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Task 6 – Noise Barrier Foundation Design

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for the Ohio Department of Transportation
Office of Statewide Planning and Research

and the
United States Department of Transportation
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16. Abstract
The Ohio Department of Transportation (ODOT) wishes to develop a design method for drilled shaft foundations of noise barriers, using the software program LPILE. To accomplish this task, the research team performed the following activities: 1) Determine appropriate design loads and design criteria, 2) Review and evaluate soil strength correlations for incorporation into the design method, 3) Develop the proposed design method, and 4) Compare the proposed design method to existing ODOT design tables.
Using wind loads from the AASHTO LRFD Bridge Design Specifications (AASHTO, 2020), the p-y method of analysis for laterally loaded piles was used to determine the drilled shaft length for all the different cases that are included in the current noise barrier foundation design tables in the Bridge Design Manual (ODOT, 2022a). The comparison of results to the existing design tables generally found very good agreement for granular soils. In the majority of cases the difference is only 0.5 foot. However, for the cohesive soils, there are some significant differences. For soft cohesive soils with N=0-1 the existing design table appears to be unconservative when compared to the results from the current study. In some cases, the drilled shaft lengths should be increased by up to 3 feet. While for stiffer cohesive soils the existing design table is much more conservative than the results from the current study. Also considered was the effect that varying the axial load and the addition of ice loads had on the shear, moment, and percent deflection for a noise barrier foundation located in a granular soil with N=10-19 and the maximum panel spacing (24 ft) and barrier height (20 ft). The increase in axial load slightly increases the shear and moment in the foundation. The small moment created by the off-center ice loads does not have a significant effect on the shear and moment in the noise barrier foundation. The addition of ice load does show an increase in the percent deflection of the noise barrier.
The proposed design method may also be used to design a noise barrier foundation that falls outside the limits of the design tables in the ODOT Bridge Design Manual. The proposed design method has been adapted for this purpose and described in a white paper. The white paper describes the loading, design procedure, and the method of interpreting the results. It is intended for ODOT design consultants to use when the standard design tables do not apply.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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1 Introduction

1.1 Scope of Work

The Ohio Department of Transportation (ODOT) wishes to develop a design method for drilled shaft foundations of noise barriers, using the software program LPILE. To accomplish this task, the research team performed the following activities:

1. Determine appropriate design loads and design criteria.
2. Review and evaluate soil strength correlations for incorporation into the design method.
3. Develop the proposed design method.
4. Compare the proposed design method to existing ODOT design tables.

In addition to the above scope, the research team also considered the effect of varying the axial loads on the noise barrier foundation.

1.2 Outline of the Report

Chapter 2 explains the current ODOT practice for noise barrier foundation design.

Chapter 3 explains the past and current design criteria and loads.

Chapter 4 describes the proposed design method.

Chapter 5 provides the interpretation of results for the study.

Chapter 6 compares the results of the study to the existing design tables.

Chapter 7 considers the effect of varying the axial loads due to different load factors and potential ice loading.

Chapter 8 presents the conclusions and describes the contents of a white paper.

2 Current ODOT Practice for Noise Barrier Foundation Design

2.1 Current Design Procedure

The current procedure that the Ohio Department of Transportation uses for the design of noise barrier foundations is described in the Bridge Design Manual (ODOT, 2022a), Section 800. The typical foundation consists of a 30-inch diameter drilled shaft with a length that varies from 6 to 30 feet. The designer selects the length of the drilled shaft from a set of two tables. One table is for use with cohesive soils and the other table is for use with granular soils. The tables are shown in Table 1 for the granular soils and in Table 2 for the cohesive soils. A summary of the design procedure is described below. For a complete description, including the process if bedrock is encountered, refer to the Bridge Design Manual.

1. Determine the SPT (Standard Penetration Test) “N” blow counts from a boring from 2.5-ft to 25-ft in 2.5-ft increments.
2. Correct all N-values for hammer efficiency to obtain N_{60}. For granular soils, correct the N_{60} values for the effect of overburden pressure to obtain $N1_{60}$.

Table 1 – Noise Barrier Foundation Depth Table for Granular Soils, (ODOT, 2022a)

Granular Soil Foundation Depth Table

	Post Spacing (PS) [ft]				Foundation Depth [ft]							
	PS ≤ 8’	8’ < PS ≤ 12’	12’ < PS ≤ 16’	16’ < PS ≤ 24’	Soil Properties	N[3]	2-3	4-9	10-19	20-29	30-49	50-60
						ϕ[4]	25-32	27-35	30-38	32-40	34-43	36-44
Barrier Height (H) [ft]	H ≤ 12’	H ≤ 10’	H ≤ 8’	H ≤ 6’	Transverse Ground Slope	Level	8.0	8.0	6.5	6.0	6.0	6.0
						5:1	8.0	8.0	7.0	6.5	6.0	6.0
						4:1	8.5	8.5	7.0	7.0	6.0	6.0
						3:1	9.0	8.5	7.5	7.0	6.5	6.5
						2:1	10.0	9.5	8.0	7.5	7.0	6.5
	12’ < H ≤ 16’	10’ < H ≤ 14’	8’ < H ≤ 12’	6’ < H ≤ 10’		Level	9.5	9.5	8.0	7.5	7.5	6.5
						5:1	10.5	10.0	8.5	8.0	8.0	7.0
						4:1	11.0	10.5	9.0	8.5	8.0	7.5
						3:1	11.5	11.0	9.5	9.0	8.5	7.5
						2:1	12.5	12.0	10.0	9.5	9.0	8.0
	16’ < H ≤ 20’	14’ < H ≤ 20’	12’ < H ≤ 16’	10’ < H ≤ 14’		Level	11.5	11.0	9.5	9.0	8.0	8.0
						5:1	12.5	11.5	10.0	10.0	8.5	8.5
						4:1	13.0	12.0	10.5	10.5	9.0	8.5
						3:1	13.5	13.0	11.0	10.5	9.5	9.0
						2:1	14.5	14.5	12.0	11.5	10.0	9.5
			16’ < H ≤ 20’	14’ < H ≤ 20’		Level	15.5	14.0	12.0	11.0	10.5	10.5
						5:1	19.0	16.0	13.5	12.5	11.0	11.0
						4:1	20.5	17.5	14.0	13.0	12.0	11.5
						3:1	24.0	19.5	15.0	14.0	12.5	12.0
						2:1	*	30.0	19.0	16.0	14.0	13.0

Notes:

1. The foundation depth is the required embedment into in-situ soil. Assume the corrected SPT N-value = 20 where soil will be placed as new embankment in conformance with C&MS Item 203.
2. Barrier Height [H] is the distance from the top of the drilled shaft to the top of the higher barrier wall at the post rounded to the nearest ft.
3. N = Corrected SPT N-value (see BDM Section 802.1.2)
4. ϕ = Estimated friction angle based on N-value
5. * = exceeds maximum drilled shaft length

Table 2 – Noise Barrier Foundation Depth Table for Cohesive Soils, (ODOT, 2022a)

Cohesive Soil Foundation Depth Table											
	Post Spacing (PS) [ft]				Foundation Depth [ft]						
	PS ≤ 8′	8′ < PS ≤ 12′	12′ < PS ≤ 16′	16′ < PS ≤ 24′	Soil Properties	N[3]	0-1	2-3	4-8	9-15	16-32
Barrier Height (H) [ft]	H ≤ 12′	H ≤ 10′	H ≤ 8′	H ≤ 6′	Transverse Ground Slope	Level	12.5	12.5	7.0	6.0	6.0
						5:1	13.5	13.5	7.5	6.0	6.0
						4:1	13.5	13.5	7.5	6.0	6.0
						3:1	14.0	14.0	8.0	6.0	6.0
						2:1	14.5	15.0	8.0	6.0	6.0
	12′ < H ≤ 16′	10′ < H ≤ 14′	8′ < H ≤ 12′	6′ < H ≤ 10′		Level	17.0	17.0	9.5	7.5	6.0
						5:1	18.5	18.5	10.0	8.0	6.0
						4:1	19.0	18.5	10.5	8.0	6.0
						3:1	19.5	19.0	10.5	8.0	6.0
						2:1	20.0	20.0	11.0	8.5	6.0
	16′ < H ≤ 20′	14′ < H ≤ 20′	12′ < H ≤ 16′	10′ < H ≤ 14′		Level	21.5	21.0	13.5	9.5	6.5
						5:1	23.0	23.0	14.5	10.0	7.0
						4:1	23.5	23.0	14.5	10.0	7.0
						3:1	25.0	24.0	15.0	10.5	7.0
						2:1	25.5	24.5	16.0	11.0	7.0
			16′ < H ≤ 20′	14′ < H ≤ 20′		Level	*	*	19.0	13.0	9.0
						5:1	*	*	20.5	14.0	9.0
						4:1	*	*	21.0	14.5	9.0
						3:1	*	*	22.0	15.0	9.5
						2:1	*	*	24.0	15.0	10.0

Notes:

1. The foundation depth is the required embedment into in-situ soil. Assume the corrected SPT N-value = 20 where soil will be placed as new embankment in conformance with C&MS Item 203.
2. Barrier Height [H] is the distance from the top of the drilled shaft to the top of the higher barrier wall at the post rounded to the nearest ft.
3. N = Corrected SPT N-value (see BDM Section 802.1.2)
4. * = exceeds maximum drilled shaft length

3. Determine the design N-value by either averaging the values along the length of the drilled shaft or using the lowest N-value along the length of the drilled shaft.
4. Establish the soil type as granular or cohesive at each boring, based on the majority soil type along the length of the drilled shaft.
5. Using the table corresponding to the majority soil type, select the group of rows based on the post spacing and noise barrier panel height. Select the column based on the design N-value and select the foundation depth based on the ground slope at the noise barrier post.

The design process can be iterative, as the soil type and design N-value depend on the drilled shaft foundation length. Therefore, as the drilled shaft length changes, the majority soil type along the length may change and the design N-value may change. The change in the soil type and design N-value may then result in additional changes to the drilled shaft length. In practice, the process generally requires only one iteration or none at all. However, the author has encountered rare situations where the design process would endlessly cycle between two drilled shaft lengths. In this case, the longer drilled shaft length is conservatively selected.

2.2 Basis of Current Design Procedure

The current ODOT design procedure for noise barrier foundations was developed in 1997 based on research performed by Dr. Robert Liang. The title of the research report is "Pressuremeter to predict lateral load capacity of drilled shafts on slopes" (Liang, 1997). Dr. Liang re-evaluated noise barrier design charts in use at that time by ODOT and introduced the use of COM624P and SPT N-values into the design process. Dr. Liang presented two sets of design tables; one for an allowable deflection of 1.0 percent of the noise barrier height and one for an allowable deflection of 1.5 percent of the noise barrier height. ODOT adopted the design tables proposed by Dr. Liang for the allowable deflection of 1.5 percent of the noise barrier height, with some changes to the formatting of the tables and a minimum foundation length of 6 feet.

Dr. Liang performed additional research projects for ODOT that further explored the use of SPT N-values for the design of laterally loaded drilled shafts, such as those used to stabilize landslides and support noise barriers. The results for one of these research projects pertinent to noise barrier foundations are presented in the report "Drilled shaft foundations for noise barrier walls and slope stabilization" (Liang, 2002).

Some years after the adoption of the noise barrier foundation design tables, ODOT discovered that the moment arm used in the calculations was based on one-third of the noise barrier panel height, instead of the correct value of one-half the noise barrier panel height. Because ODOT has a history of satisfactory performance of walls constructed using the existing design tables, this error was not a significant concern for most noise barriers. However, for walls designed outside the limits of the existing design tables (taller than 20 feet or post spacings greater than 24 feet) the continuation of the existing design methodology could result in an unacceptable, unconservative foundation design.

3 Design Criteria and Loads

3.1 Design Specifications

When the current noise barrier foundation design tables were developed in 1997, the ODOT design criteria for noise barriers was based on the AASHTO Standard "Guide Specifications for Structural Design of Sound Barriers" (AASHTO, 1992). The wind load was calculated for an 80 mph wind velocity producing a uniform pressure of 25 psf.

The current AASHTO LRFD Bridge Design Specifications (AASHTO, 2020) address the design of noise barriers in Section 15, Design of Sound Barriers. The section refers to Section 3 for loading and Sections 10 and 11 for the design of foundations. For lateral displacement, the specification states "Tolerable deformation criteria shall be developed based on maintaining the required barrier functionality, achieving the anticipated service life, and the consequences of unacceptable movements." Based on successful past performance of the existing noise barrier foundation design tables, ODOT will continue to use a deflection criterion of 1.5 percent of the noise barrier panel height.

3.2 Wind Loads

Based on Table 3.4.1-4 in the AASHTO LRFD Bridge Design Specifications, the applicable limit states that include wind loads (WS) are Strength III, Strength V, and Service I. The Service IV limit state relates to prestressed concrete columns for crack control and is not applicable to foundations.

The wind pressure on the wall is calculated using Equation 3.8.1.2.1-1 (AASHTO, 2020).

$$P_z = 2.56 \times 10^{-6}\ V^2 K_z G C_D \qquad \text{Eq. 3.8.1.2.1}$$

Where:

P_z = design wind pressure (ksf)
V = design 3-second gust wind speed
K_z = pressure exposure and elevation coefficient
G = gust effect factor
C_D = drag coefficient

Wind Exposure Category C was used for the design. While Wind Exposure Category D for flat, unobstructed areas will result in greater wind loads, it is unlikely that noise barriers would be located in such areas.

The resulting design wind pressure for the different limit states is as follows:

Table 3 – Design Wind Pressure

	Strength III	**Strength V**	**Service I**
V	115 mph	80 mph	70 mph
K_z	1	1	1
G	0.85	0.85	1
C_D	1.2	1.2	1.2
P_z	0.03453 ksf 34.53 psf	0.01966 ksf 19.66 psf	0.01505 ksf 15.05 psf

The controlling strength limit state wind pressure is 34.53 psf and controlling service limit state wind pressure is 15.05 psf. The Strength V Limit State does not need to be considered as the Strength III Limit State controls. The wind pressure is applied uniformly over the noise barrier panel. To calculate the shear and the moment at the top of the drilled shaft foundation, the uniform wind pressure is multiplied by the post spacing and noise barrier panel height, and the moment is calculated using a moment arm equivalent to 55 percent of the noise barrier height (AASHTO LRFD 3.8.1.2.4).

3.3 Axial Loads

The axial loads included by Liang (1997) in their analysis appeared to represent 81.64 psf for noise barrier panel heights from 6 to 14 feet, and 75 psf for heights from 14 to 20 feet. It is not clear why he used two different values for the axial loads. For the present study, we assumed a panel thickness of 6 inches (minimum required by ODOT standard construction drawings) and a concrete unit weight of 150 lb/ft^3. This results in 75 psf for the weight of the panels. We assume the weight of the posts and other hardware are similar. Therefore, the axial load on a noise barrier foundation, is calculated by multiplying 75 psf by the height of the noise barrier and the post spacing.

For the strength limit state, AASHTO (2020) presents both a minimum and maximum load factor for DC, the dead load of the structural components, that is the weight of the panels and posts. The specification states "In load combinations where one force effect decreases another effect, the minimum value shall be applied to the load reducing the force effect." However, in this case the axial load will tend to slightly decrease the stability of the foundation and slightly improve the moment resistance of the drilled shaft. Later in this report we present a comparison of the results from using the minimum and maximum load factors.

We also considered the effect of ice accumulation on the panels, although this is not explicitly required by AASHTO (2020). The current ODOT standard construction drawing for noise barriers (ODOT, 2009) requires inclusion of an ice load in the structural design of the noise barrier for an extreme event load case. The applied ice load is 3 inches of ice with a unit weight of 57.3 lb/ft^3, which is 14.32 lb/ft^2. The ice load and wind load are not applied concurrently according to the standard construction drawing. AASHTO (2020) only addresses ice accretion on structures by saying that "Loads due to icing of the superstructure by freezing rain shall be specified if local conditions so warrant." If ice loads are included, AASHTO (2020) would apply the ice load at the Extreme Event II limit state, which does not include wind loads. Therefore, wind loads and ice loads would typically not be applied concurrently.

Generally, all other loads are not applicable to the design of noise barrier foundations. In some cases, noise barrier panels are designed to retain soil. However, the ODOT standard design procedure does not consider earth retention in the design of the noise barrier foundations. Therefore, it was not included in this study. ODOT does not design noise barrier foundations for vehicle impact.

4 Proposed Design Method

The proposed design method consists of using the p-y method of analysis for laterally loaded piles. This design method is used by ODOT for the design of drilled shafts for landslide stabilization, as described in Geotechnical Bulletin 7 (ODOT, 2020). Two software programs that perform the p-y method of analysis are LPile (Ensoft, 2019) and RSPile (RocScience, 2022). We used LPile for this study because ODOT also uses LPile. The design method is easily adapted to other software programs.

We used the static loading analysis option and not the cyclic loading option. Due to the relative stiffness and small deflections of the noise barrier foundations, it is standard practice in Ohio to assume the soil around a noise barrier foundation does not exhibit progressive softening due to cyclic loading behavior.

4.1 Drilled Shaft (Pile) Properties

The standard noise barrier foundation used by ODOT is a 30-inch diameter drilled shaft. The pile properties in LPile for the standard foundation are as follows:

Type: Round concrete shaft (Bored Pile)
Diameter: 30 inches
Concrete: Min. compressive strength of 4 ksi
Reinforcing: 9 - #8 bars , 3" cover to outer edge of bar

4.2 Soil Properties

We used the following p-y curve types in the study. For the granular soils, we used the sand (Reese) model. For the cohesive soils, we used either the soft clay (Matlock) model or the stiff clay (Reese) model, depending on the soil stiffness. We assumed a ground water level at a depth of 3 feet below the ground surface. For stiff clay, we used the stiff clay w/o free water (Reese) model above the ground water level and the stiff clay with free water (Reese) model below the ground water level.

The existing noise barrier foundation design tables group the soil strength into ranges of SPT N-values. We used correlations recommended in Section 400 of the Geotechnical Design Manual (ODOT, 2022b) to determine the unit weight, undrained cohesion, or friction angle from the range of N-values. The values used are shown in Table 4 and Table 5 below. Where required by the soil model, we allowed LPile to select default values for k, the initial linear portion of the p-y curve, and ε_{50}, the strain corresponding to one-half the maximum stress difference. When below a depth of 3 feet, we calculated the effective unit weight by subtracting the unit weight of water from the unit weight shown in the tables below.

Table 4 – Granular Soil Properties

N-value, blows/ft	2-3	4-9	10-19	20-29	30-49	50-60
Unit Weight, lb/ft³	115	118	122	125	130	140
Friction Angle, ϕ, degrees	27	28	30	32	35	38

Table 5 – Cohesive Soil Properties

N-value, blows/ft	0-1	2-3	4-8	9-15	16-32
Unit Weight, lb/ft³	105	110	115	120	125
Undrained cohesion, lb/ft²	125	250	500	1250	2000
Soil model	Soft clay	Soft clay	Soft clay	Stiff clay	Stiff clay

4.3 Pile-head Loading and Ground Slope

For the pile-head loading, we selected the shear and moment loading condition. This represents a free-head condition for the drilled shaft (pile). The shear and moment were calculated by multiplying the post spacing by the barrier height (area) and then multiplying by the wind pressure shown in Table 3. We grouped the analyses into four groups based on the existing design tables. The grouping is shown in Table 6 below. The resulting moment load on the noise barrier foundation is relatively consistent within a group.

Table 6 – Loading Groups

PS×H	PS ≤ 8’	8’ < PS ≤ 12’	12’ < PS ≤ 16’	16’ < PS ≤ 24’
Group 1	8×12	12×10	16×8	24×6
Group 2	8×16	12×14	16×12	24×10
Group 3	8×20	12×20	16×16	24×14
Group 4			16×20	24×20

Note: PS = Post Spacing (ft), H = Barrier Height (ft)

We considered five different ground slope conditions.

- Level ground
- 5H:1V 11.3 degrees
- 4H:1V 14 degrees
- 3H:1V 18.4 degrees
- 2H:1V 26.6 degrees

We created an LPile input file for each N-value category and ground slope condition within each group and for the two soil types. This resulted in 120 input files for the granular soil and 100 input files for the cohesive soil. Within each input file, we specified up to eight loading cases, four for the service limit loads within the group and four for the strength limit loads within the group.

4.4 p-y Modification Factors for Group Action

If drilled shaft foundations are placed at a center-to-center spacing closer than 3.75 diameters, a p-multiplier reduction applied to the soil resistance must be considered. The loss in capacity is due to soil-structure-soil interaction and an overlap in the region of the soil that provides passive resistance to the deflection of the drilled shaft foundations when placed in a closely spaced group.

Reese, Isenhower, and Wang, "Analysis and Design of Shallow and Deep Foundations" (2006) published an equation for the pile group p-multiplier for a single row of piles placed side by side.

$$p_m = 0.64(S/D)^{0.34}, \text{ for } 1 \leq S/D < 3.75$$

Where $0.5 \leq p_m \leq 1.0$.

This is an empirical relationship based on testing by a number of researchers in a number of different soil types. For noise barrier foundations which use a 30-inch diameter drilled shaft, spacings less than 9.375 feet will result in a p-multiplier less than 1.0. For an 8-foot post spacing, the p-multiplier has a value of 0.95. We initially included the p-multiplier in the analyses but stopped using it. Including the different p-multiplier required a separate LPile input file. Because the p-multiplier only applied to the 8-foot post spacing and the loads for the 8-foot post spacing never controlled the results for a group, the additional effort was not warranted.

5 Interpretation of Results

To determine if the displacement criterion of 1.5 percent of the noise barrier height was met, we used the following equation with the results from the Service Limit State loads to calculate the total deflection at the top of the noise barrier panels as a percentage of the noise barrier height. We assumed the panels and posts above the foundation rotated as a rigid body.

$$(y/12H)+S <= 0.015$$

Where:

- y = deflection at the top of the foundation, inch
- H = noise barrier height, feet
- S = slope at the top of the deflected shaft, radians

We also checked the geotechnical resistance against overturning. This is not a check of the structural capacity of the foundation, but of the geotechnical resistance of the soil to resist excessive overturning forces. We performed this check by considering the pile-head deflection under the strength limit state loads. If LPile was able to converge on a solution with a deflection less than 100 inches, then the noise barrier foundation successfully met the check for geotechnical resistance against overturning.

For each input file, we adjusted the drilled shaft length until we found the minimum foundation length that met both the deflection criterion under service limit state loads and the geotechnical resistance check under strength limit state loads. We adjusted the drilled shaft length in 0.5-foot increments.

We then compared the maximum shear and maximum moment in the drilled shaft to the structural resistance of the standard drilled shaft design, which is shown below. The factored moment resistance shown neglects the effect of any axial load in the drilled shaft, which is conservative. Including the axial load will increase the factored moment resistance.

Factored shear resistance,	V_r	= 104.7 kips
Factored moment resistance,	M_r	= 4392 inch-kip (366 kip-ft)

The structural resistance of the standard drilled shaft design did not control any of the results. The loading condition that resulted in the greatest moment (3786 inch-kip or 315.5 kip-ft) was for a noise barrier foundation in cohesive soil with N=0-1, in a 2H:1V slope, a post spacing of 24 feet and a barrier height of 20 feet. The loading condition that resulted in the greatest shear (68.5 kip) was for a noise barrier foundation in cohesive soil with N=16-32, in a 4H:1V slope, a post spacing of 24 feet and a barrier height of 20 feet.

The results of the LPile analyses and tables summarizing the results are included in Appendix B.

6 Comparison to Existing Design Tables

The results of the LPile analyses are compared to the existing design tables in Table 7 for the granular soils and in Table 8 for the cohesive soils. The tables are also provided in Appendix B in a larger format that may be easier to read.

Table 7 – Comparison of Foundation Depths for Granular Soils

Granular Soil Foundation Depth Table																								
	Post Spacing (PS) [ft]				Foundation Depth [ft]																			
	PS ≤ 8'	8'< PS ≤ 12'	12'< PS ≤ 16'	16'< PS ≤ 24'	Soil Properties	N	2-3			4-9			10-19			20-29			30-49			50-60		
						ϕ	25-32			27-35			30-38			32-40			34-40			36-44		
							Ex.	New	Con.	Ex.	New	Con.	Ex.	New	Con.	Ex.	New	Con.	Ex.	New	Con.	Ex.	New	Con.
Barrier Height (H) [ft]	H ≤ 12'	H ≤ 10'	H ≤ 8'	H ≤ 6'	Transverse Graound Slope	Level	8.0	9.0	%D	8.0	7.5	%D	6.5	6.0	GR	6.0	5.5	GR	6.0	5.0	GR	6.0	4.5	GR
						5:1	8.0	9.0	%D	8.0	7.5	%D	7.0	6.0	GR	6.5	6.0	GR	6.0	5.5	GR	6.0	5.0	GR
						4:1	8.5	9.0	%D	8.5	7.5	%D	7.0	6.5	GR	7.0	6.0	GR	6.0	5.5	GR	6.0	5.0	GR
						3:1	9.0	9.0	%D	8.5	8.0	%D	7.5	6.5	GR	7.0	6.0	GR	6.5	5.5	GR	6.5	5.0	GR
						2:1	10.0	9.0	GR	9.5	8.5	GR	8.0	7.5	GR	7.5	7.0	GR	7.0	6.0	GR	6.5	5.5	GR
	12'< H ≤ 16'	10'< H ≤ 14'	8'< H ≤ 12'	6'< H ≤ 10'		Level	9.5	10.5	%D	9.5	9.0	%D	8.0	8.0	GR	7.5	7.5	GR	7.5	6.5	GR	6.5	6.0	GR
						5:1	10.5	10.5	%D	10.0	9.0	GR	8.5	8.0	GR	8.0	7.5	GR	8.0	7.0	GR	7.0	6.0	GR
						4:1	11.0	10.5	%D	10.5	9.5	GR	9.0	8.5	GR	8.5	8.0	GR	8.0	7.0	GR	7.5	6.5	GR
						3:1	11.5	10.5	GR	11.0	10.0	GR	9.5	9.0	GR	9.0	8.5	GR	8.5	7.5	GR	7.5	6.5	GR
						2:1	12.5	12.5	GR	12.0	11.5	GR	10.0	10.0	GR	9.5	9.5	GR	9.0	8.5	GR	8.0	7.5	GR
	16'< H ≤ 20'	14'< H ≤ 20'	12'< H ≤ 16'	10'< H ≤ 14'		Level	11.5	12.0	%D	11.0	10.5	GR	9.5	9.5	GR	9.0	9.0	GR	8.0	8.0	GR	8.0	7.0	GR
						5:1	12.5	12.0	GR	11.5	11.5	GR	10.0	10.0	GR	10.0	9.5	GR	8.5	8.5	GR	8.5	7.5	GR
						4:1	13.0	12.5	GR	12.0	11.5	GR	10.5	10.5	GR	10.5	10.0	GR	9.0	9.0	GR	8.5	8.0	GR
						3:1	13.5	13.0	GR	13.0	12.5	GR	11.0	11.0	GR	10.5	10.5	GR	9.5	9.5	GR	9.0	8.0	GR
						2:1	14.5	15.0	GR	14.5	14.0	GR	12.0	12.5	GR	11.5	11.5	GR	10.0	10.5	GR	9.5	9.0	GR
			16'< H ≤ 20'	14'< H ≤ 20'		Level	15.5	13.5	GR	14.0	13.0	GR	12.0	12.0	GR	11.0	11.0	GR	10.5	10.0	GR	10.5	9.0	GR
						5:1	19.0	15.0	GR	16.0	14.0	GR	13.5	13.0	GR	12.5	12.0	GR	11.0	10.5	GR	11.0	9.5	GR
						4:1	20.5	15.5	GR	17.5	14.5	GR	14.0	13.5	GR	13.0	12.5	GR	12.0	11.0	GR	11.5	10.0	GR
						3:1	24.0	16.5	GR	19.5	15.5	GR	15.0	14.0	GR	14.0	13.0	GR	12.5	11.5	GR	12.0	10.5	GR
						2:1	*	24.5	GR	30.0	17.5	GR	19.0	15.5	GR	16.0	14.5	GR	14.0	13.0	GR	13.0	11.5	GR
Controlling Criterion (Con.): %D - Percent deflection, GR - Geotecnical Resistance, SR - Structural Resistance																								

Table 8 – Comparison of Foundation Depths for Cohesive Soils

Cohesive Soil Foundation Depth Table																						
	Post Spacing (PS) [ft]				Foundation Depth [ft]																	
	PS ≤ 8'	8'< PS ≤ 12'	12'< PS ≤ 16'	16'< PS ≤ 24'	Soil Properties	N	0-1			2-3			4-8			9-15			16-32			
							Ex.	New	Con.	Ex.	New	Con.	Ex.	New	Con.	Ex.	New	Con.	Ex.	New	Con.	
Barrier Height (H) [ft]	H ≤ 12'	H ≤ 10'	H ≤ 8'	H ≤ 6'	Transverse Graound Slope	Level	12.5	13.5	GR	12.5	10.0	GR	7.0	7.0	GR	6.0	4.0	GR	6.0	3.5	GR	
						5:1	13.5	14.5	GR	13.5	10.5	GR	7.5	7.0	GR	6.0	4.5	GR	6.0	3.5	GR	
						4:1	13.5	15.0	GR	13.5	10.5	GR	7.5	7.0	GR	6.0	4.5	GR	6.0	3.5	GR	
						3:1	14.0	15.0	GR	14.0	11.0	GR	8.0	7.0	GR	6.0	4.5	GR	6.0	4.0	GR	
						2:1	14.5	16.0	GR	15.0	11.5	GR	8.0	7.5	GR	6.0	5.0	GR	6.0	3.5	GR	
	12'< H ≤ 16'	10'< H ≤ 14'	8'< H ≤ 12'	6'< H ≤ 10'		Level	17.0	19.5	GR	17.0	14.0	GR	9.5	9.5	GR	7.5	6.0	GR	6.0	4.5	GR	
						5:1	18.5	21.0	GR	18.5	15.5	GR	10.0	10.0	GR	8.0	6.0	GR	6.0	5.0	GR	
						4:1	19.0	21.0	GR	18.5	15.5	GR	10.5	10.0	GR	8.0	6.0	GR	6.0	5.0	GR	
						3:1	19.5	21.5	GR	19.0	16.0	GR	10.5	10.5	GR	8.0	6.5	GR	6.0	5.0	GR	
						2:1	20.0	23.0	GR	20.0	17.0	GR	11.0	11.0	GR	8.5	6.5	GR	6.0	5.0	GR	
	16'< H ≤ 20'	14'< H ≤ 20'	12'< H ≤ 16'	10'< H ≤ 14'		Level	21.5	25.0	GR	21.0	18.0	GR	13.5	12.5	GR	9.5	7.5	GR	6.5	6.0	GR	
						5:1	23.0	26.5	GR	23.0	20.0	GR	14.5	13.0	GR	10.0	8.0	GR	7.0	6.5	GR	
						4:1	23.5	27.0	GR	23.0	20.0	GR	14.5	13.5	GR	10.0	8.0	GR	7.0	6.5	GR	
						3:1	25.0	27.5	GR	24.0	21.0	GR	15.0	13.5	GR	10.5	8.0	GR	7.0	6.5	GR	
						2:1	25.5	29.0	GR	24.5	22.5	GR	16.0	14.5	GR	11.0	8.0	GR	7.0	6.5	GR	
			16'< H ≤ 20'	14'< H ≤ 20'		Level	*	33.0	GR	*	23.5	GR	19.0	16.0	GR	13.0	10.0	GR	9.0	6.0	GR	
						5:1	*	35.0	GR	*	25.5	GR	20.5	17.0	GR	14.0	10.0	GR	9.0	7.5	GR	
						4:1	*	35.0	GR	*	26.0	GR	21.0	17.5	GR	14.5	10.0	GR	9.0	8.0	GR	
						3:1	*	36.0	GR	*	26.5	GR	22.0	18.0	GR	15.0	10.0	GR	9.5	8.5	GR	
						2:1	*	38.5	%D	*	28.0	GR	24.0	19.0	GR	15.0	10.5	GR	10.0	8.5	GR	
Controlling Criterion (Con.): %D - Percent deflection, GR - Geotecnical Resistance, SR - Structural Resistance																						

Note: Red highlighting indicates the foundation depth resulting from the current study is longer than the existing design table, and green highlighting indicates a shorter result.

There is generally very good agreement between the two sets of results for granular soils. In the majority of cases the difference is only 0.5 foot or less. The change in wind pressure and method to calculate the effective moment arm may have offset each other. However, for the cohesive soils, there are some significant differences. For soft cohesive soils with N=0-1 the existing design table appears to be unconservative when compared to the results from the current study. In some cases, the drilled shaft lengths should be increased by up to 3 feet. While for stiffer cohesive soils the existing design table is much more conservative than the results from the current study. The most extreme difference in shaft length is for granular soil, N=4-9, 2H:1V slope, PS=24’ and H=20’. The existing design table shows a drilled shaft foundation depth of 30 feet for this case, while the current study resulted in a depth of 17.5 feet.

The controlling criterion is shown for each of the analyses in Table 7 for the granular soils and in Table 8 for the cohesive soils. The controlling criterion was geotechnical resistance (GR) in the majority of cases, with the percent deflection criterion (%D) controlling in some cases. The structural resistance of the drilled shaft foundation did not control.

7 Comparison of Change to Axial Loads

Because the axial loads may have a detrimental or beneficial effect on the performance of laterally loaded reinforce concrete piles, we considered the effect of varying the axial loads in two ways. First, we applied minimum and maximum load factors to dead load values of 75 lb/ft^2 and 100 lb/ft^2. Second, we included applied ice loads. Applying the ice loads without the wind loads would have no effect, as the wind loads control the design of the noise barrier foundation. Therefore, we applied the ice loads and wind load concurrently for comparison purposes. We assumed the three inches of ice accumulation were on only one side of the panels, which created an off-center weight and a slight increase in the applied moment in addition to the axial load.

To study the change in axial loads, we considered a noise barrier foundation located in a granular soil with N=10-19 and the maximum panel spacing (24 ft) and barrier height (20 ft). The results for the minimum drilled shaft length are shown below in Table 9 for the load factors and Table 10 for the ice loads. Results with no axial load included are also shown for comparison. The results indicate that increasing axial loads and load factors may increase the foundation depth by 0.5 foot in cases where the ground slope is 2H:1V or 3H:1V. The results also indicate that including ice loads will only increase the foundation depth 0.5 ft when a weight of 100 lb/ft^2 is used for the barrier and where the ground slope is 2H:1V or 3H:1V. Otherwise the inclusion of ice loads has no effect on the foundation depth for the cases considered. We believe the effect of the ice load may be more significant for weaker soils.

Table 9 – The Effect of Different Axial Loads and Load Factors on Foundation Depth

Foundation Depth [ft]							
Soil Properties	N	10-19					
	ϕ	30-38					
		Existing	No Axial Load	DC-75 LF=0.9	DC-75 LF=1.25	DC-100 LF=0.9	DC-100 LF=1.25
Transverse Ground Slope	Level	12	11.5	12	12	12	12
	5:1	13.5	12.5	13	13	13	13
	4:1	14	12.5	13	13.5	13.5	13.5
	3:1	15	13.5	14	14	14	14.5
	2:1	19	15	15.5	16	15.5	16

Table 10 – The Effect of Ice Loads on Foundation Depth

Foundation Depth [ft]						
Soil Properties	N	10-19				
	ϕ	30-38				
		Existing	DC-75 w/o ice	DC-75 w/ ice	DC-100 w/o ice	DC-100 w/ ice
Transverse Ground Slope	Level	12	12	12	12	12
	5:1	13.5	13	13	13	13
	4:1	14	13.5	13.5	13.5	13.5
	3:1	15	14	14	14	14.5
	2:1	19	15.5	15.5	15.5	16

We also considered the effect that varying the axial load had on the shear, moment, and percent deflection for the noise barrier foundations. The results are shown in Figures 1 to 6. The graphs for maximum shear and maximum moment are very similar with and without the ice load, showing slight increases in shear and moment. From this we conclude that it is the change in axial load alone which affects the shear and moment in the foundation. The small moment caused by the off-center ice loads does not have a significant effect on the shear and moment in the noise barrier foundation. The graphs for percent deflection, Figure 5 for the change in axial loads and Figure 6 for the ice loads, are very similar, but the graph that shows the effect of ice loads on the deflection shows a slightly greater increase than the one for varying the axial loads. From this we conclude that the small additional moment from the off-center ice load does have a small effect on the deflections, although the increased deflection is still below the displacement criterion of 1.5 percent of the noise barrier panel height. For level ground the ice loads increase the percent deflection by 0.12 percent. For other ground slopes the ice loads increase the percent deflection by 0.02 percent.

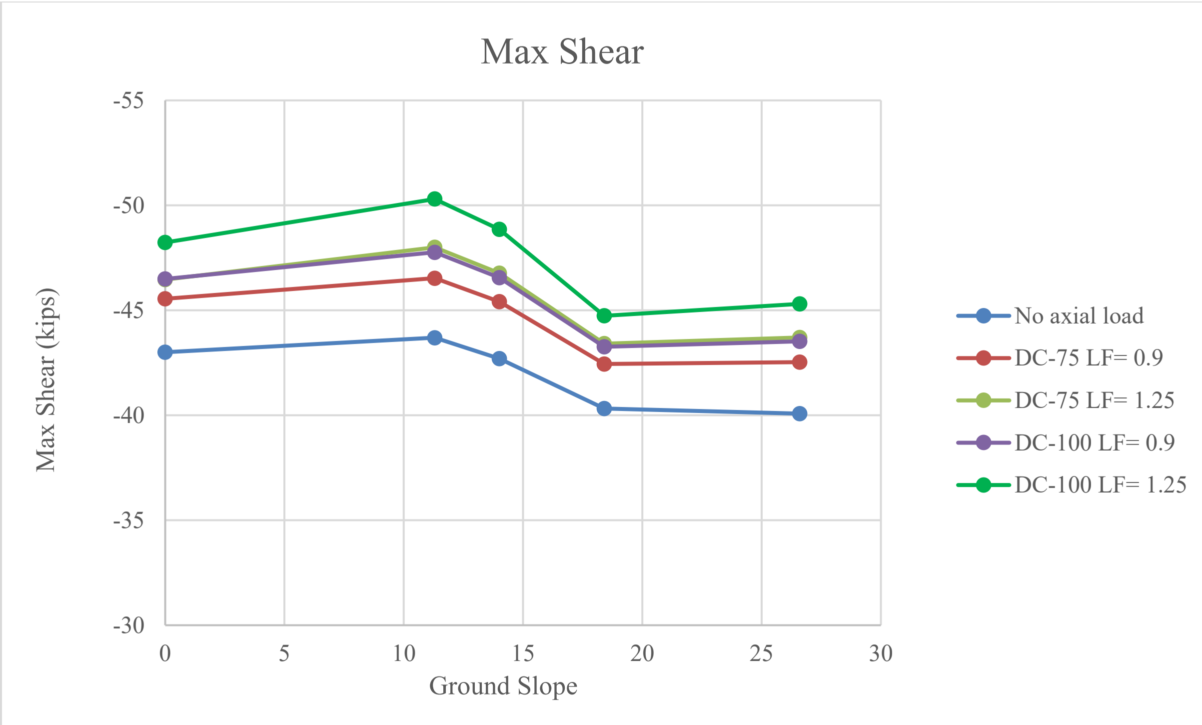

Figure 1 – Maximum Shear in Foundation with Different Axial Loads and Load Factors

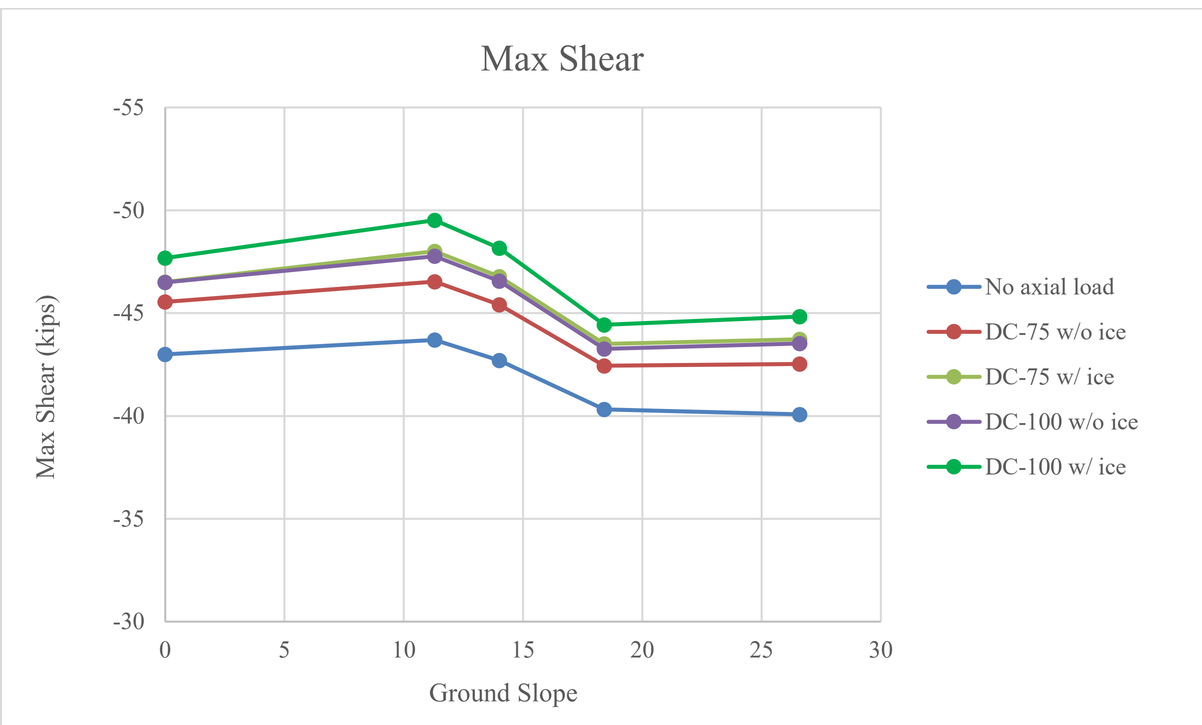

Figure 2 – Maximum Shear in Foundation with Ice Loads and without Ice Loads

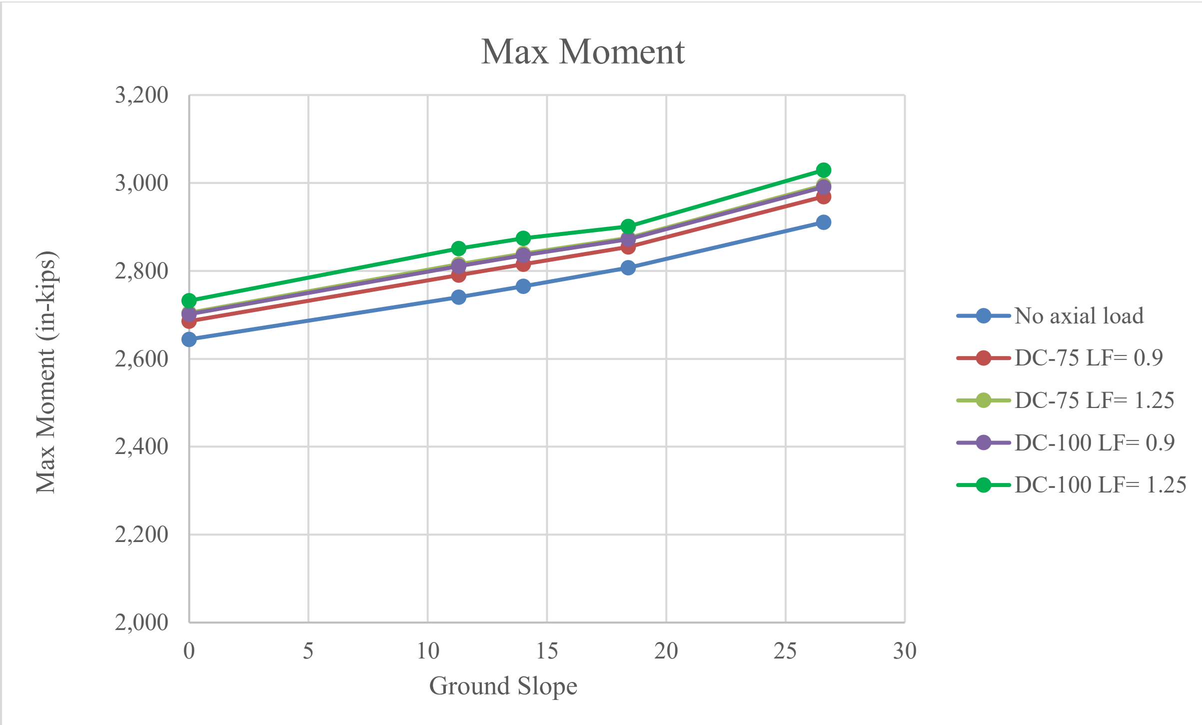

Figure 3 – Maximum Moment in Foundation with Different Axial Loads and Load Factors

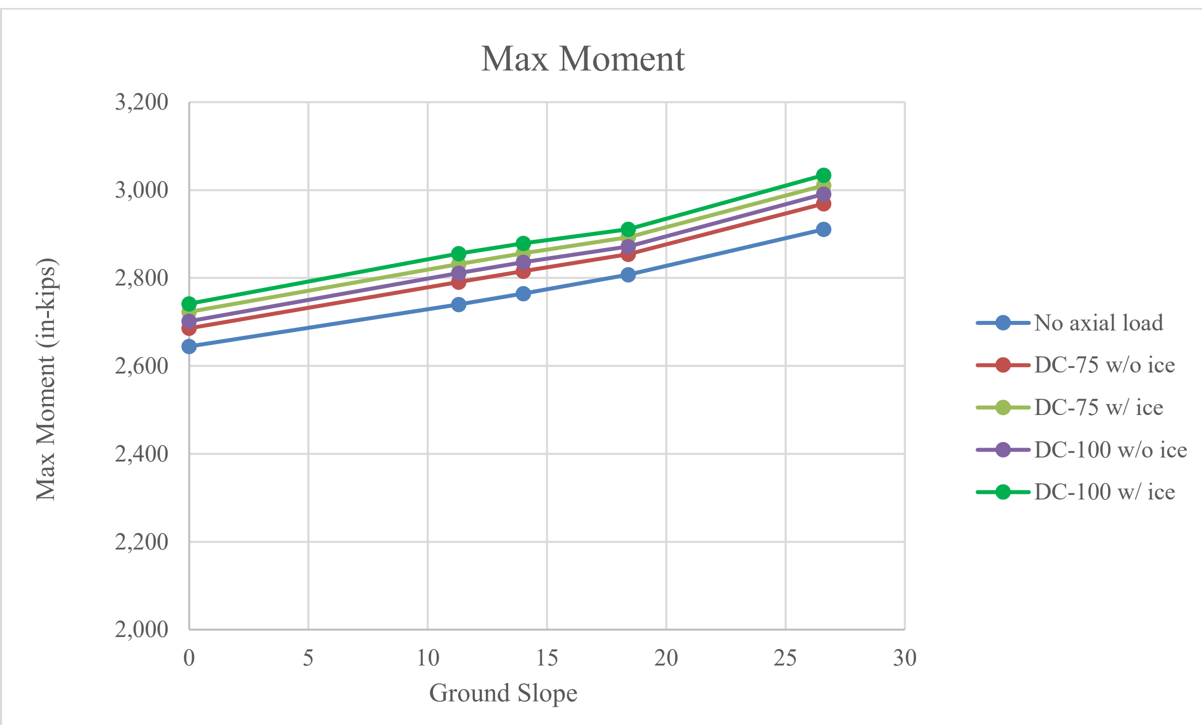

Figure 4 – Maximum Moment in Foundation with Ice Loads and without Ice Loads

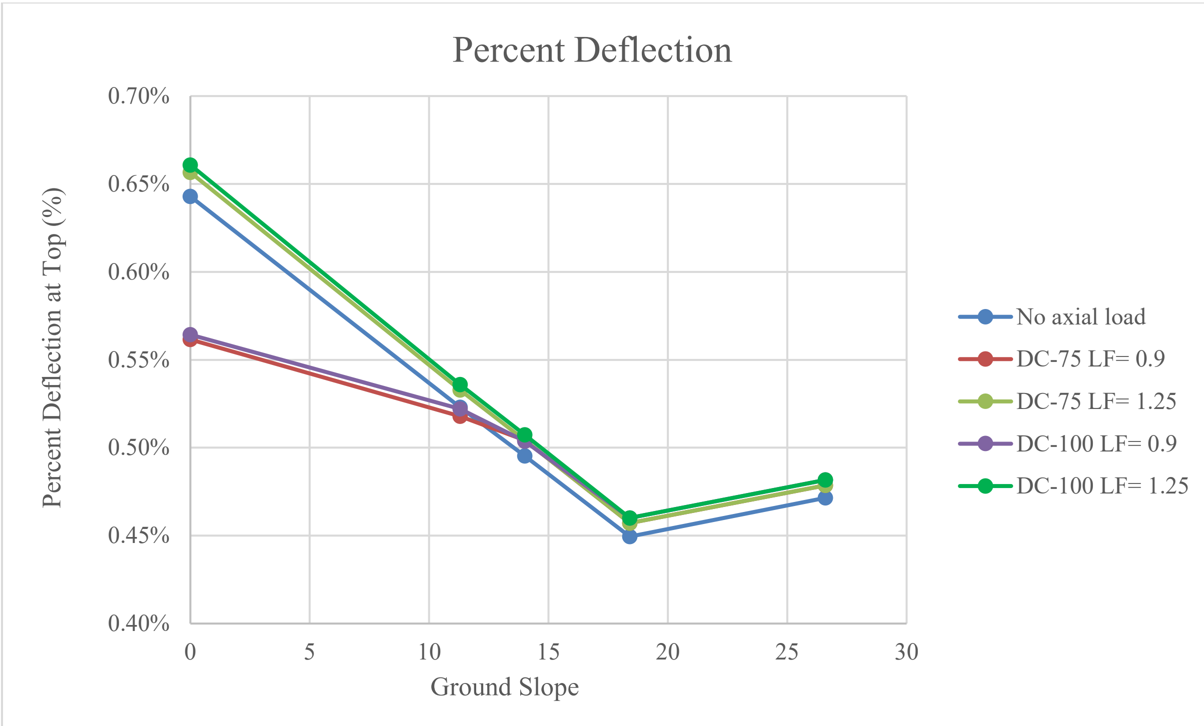

Figure 5 – Percent Deflection of Noise Barrier with Different Axial Loads and Load Factors

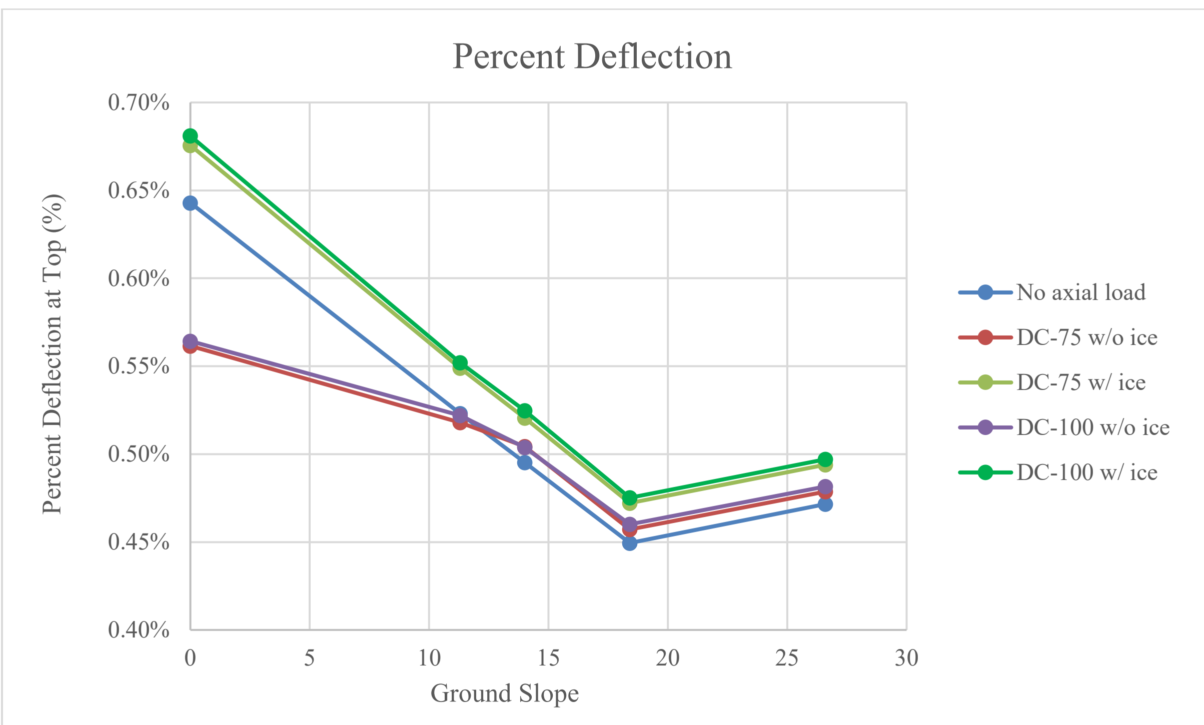

Figure 6 – Percent Deflection of Noise Barrier with Ice Loads and without Ice Loads

8 Conclusion

This study proposes a design method for noise barrier foundations that consists of using the p-y method of analysis for laterally loaded piles. The p-y method is currently used by ODOT for the design of drilled shafts for landslide stabilization, as described in Geotechnical Bulletin 7 (ODOT, 2020). We developed the design criteria and loads specifically for noise barrier foundations and the AASHTO LRFD Bridge Design Specifications (AASHTO, 2020). We then used the proposed design method to determine the drilled shaft length for all the different cases that are included in the current design tables in the Bridge Design Manual (ODOT, 2022a) and compared the results to the existing tables. We generally found very good agreement for granular soils between the results of this study and the existing design table. In the majority of cases the difference is only 0.5 foot. However, for the cohesive soils, there are some significant differences. For soft cohesive soils with N=0-1 the existing design table appears to be unconservative when compared to the results from the current study. In some cases, the drilled shaft lengths should be increased by up to 3 feet. While for stiffer cohesive soils the existing design table is much more conservative than the results from the current study.

We also considered the effect that varying the axial load and the addition of ice loads had on the shear, moment, and percent deflection for a noise barrier foundation located in a granular soil with N=10-19 and the maximum panel spacing (24 ft) and barrier height (20 ft). We conclude that the increase in axial load slightly increases the shear and moment in the foundation. The small moment created by the off-center ice loads does not have a significant effect on the shear and moment in the noise barrier foundation. The addition of ice load does show an increase in the percent deflection of the noise barrier, although the increased deflection is still below the displacement criterion of 1.5 percent of the noise barrier panel height. For level ground the ice loads increase the percent deflection by 0.12 percent. For other ground slopes the ice loads increase the percent deflection by 0.02 percent.

The proposed design method may also be used to design a noise barrier foundation that falls outside the limits of the design tables in the ODOT Bridge Design Manual. The proposed design method has been adapted for this purpose and described in a white paper that is included in Appendix A. The white paper describes the loading, design procedure, and the method of interpreting the results. It is intended for ODOT design consultants to use when the standard design tables do not apply.

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Appendices

Appendix A

White Paper for Custom Design Procedure for Noise Barrier Foundations

Appendix B

Results of LPile Analyses