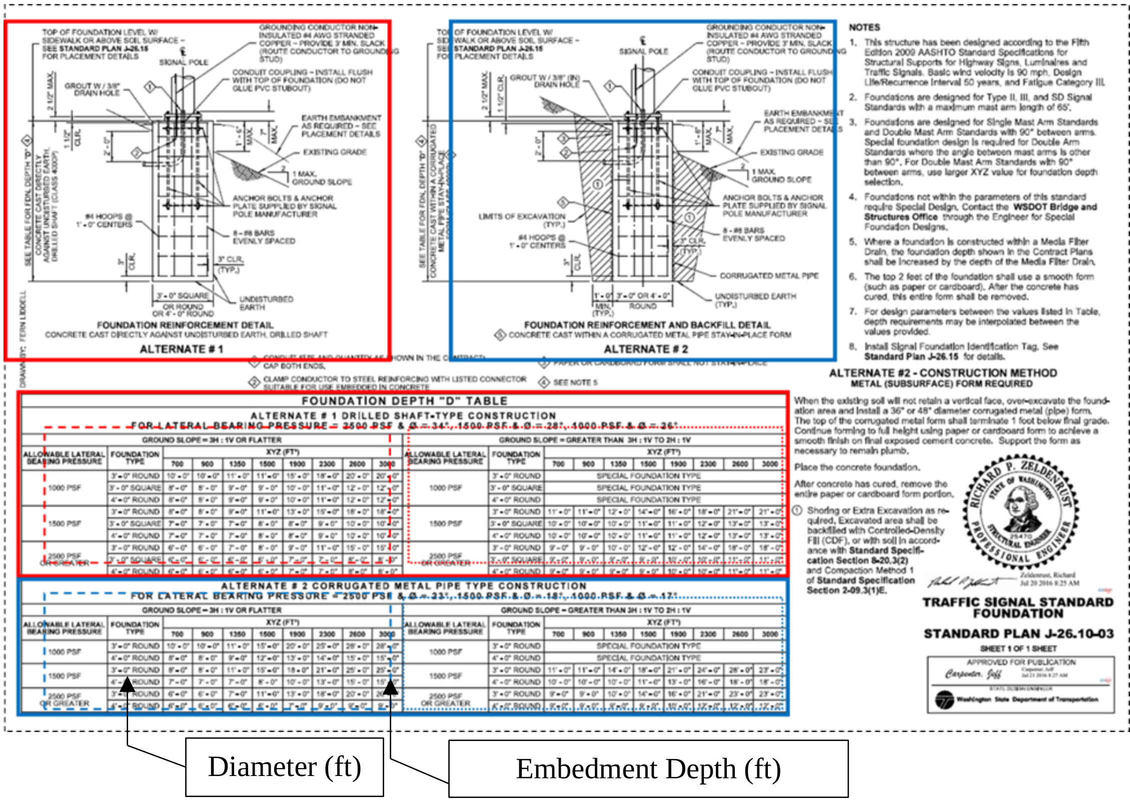


Figure C-19: Washington Plan J-26 Document (WSDOT 2018).

APPENDIX D – COPY OF SURVEY QUESTIONNAIRES RESPONSES FROM COASTAL DOTS

STATES INCLUDED IN THIS APPENDIX	
FDOT	D-a
MDOT	D-b
VDOT	D-c
SCDOT	D-d
GDOT	D-e
ALDOT	D-f
MDOT	D-g
LaDOT	D-h
TxDOT	D-i
ODOT	D-j
WSDOT	D-k

SURVEY QUESTIONNAIRES

NCDOT has an ongoing research project considering alternative foundation designs for traffic signals and highway signs. As part of this project we are summarizing the state of practice for the design of foundation systems of these structures in select states that have similar wind loading and geotechnical conditions as NCDOT. We are compiling information on: design wind speed, wind load considerations, design standards/codes used, foundation systems commonly used by your DOT, design drawings, design aids used by your DOT to select dimensions and design the foundation system, and alternative designs.

1. What are the main structure types used for supporting Traffic Signals and Highway Signs in your state?
2. Please list all of the standard and alternative foundation systems used by your DOT to support highway and traffic signal structures in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others)?

   a. Standard:

   b. Alternative:

3. What separates the use/justification of standard and alternate design systems? Is there an exceptions process required to use an alternate design? If so, what is it?
4. For design of foundation systems of traffic and highway signs, what are the design wind speed ranges typically used? Maximums? What is the basis (design code and edition) for these design wind speeds (e.g., AASHTO or ASCE code, etc.)? What analysis programs are being utilized (if any)?
5. What are the typical mast arm length ranges and maximums allowed?
6. Who has design responsibility for traffic signal and/or sign foundations? State DOT, Private Design Firm, Both?
7. Are there any FHWA requirements/directives on the use of the standard or alternative design systems?
8. In terms of geotechnical subsurface investigations (studies) for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed, etc.)?
9. When the selected foundation system corresponds to a drilled shaft, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind

10. loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

11. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

12. What issues does each foundation design present in terms of constructability challenges? What are the installation procedures for each design?

13. Please indicate any other information or comments you consider useful for the scope of this research project involving foundation under lateral, bending and torsion loading in coastal regions: Should we ask the states to discuss what soil conditions exist in their coastal regions? Any Water Table Effects? Any seismic effects?

14. Does your state have a typical/standard cost projections for any of your design alternatives? If so, please list them for each foundation type.

15. Who owns and maintains the signals/signs?

a) Florida

1. What is the main structure used for supporting both Traffic Signals and Highway Signs?

Cantilever sign YES

Cantilever Sign – Yes

Monotube Sign – Yes

Monotube Signal – Very Rare/No

Mast Arm – Yes

Strain Pole – Yes

Span Truss

2. What are the most commonly used foundation systems used by your DOT to support these highway and traffic signal structures when in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others) ?

Drilled Shafts

3. For design of foundation systems of traffic and highway signs, what is the basic wind speed(s) is typically used? What is the basis for these design wind speeds (e.g., AASHTO or ASCE code, etc)?

170/150/130- AASHTO LRFD LTS Design Specification

4. In terms of geotechnical studies for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed,etc)?

One SPT Boring to 25 ft in soil or 10 ft in competent rock with 15 ft minimum total boring depth

5. When the selected foundation system corresponds to a *drilled shaft*, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

FDOT Sign & Signal Support Programs See:http://www.fdot.gov/structures/ProgLib.shtm

6. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

Separately

7. Please indicate any other information or comments you consider useful for the scope of this research project involving foundation under lateral, bending and torsion lading in coastal regions:

Unless the foundation is in a high embankment fill, the Design Groundwater Level is always at the ground surface; the Design Windspeed most frequently occurs following 3 to 4 days of continuous heavy rainfall resulting in temporary localized flooding

b) Massachusetts:

1. What is the main structure used for supporting both Traffic Signals and Highway Signs?

Cantilever, mast arm, strain pole.

2. What are the most commonly used foundation systems used by your DOT to support these highway and traffic signal structures when in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others) ?

Drilled shafts or spread footings

3. For design of foundation systems of traffic and highway signs, what is the basic wind speed(s) is typically used? What is the basis for these design wind speeds (e.g., AASHTO or ASCE code, etc)?

Please refer to standards, but I think 130 MPH coastal and 110 inland

4. In terms of geotechnical studies for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed,etc)?

One boring per foundation is recommended per the engineering directive.

5. When the selected foundation system corresponds to a *drilled shaft*, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

Please refer to standards for reference documents used to develop the standards.

6. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

For foundation embedment, it appears the embedment depth was based upon the larger of either of the cases mentioned

c) Virginia:

1. What is the main structure used for supporting both Traffic Signals and Highway Signs?

Traffic Signals – Mast Arms and Strain Poles - Highway Signs – Cantilever and Span

2. What are the most commonly used foundation systems used by your DOT to support these highway and traffic signal structures when in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others) ?

Drilled Shafts. We used to have a foundation that consisted on drilled shaft with "wings" for torsional resistance, but we no longer use the wings.

3. For design of foundation systems of traffic and highway signs, what is the basic wind speed(s) is typically used? What is the basis for these design wind speeds (e.g., AASHTO or ASCE code, etc)?

90 mph (AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals, 6th Edition (LTS-6), 2013 with 2015 interims)

4. In terms of geotechnical studies for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed,etc)?

We require one boring (with Standard Penetration Testing) at each pole foundation. The testing general consists of simple indices tests (gradations, Atterberg limits and moisture contents).

5. When the selected foundation system corresponds to a drilled shaft, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

We currently allow the Broms' method to determine lateral capacity; however, we are getting ready to revise our procedure to only allow Broms' for preliminary calculations. We state COM624P, or any commercially available software, can be used for lateral/bending calculations. Most of our consultant designers use L-PILE.

6. Does the design method listed in Question 9 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

This is a good question. One of the changes we are considering is to add the following sentence, "Concurrent overturning and torsional forces reduce a shaft's overturning resistance. To account for this effect, the lateral loads should not be reduced by the allowable overstress when analyzing the required shaft length and deflections for overturning."

7. Please indicate any other information or comments you consider useful for the scope of this research project involving foundation under lateral, bending and torsion lading in coastal regions:

It's interesting that this research is being performed, because as I mentioned, we in the process of revising our practice (IIM-S&B-90.2) in this area. My former boss (Ashton Lawler) retired, and came back to work with us on a part-time basis. One of his primary duties over the last couple of months has been to complete this revision. I will copy Ashton on this response, in case he has anything he'd like to add. I will also attached IIM-S&B-90.2.

d) South Carolina:

1. What is the main structure used for supporting both Traffic Signals and Highway Signs?

We use all but monotube

2. What are the most commonly used foundation systems used by your DOT to support these highway and traffic signal structures when in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others) ?

Shallow foundations, drilled shafts

3. For design of foundation systems of traffic and highway signs, what is the basic wind speed(s) is typically used? What is the basis for these design wind speeds (e.g., AASHTO or ASCE code, etc)?

AASHTO specs for all

4. In terms of geotechnical studies for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed,etc)?

Typically one boring with SPT testing

5. When the selected foundation system corresponds to a *drilled shaft*, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

AASHTO methods

6. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

Not sure- whatever AAHTO requires

7. Please indicate any other information or comments you consider useful for the scope of this research project involving foundation under lateral, bending and torsion lading in coastal regions:

Our Traffic office does all of these foundations through Contractor Design-Build procurement, specifying the use of AASHTO design specs.

e) Georgia:

What is the main structure used for supporting both Traffic Signals and Highway Signs?

We use all but monotube

2. What are the most commonly used foundation systems used by your DOT to support these highway and traffic signal structures when in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others) ?

Shallow foundations, drilled shafts

3. For design of foundation systems of traffic and highway signs, what is the basic wind speed(s) is typically used? What is the basis for these design wind speeds (e.g., AASHTO or ASCE code, etc)?

AASHTO specs for all

4. In terms of geotechnical studies for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed,etc)?

Typically one boring with SPT testing

5. When the selected foundation system corresponds to a *drilled shaft*, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

AASHTO methods

6. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

Not sure- whatever AAHTO requires

7. Please indicate any other information or comments you consider useful for the scope of this research project involving foundation under lateral, bending and torsion lading in coastal regions:

Our Traffic office does all of these foundations through Contractor Design-Build procurement, specifying the use of AASHTO design specs.

f) Alabama:

What is the main structure used for supporting both Traffic Signals and Highway Signs?

Many of our signs are supported by cantilever poles. In the past we used almost exclusively strain poles but now use almost exclusively mast arms. We have not to my knowledge used either of the monotube style structures.

2. What are the most commonly used foundation systems used by your DOT to support these highway and traffic signal structures when in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others) ?

We use almost exclusively the drilled shaft for our foundations. Some units have been required to have wing walls attached to the drilled shafts, but we are looking at reevaluating the factor of safety used in our design to eliminate the use of the wings for our pole foundations.

3. For design of foundation systems of traffic and highway signs, what is the basic wind speed(s) is typically used? What is the basis for these design wind speeds (e.g., AASHTO or ASCE code, etc)? We use the AASHTO code with, in state modifications, I think. The wind speed varies for different parts of the state.

We use the AASHTO code with, in state modifications, I think. The wind speed varies for different parts of the state.

4. In terms of geotechnical studies for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed,etc)?

Typically we take borings for each pole location, unless there are a lot of poles in a close area and the geology is such that we can extrapolate information. There is also the issue of utility conflicts which requires offset or elimination of some borings. The borings consist of AASHTO T206 borings. Laboratory soil testing is typically not performed for these structures at this time.

5. When the selected foundation system corresponds to a *drilled shaft*, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

The lateral load characteristics of the drilled shaft is modeled using LPile, using parameters assigned by our in house staff. The torsion loading is checked by our consultants, so they will have to tell you what they use for this model.

6. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

I believe the torsion is considered separately but defer to our consultants to confirm how the analysis is performed.

g) Mississippi:

1. What are the main structure types used for supporting Traffic Signals and Highway Signs in your state?

Shallow Cast-in-Place Concrete Shafts for traffic signals and large guide signs. For smaller signs we use posts (smaller u-channels and smaller square tubes) that are a Direct Drive type – driven into the ground a sufficient length; if larger they are placed on a break-away sign assemblies which are set in concrete.

2. Please list all of the standard and alternative foundation systems used by your DOT to support highway and traffic signal structures in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others)?

a. Standard:

See above

b. Alternative:

Alternative foundation systems would be evaluated on a case by case basis.

3. What separates the use/justification of standard and alternate design systems? Is there an exceptions process required to use an alternate design? If so, what is it?

An alternative design system would be given consideration on its merits by the appropriate MDOT personnel and then either tested and evaluated in a test bed or in the field on a trial basis.

4. For design of foundation systems of traffic and highway signs, what are the design wind speed ranges typically used? Maximums? What is the basis (design code and edition) for these design wind speeds (e.g., AASHTO or ASCE code, etc.)? What analysis programs are being utilized (if any)?

AASHTO wind loading.

5. What are the typical mast arm length ranges and maximums allowed?

Typically, 40 to 60 feet. The longest mast arm we've built is approximately 100 feet long. Longer mast arms on some jobs have recently been necessary due to accommodating the flashing yellow arrow signal head (which is required to be placed in the center of the left turn lane) where used on certain 4-lane divided highways with offset left turn lanes and where it's desired to keep the signal pole out of the median. Due to their length, these arms were required to be straight arms where otherwise it has been MDOT's preference to use upswept mast arms.

6. Who has design responsibility for traffic signal and/or sign foundations? State DOT, Private Design Firm, Both?

State DOT if constructed by maintenance forces or designed in-house and built by a contractor; private design firm if they prepare the plans.

7. Are there any FHWA requirements/directives on the use of the standard or alternative design systems?

None other than meeting the required design guidelines.

8. In terms of geotechnical subsurface investigations (studies) for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed, etc.)?

This will depend on several factors including the type, length, complexity, and scope of the project and whether it's known there are expansive clays in the profile and whether the profile is known to be fairly consistent or varied.

9. When the selected foundation system corresponds to a drilled shaft, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

AASHTO Bridge Design standards. MDOT has developed a standard detail for the foundations for its guide signs and signals foundation designs.

10. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

Yes.

11. What issues does each foundation design present in terms of constructability challenges? What are the installation procedures for each design?

Usually, the foundations for smaller structures such as these do not present constructability challenges.

12. Please indicate any other information or comments you consider useful for the scope of this research project involving foundation under lateral, bending and torsion loading in coastal regions: Should we ask the states to discuss what soil conditions exist in their coastal regions? Any Water Table Effects? Any seismic effects?

We have experienced a couple signal mast arms that have rotated up to 90 degrees in place during storm events due to saturated soil and high wind loads. In each case the shaft rotated in its place. A solution to this would be to have a lateral reinforced concrete key built near the upper portion of the shaft.

13. Does your state have a typical/standard cost projections for any of your design alternatives? If so, please list them for each foundation type.

Yes, the MDOT Construction Division maintains cost data as bid by the contractors for each pay item and size. It may be possible to obtain this information by contacting the MDOT Construction Division.

14. Who owns and maintains the signals/signs?

MDOT owns all of the signals on state highways. The cities with a population over 20,000 are responsible to maintain the signals on State routes; however, MDOT maintains operational jurisdiction over these signals

h) Louisiana:

What are the main structure types used for supporting Traffic Signals and Highway Signs in your state?

Refer to our Standards…

2. Please list all of the standard and alternative foundation systems used by your DOT to support highway and traffic signal structures in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others)?

a. **Standard:** **Traffic Signals: Drilled Shafts are the only option. Overhead Traffic Signs: Timber piles are the standard option. Dynamic Message Signs: Timber piles are the standard option. Highmast Lighting: Drilled shafts are the only option.**

b. **Alternative:** **Overhead Traffic Signs: Drilled shafts may be used as an alternate.**

3. What separates the use/justification of standard and alternate design systems? Is there an exceptions process required to use an alternate design? If so, what is it?

Overhead Traffic Signs: It is up to the Contractor whether they use timber piles or alternatively, drilled shaft option.

Traffic Signals: A special design is required for the longer mast-arms in the weaker soil zones.

4. For design of foundation systems of traffic and highway signs, what are the design wind speed ranges typically used? Maximums? What is the basis (design code and edition) for these design wind speeds (e.g., AASHTO or ASCE code, etc.)? What analysis programs are being utilized (if any)?

Max wind speed = 130 mph for Dynamic Message Signs (Wind Load Map AASHTO 2001). For Highmast Lighting and Overhead Traffic Signs, Max wind speed = 130 mph, using (Wind Zone Map for Louisiana).

6. What are the typical mast arm length ranges and maximums allowed?

Single Mast-Arms (55 ft., 60 ft., 65 ft., 70 ft.)

Dual Mast-Arms (50 & 35 ft., 50 & 40 ft., 55 & 40 ft., 55 & 45 ft.)

7. Who has design responsibility for traffic signal and/or sign foundations? State DOT, Private Design Firm, Both?

Either, depends on who is designing the overall project.

8. Are there any FHWA requirements/directives on the use of the standard or alternative design systems?

9. In terms of geotechnical subsurface investigations (studies) for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed, etc.)?

Soil borings/tests are rarely performed for these types of structures. The standards rely on predefined Soil Zone maps for Louisiana for a general guidance of the types of soils in different areas of the state. Sometimes nearby soil borings can be located and used to analyze proposed sign foundations. When necessary, a deep soil boring similar to what is required for deep foundation design, may be taken for special design cases such as, (weak coastal soil zones, long mast-arm lengths, etc.).

10. When the selected foundation system corresponds to a drilled shaft, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

LRFD

11. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

We use Ensoft Shaft and LPILE software to design for lateral loading and bending and axial loading. Torsion is considered separately.

12. What issues does each foundation design present in terms of constructability challenges? What are the installation procedures for each design?

All piles are driven into the ground using a pile driving hammer. A drilled shaft alternative is considered when hard driving is expected for installing piles. On the other hand, drilled shafts are preferred in denser soils and structures that have single mounted poles. In soft soils, it can be difficult to install drilled shafts without the use of steel casing.

13. Please indicate any other information or comments you consider useful for the scope of this research project involving foundation under lateral, bending and torsion loading in coastal regions: Should we ask the states to discuss what soil conditions exist in their coastal regions? Any Water Table Effects? Any seismic effects?

Many of your questions can be answered by reading our standard plans.

14. Does your state have a typical/standard cost projections for any of your design alternatives? If so, please list them for each foundation type.

Currently we do not perform cost projections for signs and light foundation alternatives.

15. Who owns and maintains the signals/signs?

I believe all signals/signs constructed by LADOTD are owned by LADOTD.

i) Texas:

1. What is the main structure used by TxDOT for supporting both Traffic Signals and Highway Signs?

TxDOT has used all of these structure types. Cantilever signs are the most common structures used for supporting highway signs. Additionally, overhead sign bridges are used when cantilever signs cannot provide the desired arm length. Mast arms are the main structure used for traffic signlas.

2. What are the most commonly used foundation systems used by TXDOT to support these highway and traffic signal structures when in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others) ?

Drilled shafts are the most common foundation system.

3. For design of foundation systems of traffic and highway signs, what is the basic wind speed(s) is typically used?

Designs are based on AASHTO 1994 Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals and Interim Revisions thereto. Designs are based on either 70, 80, 90, or 100 MPH wind speed as defined by the 50 year mean recurrence interval of fastest mile wind velocity at 33 feet height.

4. In terms of requirements for geotechnical studies for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed, etc)?

Soil borings are performed to classify soil type and perform Texas Cone Penetrometer (blow count) testing. Soil classification (cohesionless vs cohesive) is used in conjunction with blow counts on standard foundation embedment charts to determine embedment depth._ Boreholes for overhead sign structures are generally 30 to 50 feet in depth and are typically located within 100 feet of the structure.

5. When the selected foundation system corresponds to a *drilled shaft*, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

Design charts with design guidance are provided on standards to aid in the design of the foundation depths for drilled shafts supporting overhead sign structures. This guidance includes both consideration of bending moment and torsional forces. The approach was developed in 1984. The design charts go back to 1984 and are based on Brom's method for moment resistance while torsional

resistance is based on soil shear resistance along the side of the shafts. In addition to using the design guidance on the standards, TxDOT also utilizes soil-structure interaction programs (such as LPILE) to determine the appropriate depth of drilled shaft for the required lateral loading condition.

6. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

Lateral loading and torsion are included on the foundation embedment selection charts. The foundation design is based on evaluation of torsion and bending independently. The design process outlined on our standards specifies that the longer of the length required for bending or torsion be used for the embedment length.

7. Please indicate any other information or comments you consider useful for the scope of this research project involving foundation under lateral, bending and torsion lading in coastal regions:

TxDOT's standards for overhead sign structures are available for download from the TxDOT website:
https://www.dot.state.tx.us/insdtdot/orgchart/cmd/cserve/standard/toc.htm#CANTILEVEROVERHEADSIGNSUPPORTSTANDARDS

j) Oregon:

1. What is the main structure used for supporting both Traffic Signals and Highway Signs?

Monotube and Mast arm

2. What are the most commonly used foundation systems used by your DOT to support these highway and traffic signal structures when in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others) ?

Drilled shafts and Spread footings (Pad and Pedestal)

3. For design of foundation systems of traffic and highway signs, what is the basic wind speed(s) is typically used? What is the basis for these design wind speeds (e.g., AASHTO or ASCE code, etc)?

AASHTO 6th Ed. ASD 110 mph

AASHTO 1st Ed. LRFD 145 mph Extreme and 91 mph Service

Oregon Structural Specialty Code State specific wind maps

4. In terms of geotechnical studies for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed,etc)?

Signal poles – Foundations within 75' with uniform soil have one boring with SPT.

Sign Cantilevers and Truss Bridges – One boring at each foundation with SPT.

5. When the selected foundation system corresponds to a drilled shaft, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

LPile used for overturning moment

Skin friction used for torsion

6. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

Torsion is considered separately

k) Washington:

1. What is the main structure used by WSDOT for supporting both Traffic Signals and Highway Signs?

For support of traffic signals, WSDOT uses pole structures with cantilevered mast arms.

Overhead support of highway signs is generally accomplished with sign bridges or cantilever sign structures.

2. What are the most commonly used foundation systems used by your DOT to support these highway and traffic signal structures when in coastal regions of your state (e.g., drilled shafts, driven piles, shallow foundations, drilled shafts with wing walls, others) ?

Signal poles and overhead sign structures are most often supported on drilled shaft foundations.

3. For design of foundation systems of traffic and highway signs, what is the basic wind speed(s) is typically used?

We use the LRFD Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals, First Edition 2015, and Amendments. (AASHTO)

- What is the basis for these design wind speeds (e.g., AASHTO or ASCE code, etc)?

Basic Wind Speed is 115 mph, for a 1700 year MRI, per Fig 3.8-2a in the Code.

4. In terms of requirements for geotechnical studies for the foundation design of these structures, what is the usual scope of the field geotechnical exploration (e.g., number of boreholes, types of field tests required, soil tests performed, etc)?

Ideally, we would have a borehole or test pit for each location, but this is rarely the case in practice. If the Geotechs see some consistency in subsurface soil profiles and properties, then we may generate foundation designs based on much more widely-spaced test pits or bore holes, laid out to cover a longer length of highway. We generally ask for soil unit weight, soil phi angles, and allowable lateral bearing pressures (used to reference some of our older Standard Plan solutions which are based on earlier WSD versions of the Code). The Geotechs will also identify any potential complications anticipated for drilled shaft foundations (high water table, artesian conditions, caving soils, obstructions, rock, etc).

5. When the selected foundation system corresponds to a *drilled shaft*, what design methods or procedures are used to design against lateral, bending, and torsion loading associated to the wind loads acting on the structure (e.g., please indicate methods used or a DOT report or design drawings)?

For drilled shaft foundation design, we use the Broms Approximate Method, described in the Code Commentary 13.6.1.1. Torsional Capacities are not covered in the Code. Please refer to the WSDOT Bridge Design Manual 10.1.5C for torsional considerations.

6. Does the design method listed in Question 5 include lateral loading and bending coupled with the torsion, or is torsion considered separately in the foundation design?

The method described in the WSDOT BDM takes lateral loading into account for the torsional design.

7. Please indicate any other information or comments you consider useful for the scope of this research project involving foundation under lateral, bending and torsion lading in coastal regions:

Please refer to WSDOT Standard Plan J-26.10 for typical Signal Pole Foundation detail