APPENDIX F: Downdrag Load (Dragload, Drag Force) and Downdrag

F Background

Appendix F subsections:

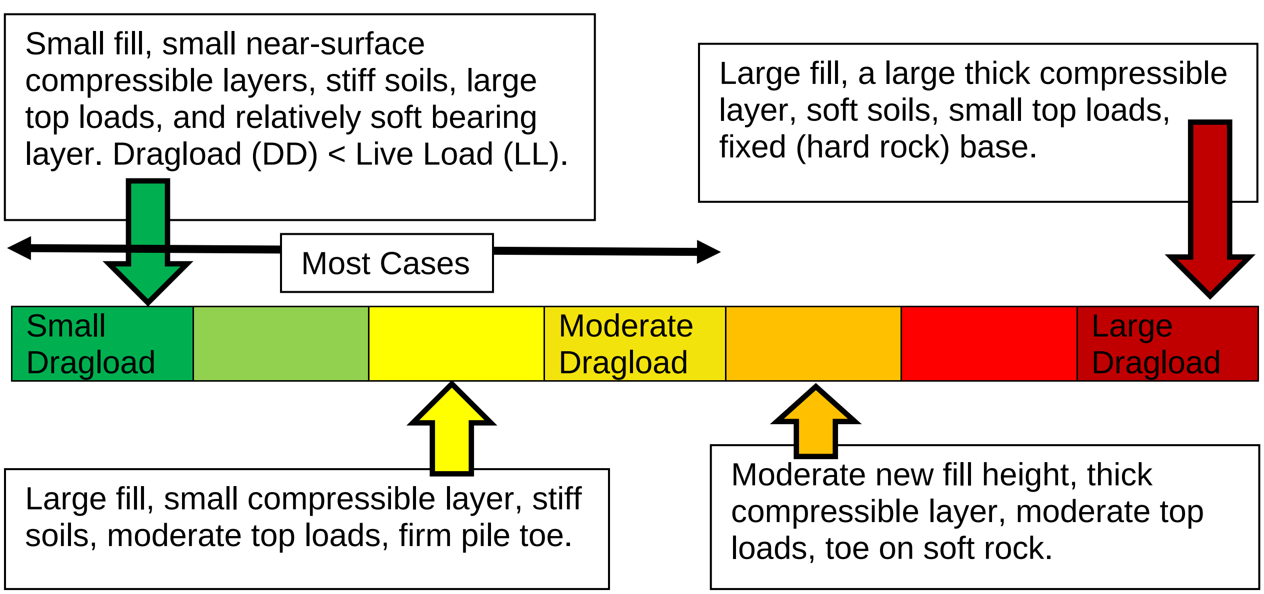
APPENDIX F: Downdrag Load (Dragload, Drag Force) and Downdrag

Background

Through the adoption of the LRFD framework, more pile capacity is being utilized for greater economy and effectiveness, resulting in the need for an improved understanding of the mechanisms and implications of dragload (forces applied in the NSF region of the pile) and downdrag (deflection or movement specifically caused by dragload).

While in the past, downdrag and dragload were either misunderstood or completely ignored (and the nomenclature often confused and interchanged), recent instrumentation projects and computational modeling work [as well as a rigorous literature review and recent research] has provided an improved understanding of the nature of this soil/pile interaction problem and the associated mechanisms and, importantly, the practical effects related to pile performance. An important component of the new policy is that dragload acts on a continuum and the phenomenon is present in some form in all deep foundations unless the foundation is at the geotechnical strength limit state and on the verge of moving (where all available toe and side resistance is fully mobilized).

Prediction of the actual in-service value of dragload is complex, as it acts differenetly depending on the location along the pile and the state of stress and strain along the pile length and at the top and bottom, as well as material stiffnesses. Generally speaking, the amount of new fill or soil surcharge loading, location and thickness of compressible soils, end bearing condition, and amount of top (structural) load, result in combinations of scenarios which are unfavorable or favorable for dragload. Most sites and foundations (geometry and material properties) have conditions which both tend to promote and mitigate dragload. The state of stress in the pile, resulting from dragload, is *always less than that at geotechnical failure* (geotechnical strength limit state); not all foundaitons, however, are designed to use the entire available geotechnical capacity.



Ongoing field studies at MnDOT support that dragload and downdrag effects are far more common than previously appreciated- so common that the effect has been observed to some degree on every instrumented pile performance project. Based on recent study of pile loading in dragload susceptible soils where new fill was limited in height, dragload was found to exist, but the magnitude was small. Although the neutral plane continues to develop (usually between the pile middle and bottom 1/3 of the pile) there is minimal load accrual above the neutral plane. Top load shedding begins relatively distant from the pile head, and the shedding tends to occur at a faster rate (per unit pile length) than indicated by capacity models that represent conditions at the geotechnical strength limit state.

In most circumstances there is little physical impact on loading, deflection, safety, or performance where conditions are not favorable for dragload accumulation. The cases with the most potential for risk (uncaptured high pile loads) are related to construction of high fills adjacent to efficiently designed piles driven through thick layers of compressible materials to strong intact bedrock where soil set-up [long-term strength gain] may also play a role.

Settlement associated with dragload should also be considered and in some cases can be a greater concern depending on the pile design (such as settlement mitigation platforms which are designed and intended to deflect to a controlled degree).

Based on recent work, MnDOT policy guidelines have been significantly updated to better reflect the most current understanding of the physical impacts of this complex soil-structure interaction phenomenon. This guidance is described in Appendix F.

A separate document containing project case histories and commentary on how the Dragload policy and these appendices were developed is available (Spring 2017) on the MnDOT Geotechnical webpage.

APPENDIX F-1: General Design Process Steps, Neutral Plane (NP) Method

Overview of the Process to Evaluate Dragload (including a simplified check to determine if more rigorous calculations are needed)

STEP 1: Obtain necessary design information

- Soil properties and stratigraphy of site soils.
- Pile type, dimensions, and proposed pile depth (installed length).
- Information on amount, extent, and construction timeline associated with soil fills.
- Unfactored structural 'top loads', particularly dead load, applied to the pile head [for rigorous methods].
- Locally adopted LRFD load and resistance factors for the neutral plane method.
- If available: Soil behavior models (based on load tests or existing models) for pile load vs. deformation behavior- (T-z and Q-z curves), [for rigorous methods].

STEP 2: By inspection of the site conditions, determine if the site conditions are "favorable" for dragload. If in doubt, take the conditions as favorable.

Dragload is induced by even modest changes in grading around piles, such as work platforms, typical temporary excavations and soil backfill in the vicinity of abutments and pile caps as well as final build-out and final grading and earth cover near foundations. It may also be induced by dewatering or other changes in stress state of the soil (such as densification by earthquake, blasting, or vibrocompaction). Critically, assess the site for favorability.

- "**Unfavorable" dragload conditions (dragload magnitudes are small) include:**
    - "No fill" conditions (such as at bridge piers)
    - Small construction excavation and backfill areas for pile caps
    - Small side-hill or embankment fills (generally 4 feet or less)
    - Generally stiff soil layers without a 'defined' compressible layer
- **"Favorable" dragload conditions include:**
    - Embankment fills or side hill fills placed over loose or compressible soils

- New structures, with shallow foundations, being placed near existing or new deep foundations
- Sites with substantial dewatering
- Sites with potential for consolidation or compaction due to vibration or seismic effects

STEP 3: Use the diagrams included in Appendix F-2 to estimate if dragload is likely to exceed the live load.

- **If estimated dragload is small, where: dragload ≤ live load, no further dragload calculations are required†. Proceed to Step 7.**

- **If the estimated dragload is ≥ live load, use the provided graphical "Compressible Layer Approximation" methods or rigorous methods (Appendix F-7 or alternates) to determine a design value.**

- **If the estimated dragload is >> live load, use the rigorous methods (Appendix F-7 or alternates) to determine a design value.**

In each case, the peak pile load will occur at the neutral plane (above the NP, load accumulates, below the NP the load sheds).

STEP 4: Calculate the dragload using NP methods: the provided graphs OR use the rigorous methods related to pile and soil movement compatibility OR methods related to % tip mobilization.

STEP 5: Apply the MnDOT locally adopted load factor (Appendix F-4).

STEP 6: Consider recommending instrumentation and monitoring to confirm design parameters for projects where predicted dragload is large.

STEP 7: Report the dragload profile and/or peak dragload values, location of the neutral plane (NP) and related information in the design document and recommend mitigation strategies, if necessary for design consistent with Appendix F-6.

† Consult with the Geotechnical Section if values are found to be in excess of the design live load (LL) values, but still relatively close (exceeding by 50% or less).

APPENDIX F-2: Simplified Diagrams for Dragload Estimation

Simplified NSF, PSF, NP Diagram at the Service Limit State (for Preliminary Check where "Dragload Conditions" are not favorable)

A series of simplified diagrams has been adapted (and modified) from Sun, Yan, and Su (ASCE 2014)† which relates the position of the neutral plane, when the pile head load is zero, to the mobilization of the negative skin friction (NSF) and positive skin friction (PSF). An example calculation is provided at the end of Appendix F-2.

Use these diagrams in combination with an evaluation of the pile side resistance at the strength limit state (nominal geotechnical resistance graph).

These diagrams formatted to apply to all installation situations based on a normalized pile length, therefore any pile length can be used for evaluation:

X Axis: Depth

D = Full pile length
Z = depth below soil along the pile length

The left axis is the depth below the top of the pile (pile head) where the fractions are percentages (expressed as a decimal) of the pile length.

Y Axis: % skin friction mobilization

-100%	=	-1.0 * geotechnical strength limit PSF prediction for that layer	(NSF)
-50%	=	-0.5 * geotechnical strength limit PSF prediction for that layer	(NSF)
0%	=	0.0 * geotechnical strength limit PSF prediction for that layer	(0)
50%	=	0.5 * geotechnical strength limit PSF prediction for that layer	
100%	=	1.0 * geotechnical strength limit PSF prediction for that layer	

Diagram F-2-1 is used to evaluate previously considered "no dragload" cases where site conditions do not promote dragload (motivating factors such as added fill are not present). These conditions are considered unfavorable for the development of large magnitude of dragload. A neutral plane forms (reflecting Service Limit State conditions) with the upper 60% of the pile exhibiting NSF and the lower 40% of the pile exhibiting PSF, unlike at the Geotechnical Strength Limit where load shedding begins at the ground surface and the entire pile is mobilized with PSF.

This diagram reflects that dragload develops as a consequence of static equilibrium and stiffness contrast, although the magnitude of added load imparted into the pile is often small where conditions are not favorable for dragload development. Calculate dragload based on percentages of the fully mobilized side resistance, predicted at the Geotechnical Strength Limit State, based on Figure F-2-1.

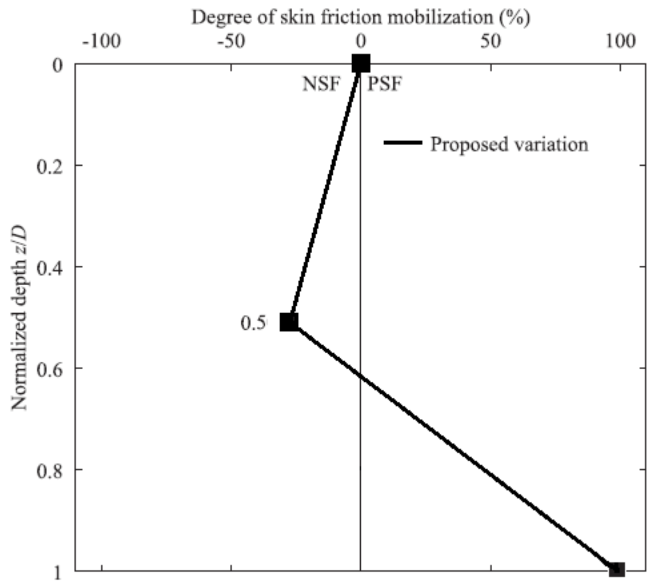


Figure F-2-1: Degree of skin friction mobilization based on position using normalized pile length. The neutral plane is assumed to be at a position of 0.6D measured from the pile head. Negative skin friction increases linearly through a transition zone from 0 at 0.0D to 25% at 0.5D. Below 0.5D, the transition zone extends to the base of the pile. PSF does not begin until 0.6D below the top of pile and is not fully mobilized until the pile toe.

The magnitude of dragload (NSF), for cases where significant motivating factors are not present (unfavorable conditions), may be estimated, for reasonably homogeneous soil deposits, as 12.5% of the calculated shaft resistance (at the Geotechnical Strength Limit State) over the top 60% of the pile. (60% of the pile length is exposed to NSF, even though the neutral plane, NP, is located at the pile midpoint).

The positive side resistance (PSF) may be estimated (for reasonably homogeneous soil deposits) as 50% of the calculated side resistance (at the Geotechnical Strength Limit State) over the bottom 40% of the pile. If the stratigraphy changes significantly in the lower 40% of the pile length, the distribution shown in Figure F-2-1 should be used.

“Compressible Layer Approximation” (Unfavorable Conditions for Dragload)

If there is a clearly defined “compressible layer,” underlain with very dense or stiff soils such that consolidation or settlement may be assumed to be completely limited to this upper softer compressible layer, it may be appropriate to assume that load accrual continues to the base of the compressible layer and load shedding begins immediately below this layer.

The location of the neutral plane can be determined graphically using Diagram F-2-2 as a guide (selected points are also provided in Table TF-2-1). For this approximation, model the dragload (NSF) as linearly mobilized from 0% to a maximum of 25% of the calculated side resistance from the top of the pile to the base of the compressible layer.

Below the compressible layer, model the pile behavior as linearly varying from 25% NSF to 100% PSF along the portion of the pile below the compressible layer. The location of the neutral plane may be approximated from a similar construction to Figure F-2-2 depending on the actual location of the compressible layer for the project site conditions. Table TF-2-1 provides the approximate location of the neutral plane based on the depth of the compressible layer (normalized as a percentage of pile length).

Table TF-2-1 Location of Neutral Plane Using Compressible Layer Approximation (unfavorable conditions for developing dragload)

Depth to Base of Compressible Layer (based on % of pile length)	Location of Neutral Plane (NP) (based on % of pile length)
10%	28%
20%	36%
30%	44%
40%	52%
50%	60%
60%	68%
70%	76%
80%	84%
90%	92%
100%	100%

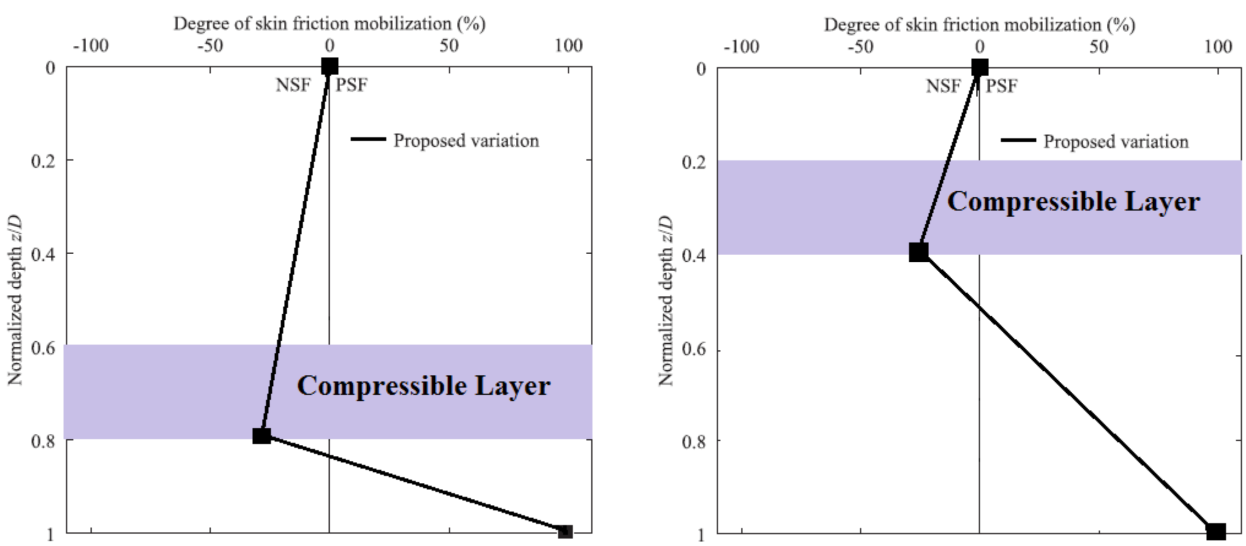


Figure F-2-2: Degree of skin friction mobilization based on position using normalized pile depth. The inflection point of load accrual/shedding is approximated at the base of the compressible layer, shown at 0.8D (left) and at 0.4D (right). The maximum developed NSF used here (at the service limit) is 25% of the calculated value at the Strength Limit State. The neutral plane is below the compressible layer where % mobilization = 0.

Note that although the dragload condition is fully mobilized (developed) along the pile length, the degree of skin friction mobilization (magnitude) is variable [not 100%].

†Fully Coupled Consolidation Analysis of Shear Strength Mobilization and Dragload of a Pile Subject to Negative Skin Friction T. K. Sun; W. M. Yan, M.ASCE; and Dong Su International Journal of Geomechanics, 10.1061/(ASCE)GM.1943-5622.0000381. © 2014 American Society of Civil Engineers.

Simplified NSF, PSF, NP Diagram at the Service Limit State (for Preliminary Check where "Dragload Conditions" are favorable)

A second simplified set of diagrams has been adapted (and slightly modified, for simplicity) from a paper by Sun, Yan, and Su (ASCE 2014)† which relates the position of the neutral plane, when the pile head load is zero, to the mobilization of the negative skin friction and positive skin friction as assessed by numerical methods. The results of the work were found to be in good agreement with MnDOT instrumented pile projects. Note that as pile top load is added, the neutral plane will tend to shift upward, although the effect is small until the loading approaches 2/3 of the pile axial capacity. An example calculation is provided at the end of Appendix F-2.

It is recommended, and strongly encouraged, that a more rigorous analysis be conducted for structures where dragload magnitude effects could be problematic. The simplified approach, based on the following diagram, is useful as an estimation tool.

The diagram is based only on the installed depth of the pile; it is independent of the top load, the location and thickness of the compressible layer, and soil or pile material properties. Use information from pile capacity prediction software and apply the chart to estimate the amount of dragload (DD) for design purposes.

The chart uses a normalized pile depth. The mobilization of NSF changes from 100% through a transition zone beginning at 60% of the installed pile length below ground. The neutral plane (NP) is taken to be at a position 20% (of the pile length) above the pile toe. In-situ the true NP location will likely be lower for piles bearing on hard bedrock, and will be higher for friction piles (piles with comparatively compliant toe bearing). The NP will also be higher for piles with larger top loads. For most cases, this diagram is a reasonable design assumption, but engineering judgement may also be necessary for proper evaluation of specific sites where more information is known.

For the embedded portion of the pile from the pile top to a length of 60% of the total length, evaluate the shaft resistance as 100% mobilized and acting as negative skin friction (NSF). The diagram shows this as a negative (-) value.

For the embedded portion of the pile from 60% of the total length to 80% of the total length, evaluate the shaft resistance as 50% mobilized and acting as negative skin friction (NSF). The diagram shows this as a negative (-) value.

Several software packages present the dragload as being mobilized depending on assumptions related to the "% mobilized base resistance." In this simplification, the maximum side resistance values can be used and adapted, as described above (100% for length 0 to 0.6D {where 'D' is the pile toe depth (installed length, L)} and 50% from length 0.6D to 0.8D}.

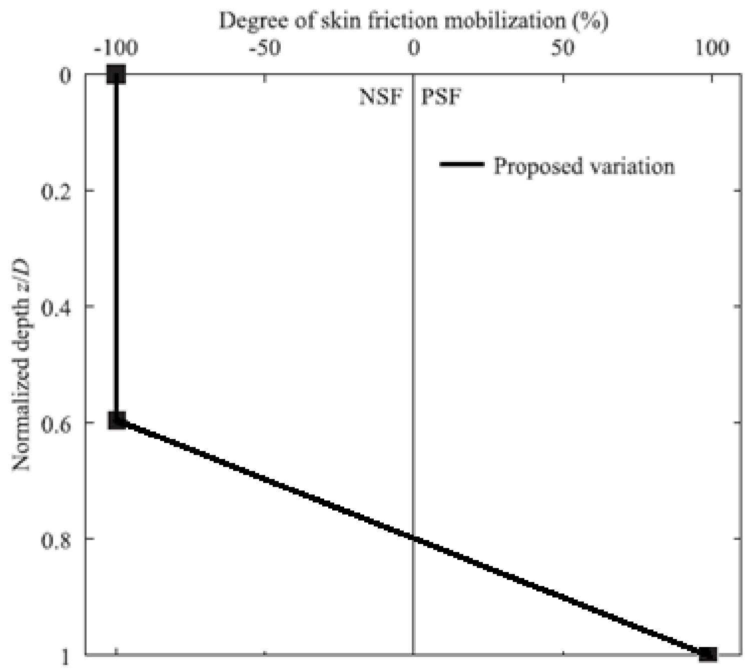


Figure F-2-3: Degree of skin friction mobilization based on position using normalized pile depth. The neutral plane is located at 0.8D measured from the pile head. Above 0.6D, negative skin friction is fully mobilized; only at 1.0D is positive skin friction fully mobilized. The region between 0.6D and 1.0D constitutes a "transition zone."

While it is not necessary to calculate the following values, for completeness: For the embedded portion of the pile from 80% of the total depth to 100% of the total depth, evaluate the shaft resistance as 50% mobilized and acting as positive skin friction (PSF). The diagram shows these resistances as positive (+) values.

Using the chart, a reasonable estimate of dragload can be determined for preliminary design purposes. The estimate assumes that pile installation and soil conditions permit a "representative" amount of dragload to accrue on the pile.

If the dragload appears to be large or problematic from settlement or structural design/capacity standpoints, further evaluation is necessary. Refined analysis requires knowledge of the structural top load, which will tend to reduce the dragload.

The dragload magnitude of may be estimated (for reasonably homogeneous soil deposits) as 100% of the shaft resistance over the top 60% of the pile depth + 50% of the shaft resistance over the 60% to 80% installed length of the pile.

If this amount of dragload controls the design (DL+DD) > (LL+DD) it is recommended that the more rigorous neutral plane development method described in the appendix be used, this method considers the top load of the pile at the service limit state.

The positive side resistance may be estimated (for reasonably homogeneous soil deposits) as 50% of the shaft resistance over the 80% to 100% depth of the pile. If the stratigraphy changes significantly in the lower 20% of the pile length, the distribution shown in Figure F2-3 should be used.

“Compressible Layer Approximation” (Favorable Conditions for Dragload)

If there is a clearly defined “compressible layer,” underlain with very dense or stiff soils such that consolidation or settlement may be assumed to be completely limited to this softer compressible layer, it may be appropriate to assume the load accrual continued through the compressible layer and load shedding begins immediately below the layer. As dragload acts along a continuum, there is a gradual stress reversal. The location of the neutral plane can be approximated, as shown below, for simplicity.

Model the dragload (NSF) as 100% mobilized to the base of the compressible layer. Below the compressible layer, model the pile behavior as linearly varying from 100% NSF to 100% PSF along the remainder of the pile to the pile toe. Refer to Table TF-2-2 and Figure F-2-4 for the location of the neutral plane.

Table TF-2-2 Location of Neutral Plane Using Compressible Layer Approximation (favorable conditions for developing dragload)

Depth to Base of Compressible Layer (based on % of pile length, measured from pile head)	Location of Neutral Plane (NP) (based on % of pile length, measured from pile head)
10%	55%
20%	60%
30%	65%
40%	70%
50%	75%
60%	80%
70%	85%
80%	90%
90%	95%
100%	100%

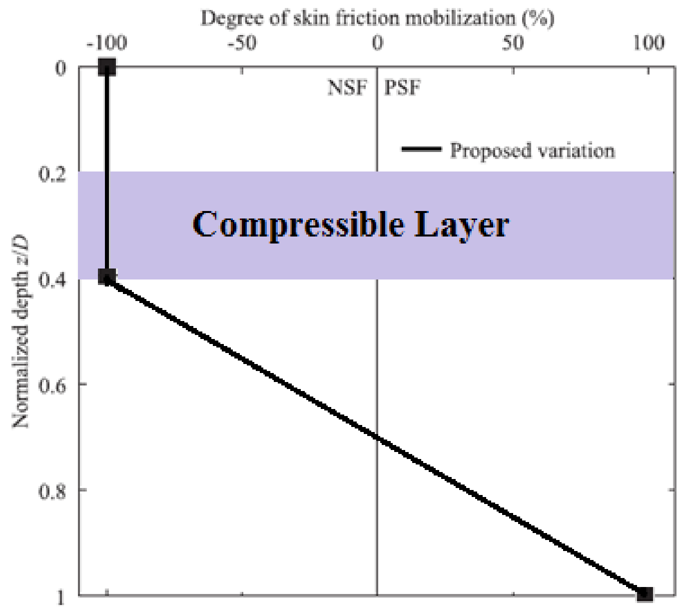


Figure F-2-4: Degree of skin friction mobilization based on position using normalized pile depth. The point of transition to PSF is approximated at the base of the compressible layer. Above the base of the layer [shown at 0.4D], negative skin friction is taken to be 100% (fully) mobilized; below the base of the compressible layer exists a "transition zone." The neutral plane is at ½ the remaining pile length between the base of the compressible layer and the pile toe, shown at 0.7D. The degree of mobilization is 0% at the neutral plane. PSF is not 100% (fully) mobilized until the pile toe.

After estimates of the NSF and PSF values are compiled, if desired, the % mobilization of the toe (base) can be calculated using the unfactored Service Limit loads and the estimate for the Base Resistance at the Geotechnical Strength Limit (Nominal Geotechnical Base Resistance). Sum values for the side resistance "capacity" components, using the graphs above, and solve for % Base Mobilization as described in the equation below (rearranging to solve):

[NSF Shaft Resistance* + PSF Shaft Resistance*] + [(% Base Mobilization) X (Base Resistance @ Geotechnical Strength Limit)] = Service Load

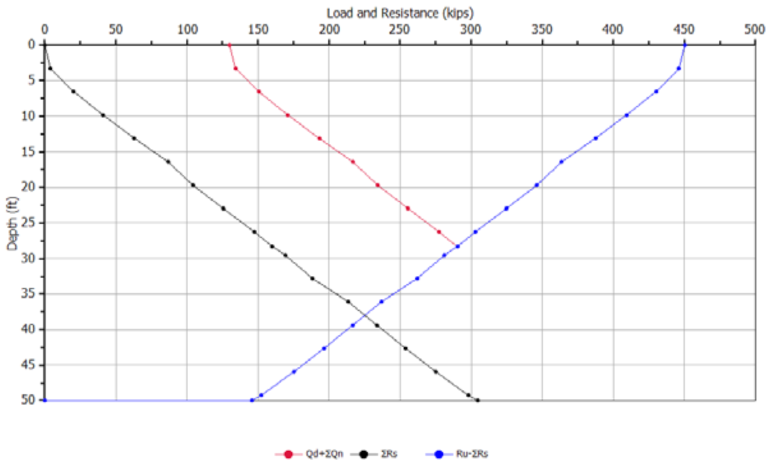
**Based on the charts above, the first two terms are converted into anticipated Dragload at the Service Limit State and Mobilized PSF Resistance at the Service Limit State*

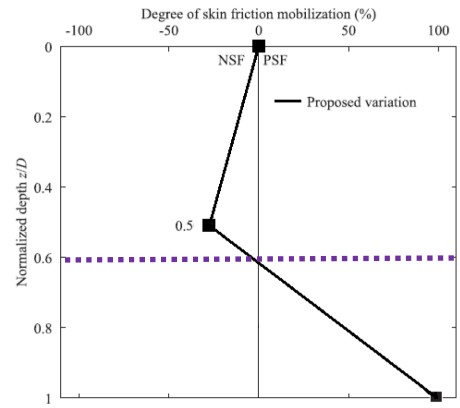
The % base mobilization will increase when more of the pile is within a compressible layer (less of the pile is available for load shedding) at the Service Limit.

Provide a dragload estimate in the geotechnical report.

Dragload Estimate in Conditions Unfavorable for Dragload (Example 1):

Pile length = 50 feet





The Geotechnical Nominal Pile Capacity Chart for this pile is shown (above, left). Based on simplified chart (above, right), the NP location is estimated at 60% of the pile length (30 feet). The region of NSF is the upper 60% of the pile (0 feet – 30 feet).

As described in F-2 (above): *Use the pile analysis and the provided graphic method.*

The dragload (NSF) may be estimated, for reasonably homogeneous soil deposits, as 12.5% of the calculated shaft resistance (at the Geotechnical Strength Limit State) over the top 60% of the pile.

In the top 30 feet of the pile the fully mobilized strength limit resistance, (from the chart) appears to be about 160 kips. Calculating the NSF: 0.125 * 160 kips = 20 kips

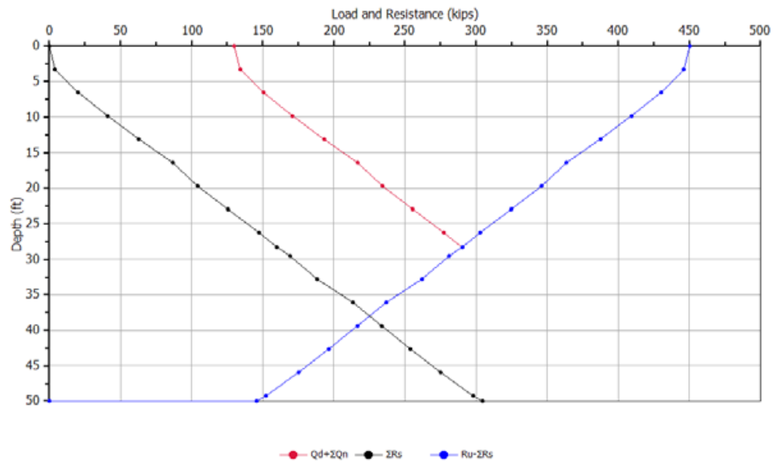
The positive side resistance (PSF) may be estimated (for reasonably homogeneous soil deposits) as 50% of the calculated side resistance (at the Geotechnical Strength Limit State) over the bottom 40% of the pile.

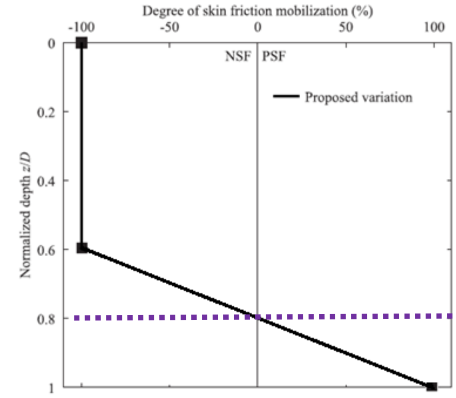
In the bottom 20 feet of the pile, the PSF is calculated using the fully mobilized strength limit resistance, (from the chart evaluating only the region between 30 feet and 50 feet). (300 kips – 160 kips) = 140 kips; 0.50 * 140 = 70 kips

The dragload estimate is 20 kips. This results in a net 50 kips side resistance available for structural top-load support with the remaining mobilized capacity being contributed by the pile toe. Neither base nor side "capacity" is being fully mobilized with the applied service loading, with the exception of the near-toe-area in order to mobilize base capacity. Note that the neutral plane is relatively deep, but the additional applied load is not unmanageably large. *An improved estimate may be available using the Compressible Layer Approximation.*

Dragload Estimate in Conditions Favorable for Dragload (Example 2):

Pile length = 50 feet





The Geotechnical Nominal Pile Capacity Chart for this pile is shown (above, left). Based on simplified chart (above, right) the NP is estimated at 80% of the pile length (40 feet).

As described in F-2 (above): *Use the pile analysis and the provided graphic method.*

The dragload may be estimated (for reasonably homogeneous soil deposits) as 100% of the shaft resistance over the top 60% of the pile length + 50% of the shaft resistance over the 60% to 80% length of the pile.

In the top 30 feet of the pile the fully mobilized strength limit resistance (from the chart) is about 160 kips. Calculating the NSF: 1.00 * 160 kips = 160 kips. In the region from 30 feet to 40 feet deep of the pile, the fully mobilized strength limit resistance, (from the chart) is, by inspection, (230 kips – 160 kips) = 70 kips; in this region, calculating the NSF: 0.50 * 70 = 35 kips. Calculating the total NSF: 160 kips + 35 kips = 195 kips

The positive side resistance may be estimated (for reasonably homogeneous soil deposits) as 50% of the shaft resistance over the 80% to 100% length of the pile.

Recalling the pile length of 50 feet, the bottom 20% is 10 feet. In the bottom 10 feet of the pile, the PSF is calculated using the fully mobilized strength limit resistance, (from the chart evaluating only the region between 40 feet and 50 feet).
(300 kips – 230 kips) = 70 kips; 0.50 * 70 = 35 kips PSF

The dragload estimate is 195 kips. This condition results in a (195 kips – 35 kips) = 160 kip net added side load acting along the pile, which must be carried by the base in addition to structural top loads to maintain equilibrium*. _This dragload estimate is large and the more rigorous methods presented in Appendix F-7 (or similar other NP methods) must be used to ensure that designs are safe but not overly conservative._

*All NSF becomes available as PSF as the pile approaches the Strength Limit State.

APPENDIX F-3: Definition of "Incompressible Material" at the Pile Toe

The neutral plane will tend to be located at the pile tip when the pile tip is founded on an incompressible material. For this condition, the pile top movement will be equal to the elastic shortening of pile, noting that this deformation will result from a combination of top loads and any dragload acting on the pile along the entire shaft length of the pile.

Soil material type and strength were found to be less important in the models than soil stiffness and the influence of the pile material properties and applied top loads. Increasing stiffness and decreasing top loads promoted dragload development, while lesser base stiffness and greater top loads resulted in reduced accumulation of dragload. This relationship is shown graphically in Figure F-3-1.

Based on computational modeling work, very few "real world" cases of end bearing were determined to be "incompressible" in nature due to the very large stiffness associated with structural steel as compared to most geomaterials. Additionally, there may be regions of load shedding above the top of rock.

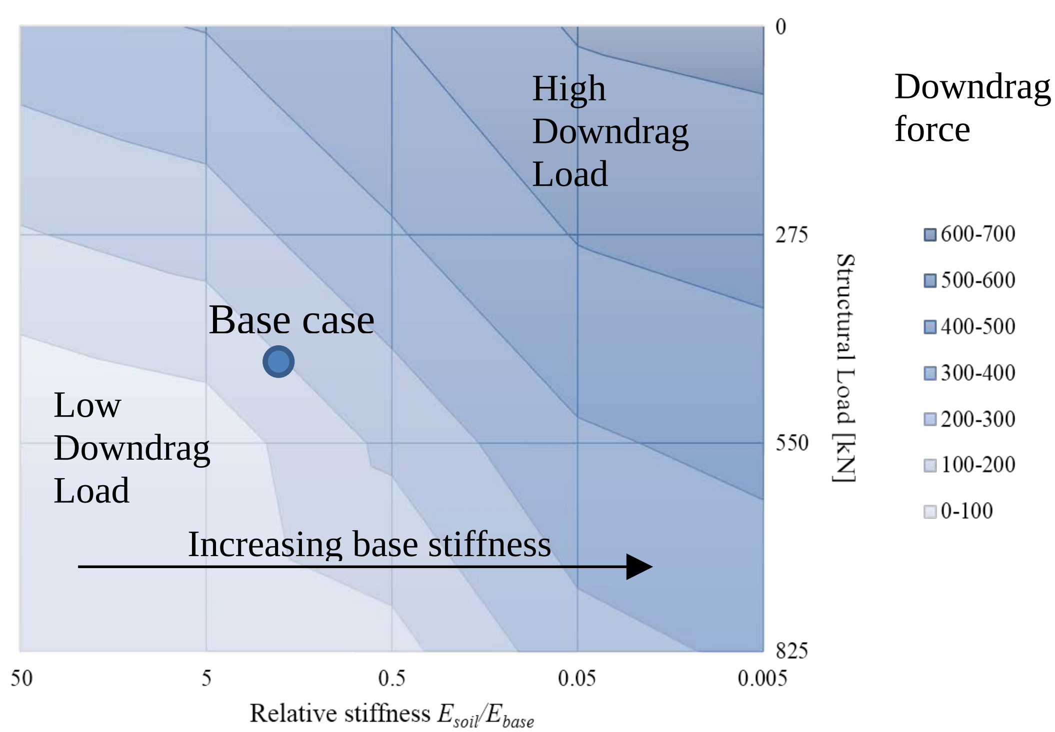


Figure F-3-1: Dragload contours, developed from computational modeling, showing the qualitative relationship of dragload with respect to pile top load (structural load) and pile base stiffness. The base-case is based on calibrated field data from a test pile project in Owatonna, MN where 30 feet of new fill was introduced over 50 feet of compressible native clay overlying Galena Dolomite bedrock.

Only intact, fresh, metamorphic and igneous rocks were found to have sufficient stiffness to be considered “incompressible” with the neutral plane arbitrarily located at the pile toe.

The former definition of “hard bearing layer” present in MnDOT guidance prior to 2015 has been significantly changed based on recent field studies and computational modeling. The new definition, used for this guidance, of a “hard bearing layer” for purposes of dragload and neutral plane location assumptions is: intact, fresh, metamorphic or igneous rock.

From research at the University of Minnesota, St. Peter Sandstone displays a Young’s modulus value of about 1 GPa. Iron formation rock from 2015 testing associated with BR 69129 in Virginia, MN displayed Young’s modulus values in the range of 20 GPa to 70 GPa. Structural steel has a modulus of about 200 GPa.

In most cases, the stiffness of the base of the pile (due to existing fractures, weathering, damage caused by pile driving, or other material properties of most Minnesota rock) allows some deflection to occur, and hence some mobilization of positive shaft resistance above the pile toe, and therefore a neutral plane somewhere at least slightly above the toe, along the pile shaft.

Note that assuming the neutral plane at the pile toe may also be exceptionally conservative if a large portion of the pile is below the compressible layers (Refer to the compressible layer assumptions in section F-2). Load shedding could begin well above rock, which will influence the actual location of the neutral plane. As shown in the diagram, the structural loading also affects the dragload accrual.

As structural loads increase, there is greater elastic shortening of the pile- if the pile translates downward with respect to adjacent soil dragload will be reduced. Taken to the extreme- if structural loads are increased so great as to cause geotechnical failure (large toe and shaft movement), the neutral plane migrates to the top of the pile.

APPENDIX F-4: Locally Adopted (MnDOT Practice) Dragload (DD) Load Factor for Neutral Plane Method (Pending Locally Calibrated Factor)

An effort is underway to review pile behavior for the development of a locally calibrated load factor representative of MnDOT pile driving practice and pile performance at sites where dragload exists. A research project is planned to assess the data from several existing and planned field sites.

Load factors for 'α' and 'λ' methods in the existing AASHTO code are provided for the explicit dragload evaluation process outlined in the code and are *not provided* for the Neutral Plane Method outlined in Appendix F. The AASHTO code acknowledges the 'β' methods are used to calculate pile loading- but does not contain guidance on associated load factors. It is <u>incorrect</u> to apply the load factors presented in the AASHTO code to the neutral plane method, used here.

Until the local calibration effort is completed, a load factor associated with an "equivalent minimum safety factor" of 1.5 will be used to ensure a consistent and appropriate level of conservatism. There is precedent in the geotechnical community for using an [equivalent] FS = 1.5 for material strength when considering dragload. This risk/reliability factor is used in Canadian geotechnical practice is recommended for use until the dataset of local sites with dragload performance monitoring is available for a statistically-based reliability calculation.

Load Factors and the Pile Structural Strength Limit Check equation:

$$[1.25*(DL) + 1.1*(DD) < \varphi * (\text{pile structural capacity})]$$

Until the reliability effort is complete, based on existing studies, a MnDOT-developed *geotechnical-based* load factor for dragload (downdrag) [DD] of 1.1 is recommended for the procedure outlined here using the Neutral Plane Method.

Table F-4-1 MnDOT Local Load Factors for Dragload Force

Method	DD load factor, φ	Applicability
Neutral Plane Method	1.1	AASHTO Table 3.4.1-2

This table supplements the AASHTO Table 3.4.1-2 based on local practice. This value represents an equivalent factor of safety of approximately 1.57 for cases where the neutral plane is located well above the pile tip and an associated structural resistance factor of 0.7 is applied.

APPENDIX F-5: Battered (Inclined) Piles in Downdrag Susceptible Soils

While the practical effects of dragload and downdrag movements have not been well documented in past MnDOT practice, battered piles should be avoided to the maximum reasonable extent possible where soil settlement is likely to occur adjacent to piling.

Downdrag movement could result in such adverse effects as:

- Pile bending
- Pile distortion and distress at the pile cap due to undesirable deformation in the pile system.
- Additional lateral load or moment being introduced into the pile cap
- Loss-of-ground below inclined pile elements due to surrounding soil settlement and 'shadowing' below the inclined pile resulting in a lack of pile support and increased distortion.

Some engineering judgment is appropriate for large pile groups where fill is placed on only one side of the foundation due to pile shadowing.

Note that soil fill placed at the rear of an embankment fill with many rows of piles may have little or no effect on battered piles in the front row of a pile group where no load is placed.

A finite element or similar analysis is appropriate to investigate soil deformation and pile group effects. Battered piles may be allowed at the front of a multi-row pile group if the only added loads are behind the abutment.

Where Battered Piles are Necessary and Soil Settlement is Anticipated

Battered piles (i.e., non-vertical piles) will experience bending as a result of the vertical settlement of the surrounding soil and non-uniform interaction due to the incline of the pile element. The distribution in bending moment in a battered pile can be estimated using LPILE Version 7 using the lateral soil movement option.

The approach is described in the following steps (T. Siegel 2015):

1. Calculate the profile of downward ground movement along the pile using the established soil mechanics concepts;

2. Subtract the downward ground movement of the pile toe from the profile of downward ground movement to determine a profile of downward ground movement that is normalized to zero pile toe movement;

3. Calculate the component of the normalized downward ground movement that is perpendicular to the pile's long axis for the pile's full length;

4. Using LPILE, create a model with a representative soil profile and pile section using a vertical pile orientation.

5. Select the option that allows the input of lateral ground displacements and input lateral ground displacements at sufficient increments (2 ft +/-) that will sufficiently represent the movement profile developed in step. 3.

6. Run the analysis to determine the pile and soil response due to the influence of settling ground on batter piles.

7. Report the outcome to the structural engineers such that the additional forces can be accounted for in design.

APPENDIX F-6: Dragload Mitigation Strategies

Piles must be designed to structurally accommodate the dragload (when driven to a hard layer) or the superstructure to be able to withstand the settlement (including potential differential settlement) due to the downdrag movement that will occur (when not driven to a hard layer).

Researcher Bengt Fellenius has recommended using an equivalent “factor of safety” of 1.5 on structural material properties as stated in the International Building Code (IBC). Load and resistance factors based on the neutral plane method have yet to be established.

A relatively high structural resistance factor may be appropriate for evaluation of a pile section’s structural capacity in the LRFD framework for dragload, given that the maximum load generally occurs well above the pile tip and well below the ground surface where the pile is 1) well confined 2) unlikely to have been damaged and 3) unlikely to become damaged due to loading, corrosion, or other effects. Similarly, a favorably high resistance factor may be appropriate based on local evaluation of dragload measured in instrumented deep foundations in Minnesota.

The most practical method for ensuring downdrag loads are accommodated appears to be through a good engineering design which provides piles with sufficient structural strength to support the sustained pile loading (top loads and dragload being resisted by positive side resistance and end bearing).

Acceptable Dragload Mitigation Strategies

Several strategies to design for large downdrag load conditions have been found to be reliable to address the added loading in a measurable and reliable manner:

- Increase pile structural capacity by using increased wall thickness or increased pile section.
- Increase pile structural capacity by using a larger pile diameter (noting that dragload may increase due to the larger perimeter area).
- Using shallow foundations in lieu of deep foundations.
- Increasing the number of piles in conjunction with revising the structural (top) loading requirements (decrease structural load per pile).
- Install pile elements after a suitable time delay allowing consolidation effects to occur (this is often not possible due to time constraints), when the site is at “steady state” conditions, and not subject to large additional settlement due to added fill, groundwater lowering, or seismic effects.

Soil Surcharging and Preloading

Site surcharging and preloading may lessen pile deflection by reducing the compressibility of soil below the neutral plane. Preloading of soil above the neutral plane does not appear to have a significant effect on pile deflection. Overall pile movement is related to the movement (soil settlement and corresponding equal pile movement) at the neutral plane and the pile's own elastic deformation above that location.

Preloading will not preclude the development of all "future" negative side resistance as negative side resistance will develop over time as small relative movements between soil and pile occur. Many soils have some elastic component to their behavior and although soils may settle when preloaded, they rebound to some extent when the preload is removed. The soils then again deflect (either elastically or on a flattened reloading curve) when embankment fill or other materials are replaced during final construction activities.

Preloading can be useful to reduce dragload [force] to manageable levels, provided that sufficient time is allowed for soils to be brought completely to a steady-state condition. For clayey soils this could take years and is not recommended as a practical alternative for most design cases.

Preloading and soil surcharging does however have project benefits for shallow foundations and embankments, where promoting settlement in advance of other construction activities can significantly reduce both absolute and differential movement.

Coatings

Coatings such as bitumen and Teflon adjust the interface friction properties between the pile element and the site soils. Generally, research and case history evidence suggests coatings reduce the geotechnical capacity of the pile where applied, are expensive, are difficult to specify and procure, are problematic to install and inspect, and appear to provide an unquantifiable (and probably variable) effect. Even in controlled research applications [as described in an NCHRP study] the results were variable and the effectiveness was inconclusive and questionably reproducible.

Based on MnDOT performance monitoring, dragload which may have otherwise accrued in coated pile sections may be re-distributed to a section of the pile below the coated zone, changing the loading distribution, but not significantly mitigating the peak load increase.

As their effectiveness cannot be reasonably predicted, measured, or evaluated, the use of coatings is not recommended on MnDOT projects. Exceptions may be granted for research purposes or when combined with a GEMINI performance monitoring program (described in this manual) to actively measure and confirm the effectiveness of the coatings.

Sleeves

Pile sleeves, such as metal and plastic corrugated pipe infilled with aggregate, do appear to influence the pile loading distribution. While pile loads appear to be reduced in the section of the pile which is sleeved, it is unclear if the overall dragload (accumulated along the entire pile) is reduced or if the magnitude of peak dragload, usually acting in an un-sleeved region, is reduced.

As the pile sleeves are often installed in above-grade areas with good quality (and not particularly compressible) backfill, their cost effectiveness and overall design benefit is unclear. The neutral plane (and peak dragload) is often well below the ground surface within compressible native soils. For this reason, pile sleeves appear unnecessary as they are not reducing overall stress and are not placed in a region with particularly large stress concentrations.

APPENDIX F-7: Rigorous Method for Determining Dragload: Fully Mobilized Dragload (Neutral Plane, Service Limit) Methodology

PREDICTING THE MAXIMUM MAGNITUDE OF FULLY MOBILIZED DRAGLOAD (For use in cases where dragload is assumed to be fully developed).

Locating the Neutral Plane by Graphical Construction

In order to develop the location of the neutral plane at the service limit state, a pile load and resistance chart needs to be created; much of the information in the graphical construction is available from pile capacity software output. The neutral plane location for a pile or a pile group is determined by preparing a plot similar to Figure F-7-1 for the specific pile and soil conditions. In addition to the geotechnical model, unfactored structural loads are needed to perform the calculation, as the location of the neutral plane and the corresponding maximum magnitude of dragload/downdrag is influenced by the applied loads on the piles. Results can be skewed, and the magnitude of the dragload influenced, if the parameters are not well chosen based on site conditions or if certain factors such as the top loading are neglected or ignored.

This graphical method assumes the following:

- The pile length is fixed for a given plot
- The top load is zero, known, or assumed as a reasonable value
- NSF is fully mobilized above the NP
- PSF is fully mobilized below the NP
- The base resistance is fully mobilized*
- Unfactored structural pile "top" loading can be estimated, even if not known

  *Note: The evaluation occurs at the service limit state where the toe mobilization is often less than 100% (geotechnical failure is not occurring) and plots should be evaluated adjusting the toe mobilization to a value less than what software predicts at failure for most cases other than pile end-bearing on rock, based on engineering judgment.

Prepare a diagram, plotting the cumulative side resistance of the pile as a function of depth. This is shown in black in Fig F-7-1.

Plot the fully mobilized toe resistance plus the cumulative positive side resistance as a second curve (R_u - $\sum R_s$) as shown in blue in Figure F-10-1. This information is available from geotechnical software predicting pile geotechnical capacity (nominal resistance). Unlike plots showing total capacity as a function of depth for multiple pile depths, a set pile depth must be selected to properly plot this curve.

Plot a third curve of permanent [unfactored] top load at the pile head plus the cumulative skin friction, (Q_d + $\sum Q_n$) as shown in red in Figure F-7-1.

For an improved analysis, assume a mobilized toe resistance (at the Service Limit this will be less than the nominal toe resistance predicted by software at the Strength Limit). Plot this value at the pile tip.

The intersection of the red and blue curves is the estimated location of the neutral plane (NP). Therefore, the pile interface shear above this depth is contributing negative skin friction (NSF) and the pile shear below this depth is positive skin friction (PSF).

Consider figure F-7-1 where a pile has a permanent top load of 130 kips. The neutral plane occurs where the blue and red lines intersect, at a depth of 28 feet. The point where the neutral plane intersects with the black line is shown with an orange circle. The black line represents the skin friction force acting on the pile. The dragload is at a maximum at the neutral plane; for this example the dragload is approximately 160 kips, and the maximum load in the pile is the sum of the sustained top load plus the dragload, about 290 kips (purple dot). The blue dot, in the upper right, represents the load at the pile head at a condition of geotechnical failure if all shaft and base resistance is mobilized at the strength limit state.

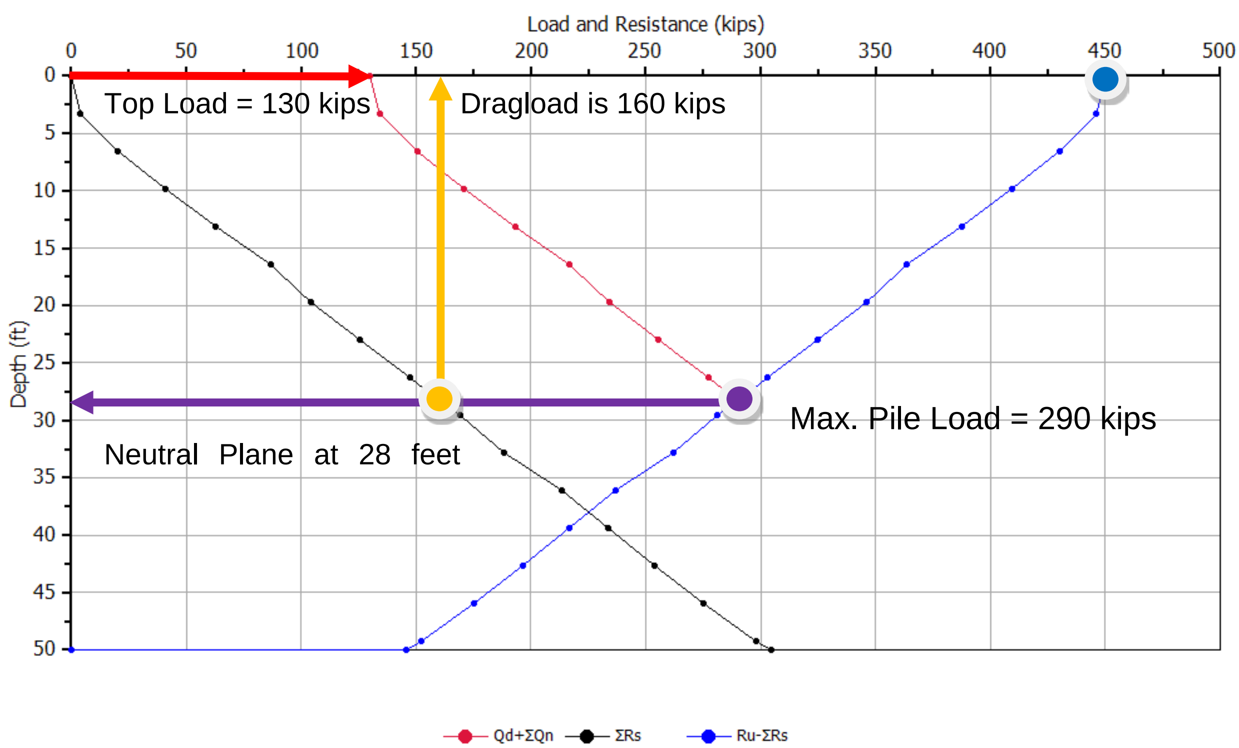


Figure F-7-1: A typical chart developed for neutral plane analysis. The black line is the pile side resistance as a function of depth. The red line represents an offset equal to the permanent structural "top load' (in this case 130 kips). The blue line is the sum of maximum available toe resistance and maximum cumulative side resistance at the Strength Limit State (geotechnical failure); a fixed pile length must be selected to develop the blue line (in this case, 50 ft.) and evaluate the case.

Continuing the example in Figure F-7-1, if the sustained structural top load is increased to 225 kips, as shown in Figure F-7-2, the red line (representing the contribution of the top load) shifts to the right and the location of the intersection with the blue line changes. This intersection point shifts both to the right and upward. The depth of the neutral plane moves up to a depth 21 feet from the ground surface. This also reduced the magnitude of the dragload contribution to approximately 110 kips.

Consistent with what would be expected in a “dragload-free environment” by adding additional top load, the total load everywhere on the pile has increased (despite the reduction in dragload) and the pile is closer to geotechnical failure. The maximum top load plus dragload (peak load in the pile) in Figure F-7-2 is 335 kips, compared to 290 kips in Figure F-7-1. The pile is being used more efficiently, carrying more top load, but the reduction in dragload does not constitute a reduction in overall load within the pile.

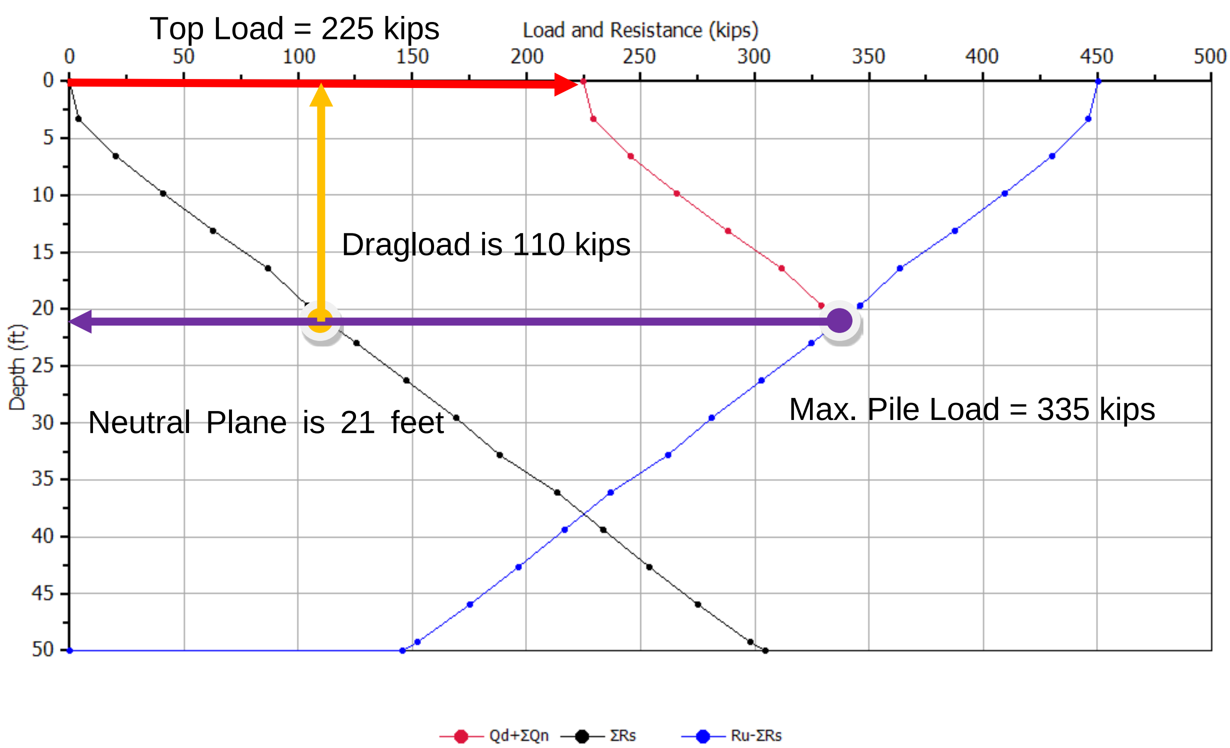


Figure F-7-2: A structural top load of 225 kips is applied to the pile modeled in Figure F-7-1. As a result the neutral plane moves upward and the dragload has been reduced. The maximum load in the pile is at the neutral plane and the sum of sustained top load plus dragload has increased 45 kips to 335 kips.

As seen in Figures F-7-1 and F-7-2, using a close estimate of the permanent top load has an impact on the severity of the expected dragload. While it is conservative to assume no top load (which may be reasonable if top loads are unknown) this can result in larger dragload values than may realistically develop. For completeness, Figure F10-3 shows how a reduction in top load has the opposite effect of increasing the top load.

If structural loads are not considered (as in Figure F-7-3A) the “top load’ would be 0 kips. The sum of available toe resistance and cumulative side resistance at geotechnical failure (blue line) would predict the NP at 38 feet with a corresponding dragload of 225 kips. This is also the largest load within the pile, and is caused solely by soil acting on the pile above the neutral plane; the top load is 0 kips.

Structural top loads help reduce dragload by imparting downward deflection, however, as greater top loads are applied the pile approaches geotechnical failure and deflects downward.

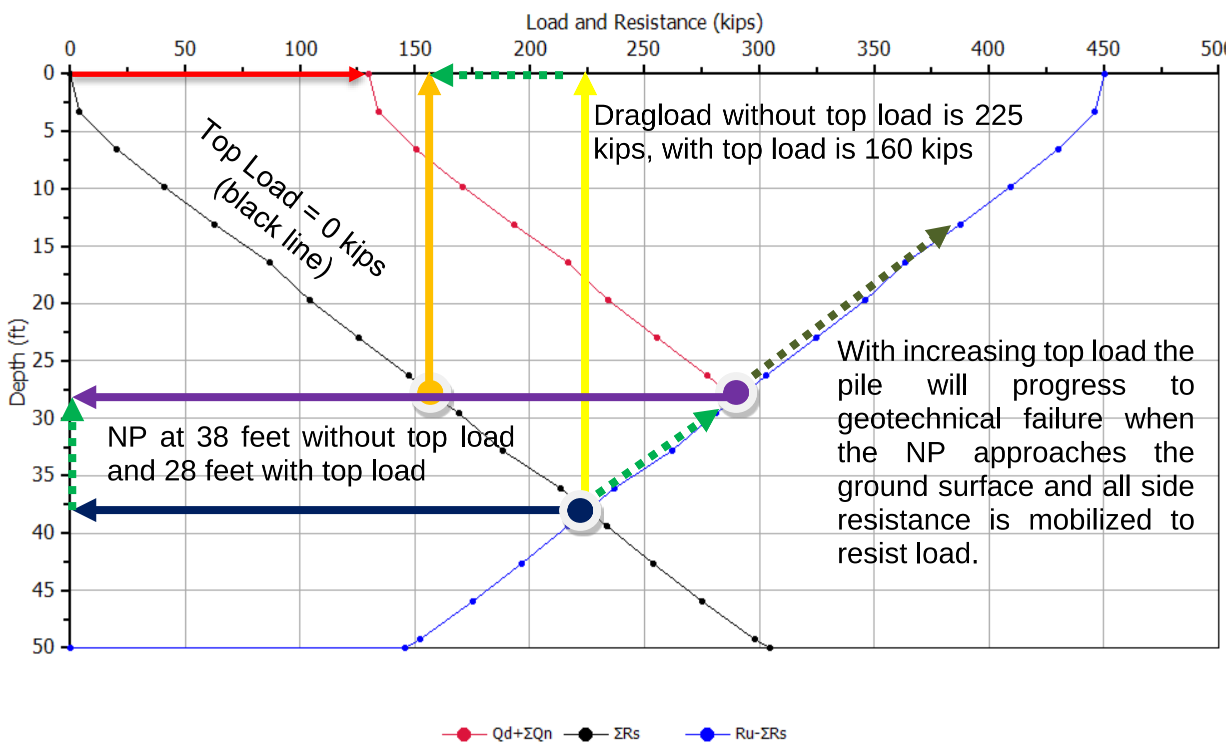


Figure F-7-3A: If structural loads are not considered (as in Figure F-7-1) the sum of available toe resistance and cumulative side resistance at geotechnical failure (blue line) would predict the NP at 38 feet with a corresponding dragload of 225 kips. As top loads are applied (red dashed line) the conditions change (dotted green lines indicate changes from one condition to the next).

As shown in Figure F-7-3B, the pile system can be thought of as consisting of four regions:

- At the pile top, only structural “top” loads are applied
- Along the pile above the neutral plane, top loads are present and additional soil loads are accruing

- Along the pile, below the neutral plane, top loads and soil loads are present and all loads are shedding in side resistance
- At the pile toe all remaining load is supported by the base

Above the neutral plane, negative skin friction is adding load along the pile, below the neutral plane, positive skin friction is shedding load into the soil. Any remaining load at the pile tip is carried in end bearing. Depending on the loading, the stiffness at the tip and settlement characteristics along the pile, the shape of the plot can change.

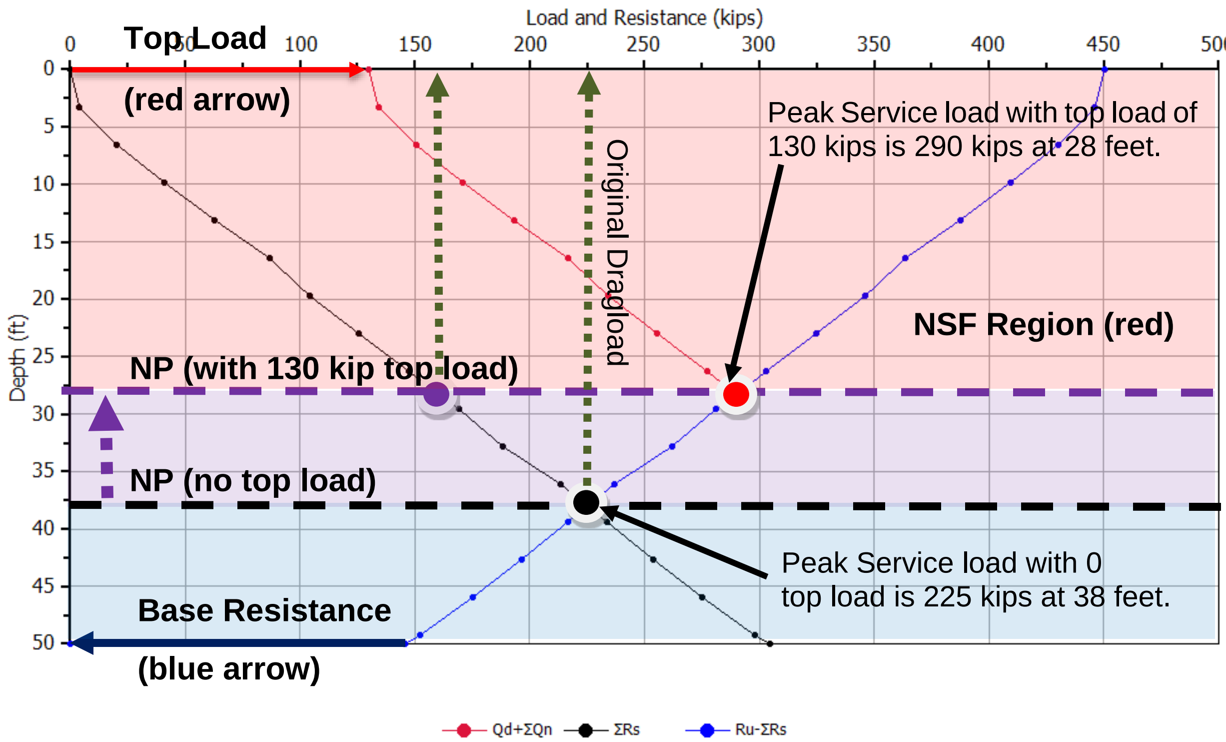


Figure F-7-3B: If structural loads are not considered (as in Figure F-7-1) the sum of available toe resistance and cumulative side resistance at geotechnical failure predicts the NP at 38 feet with a corresponding dragload of 225 kips (black dot). As top loads are applied (red solid arrow) to 130 tons, conditions change, the NP moves up 10 feet and the area in purple begins to contribute PSF. The NP moves up to 28 feet and the dragload reduces to 160 kips (purple dot). In the analysis, the base resistance remains the same at 150 kips, although it is likely to increase slightly under the added loading; the dragload decreases from 225 kips to 160 kips (-65 kips), however the structural loads increased 130 kips, the largest load in the pile, seen at the NP, increased 65 kips, to 290 kips, and moved up 10 feet). While the added structural loading reduces dragload- the effect is not an equal exchange- and changes in both magnitude and location occur.

The graphical process, using values from the pile capacity analysis, assumes the base is 100% although this is unlikely at conditions well away from geotechnical failure.

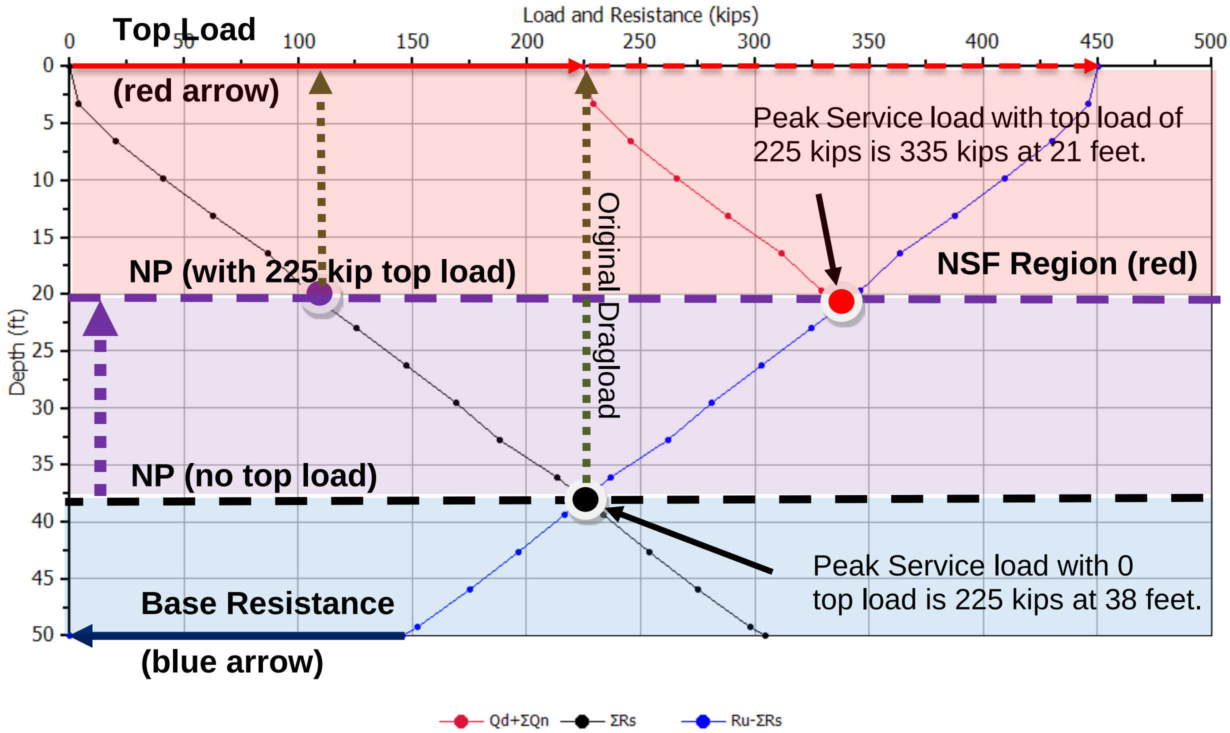


Figure F-7-3C: If structural loads are not considered (as in Figure F-7-3A and F-7-3B) the NP is at 38 feet with a corresponding dragload of 225 kips (black dot). As top loads are increased (red solid arrow) to 225 tons, conditions further change, the NP moves further up and the area in purple enlarges, contributing more PSF, over an additional 7 feet of pile length (as compared to Figure F-7-3B). The NP moves up to 21 feet and the dragload reduces to 110 kips (purple dot). In the analysis, the base resistance remains the same at 150 kips, although it is likely to increase further under the added loading; the dragload <u>decreases</u> from 225 kips to 110 kips (-115 kips), however the structural loads have increased to 225 kips, the largest load in the pile, seen at the NP, <u>increased</u> 110 kips, to 335 kips, and the NP location moved up 17 feet). While the added structural loading reduces dragload- the effect is not an equal exchange- and changes in both magnitude and location occur. With added top loading (red dashed line), the progression continues until the geotechnical strength limit is reached as in Figure F-7-3D.

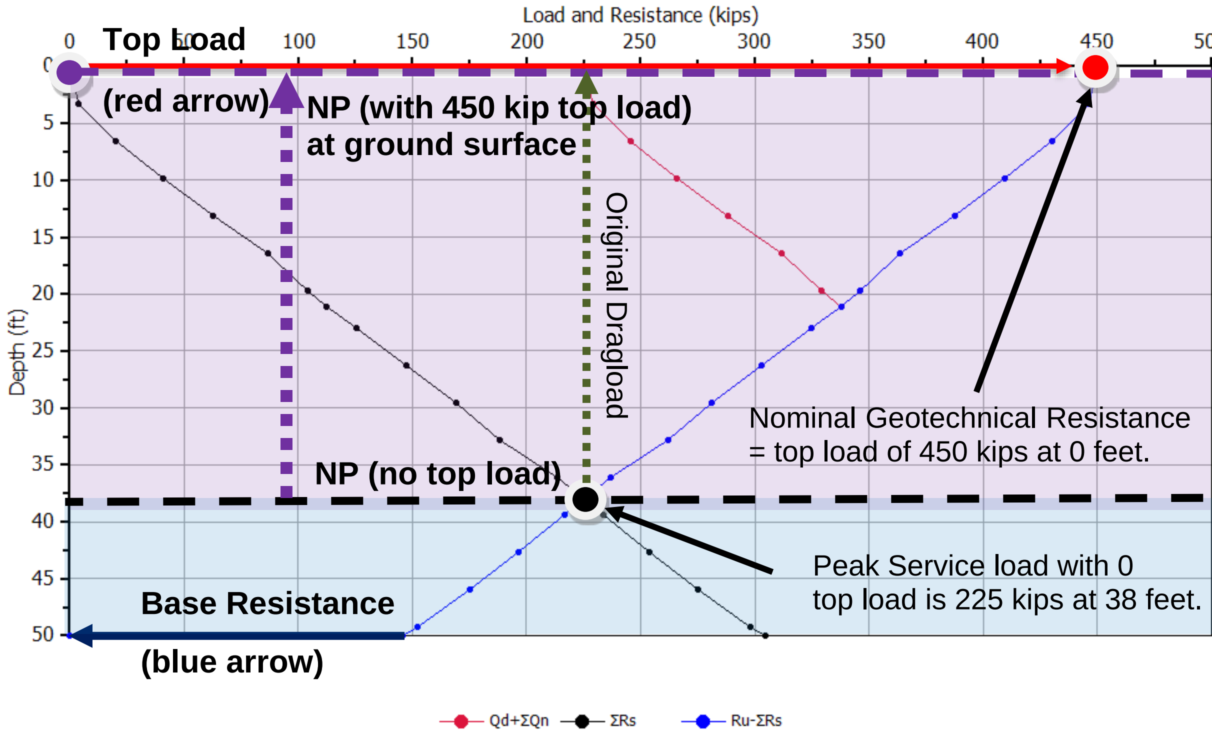


Figure F-7-3D: If structural loads are not considered (as in Figure F-7-3A and F-7-3B) the NP is at 38 feet with a corresponding dragload of 225 kips (black dot). As top loads are increased (red solid arrow) to 225 tons, conditions further change, the NP moves further up and the area in purple enlarges, contributing more PSF. In the extreme case, when added top loads are equal to available geotechnical resistance, the NP moves up 38 feet and dragload reduces to 0 kips (purple dot). The entire soil area now exhibits positive side friction (purple and blue zones). The dragload decreases from 225 kips to 0 kips (-225 kips from the initial condition), however the structural loads have increased to 450 kips; the largest load in the pile continues to be at the NP at the ground surface, above where any load can shed into the soil. While the added structural loading now had reduced dragload to 0, the result is that the pile is on the verge of failure. All side resistance is now positive (PSF); the purple region extends to the ground surface. The pile remains in static equilibrium however any increase in load will tend to deflect the pile until there is an increase in side resistance (through a longer embedded pile, or greater base resistance from a deeper base layer).

As shown in earlier figures, changing the top load (shifting the solid red horizontal line) results in different values of maximum dragload, at different locations, as shown in Figures F-7-1 through F-7-3D. The location and magnitude of the lowest position of the neutral plane and maximum dragload depends on material properties and site conditions.

Dragload is also influenced by the construction of the blue line (in the figures above)- which is affected by the % mobilized base resistance.

Some simplifying methods assume the "worst case" dragload condition by very conservatively approximating the neutral plane at the base of the pile (rigid base). In the example shown in Figure F-7-4, if the neutral plane was assumed to be at the bottom of the pile, with no structural top load, the dragload would be slightly over 300 kips (black line at 50 feet deep). If the pile were structurally loaded with the 130 kips of top load used in the Figure F-7-1 example, the maximum load in the pile would be 430 kips at the pile tip (about 150% of the more realistic value). In Figure F-7-4, the nominal geotechnical resistance (geotechnical failure load) is 450 kips- irrespective of dragload processes, if the pile were loaded to failure, this would be the expected pile top load, and the maximum load seen in the pile.

The methods used to develop the toe resistance plus cumulative side resistance (dark blue arrow) are more difficult that obtaining an estimate of the structural loads (used for developing the red solid arrow).

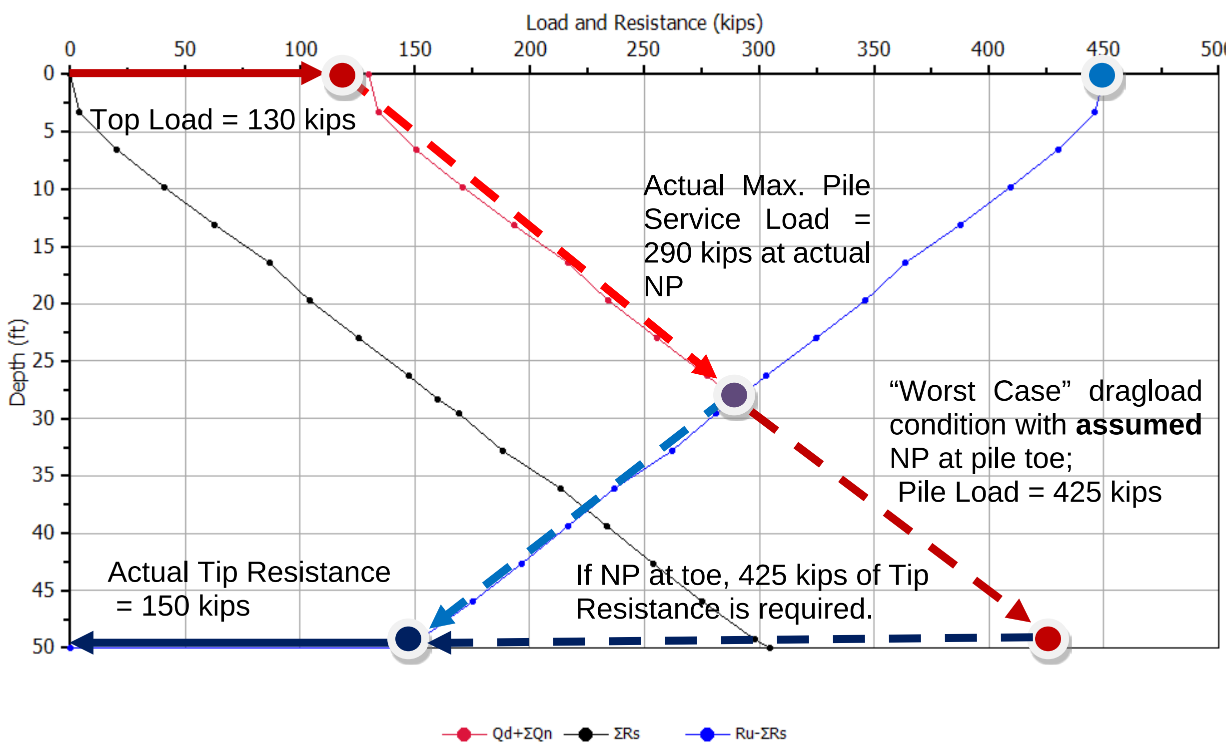


Figure F-7-4: The peak dragload is influenced by the top loading as well as the mobilized tip resistance. The sum of available toe resistance and cumulative side resistance at geotechnical failure shifts the dark blue line (at the toe) and the NP location will adjust based on this parameter similarly to how it shifts based on construction of the red line.

As mentioned earlier, a trial [expected] length of pile should be selected and evaluated. If it is likely that the piles will be driven to a depth of 50 feet, then a chart with data extending to a depth of 50 feet should be used to evaluate dragload. For comparison with

Figures F-7-1 through F-7-4, where a pile length of 50 feet was used, Figures F-7-5 through F-7-7 are included where the pile depth has been changed to 60 feet.

As described earlier, the engineer can elect to reduce the contribution of tip resistance to reflect a more realistic tip mobilization at the Service Limit State. This will shift the blue line to the left to reflect more a realistic loading scenario. Generally, a fraction of the available tip capacity is used for real service loads on a pile that has a significant frictional contribution. Depending on software used, this may require that a “user biased” resistance (using valued less than the values obtained from the geotechnical exploration program) be used as an input value.

Without placing strain gages in the piling or running a static load test, in most circumstances, the % of base capacity mobilized at the service limit will be unknown. Some reasonable assumptions can be made- such as more base capacity acting when the pile is [or will be] bearing on very stiff soils or rock (as judged using information recovered from the geotechnical site investigation).

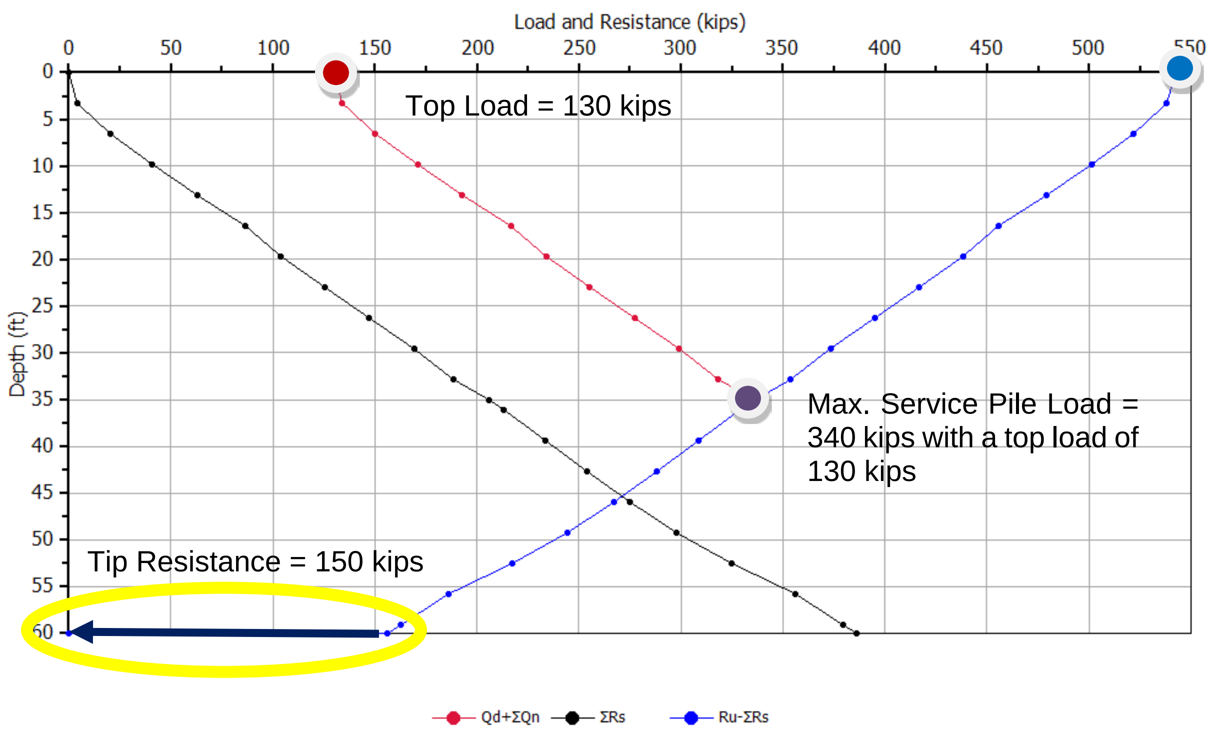


Figure F-7-5: Driving depth has increased to 60 feet (from 50 in Fig F-7-1 –Fig F-7-4), as a result the black line is extended and the blue line has moved to the right to reflect the additional geotechnical capacity available at this new deeper depth (550 tons total). The neutral plane for a zero top load has lowered to 45 feet, (or to 35 feet if a top load of 130 kips is considered). The dragload for a top load of 130 kips has increased to 210 kips. The base capacity is assumed 100% mobilized at 150 kips.

Static load tests (SLT) performed by MnDOT and others have shown both additional tip (base) resistance and additional side resistance becomes available when top load is added to a pile, until geotechnical failure. It is believed the additional side resistance comes about from changes in the shape of the accrual and shedding regions of the pile and degree to which portions of the pile are moving with respect to adjacent soil combined with the non-linear properties of soils and the shape of the soil stress-strain curves.

Without SLT data it would be difficult to model pile loads by adjusting both the tip and side contributions to top resistance. Usually the side resistance is assumed to be fully mobilized and the tip contribution is adjusted, although it is possible to adjust the graphs to reflect lesser mobilization of side shear values. The easiest way to do this may be to use % reductions based on driving disturbance. Figure F-7-6 shows how adjusting the tip mobilization impacts the graphical construction of the anticipated loading behavior, as compared with Figure F-7-5.

Figure F-7-6: The 60 foot deep pile is modeled here with a 50% mobilized tip capacity (75 kips). This reduced contribution of tip resistance is likely a more realistic loading at the service limit where loads are well below the strength limit (and correspondingly mobilized resistances are less than the maximum used for Strength Limit calculations).

There may be times when it may be desirable to model an end-bearing pile with most of the load bearing on the pile tip, such as when a pile is driven to rock. In this case, a toe mobilization of up to 100% of calculated tip capacity may be an appropriate characterization of how the pile will perform (Refer to Figure F-7-7).

Depending on the stiffness of the rock and the compressibility of any soils in layers above the rock, there will still be some variability in the location of the neutral plane.

More rigorous and refined analysis can be performed using t-z curves although for most applications this is not required. These curves are difficult to develop in the absence of static load testing performed for particular pile lengths, as the stiffness of the toe may change considerably depending on what depth the pile is founded.

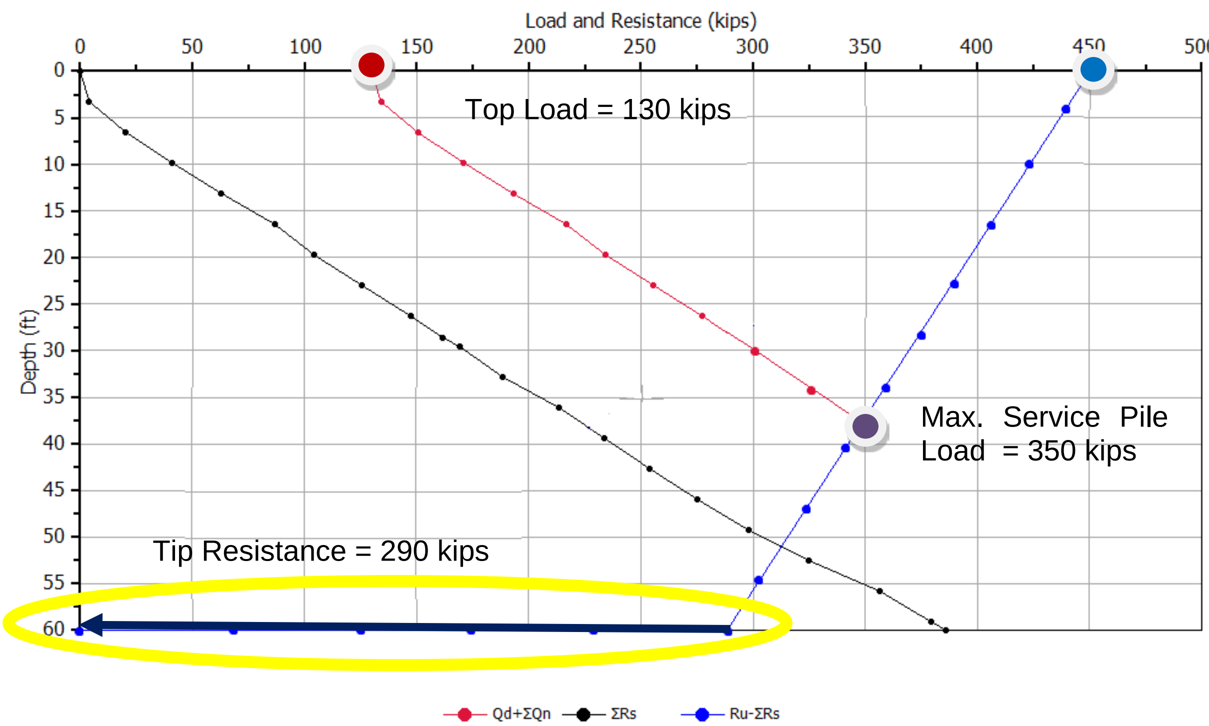


Figure F-7-7: A pile loading scenario where tip resistance contributes most of the total resistance in the pile, while there is still a large frictional contribution to the pile along the length of the pile. The location of the neutral plane will depend on the nature of any compressible layers, soil loading, and other site conditions.

As a practical matter, extensive effort may not be necessary in most design cases as estimations may provide values which are representative enough for design purposes- provided a reasonable level of conservatism is used.

The primary reasons for modeling dragload with reasonable care and attention are:

(1) To ensure that the piles have sufficient structural capacity at the neutral plane to accommodate both the additional accrued soil loads (which can be small, moderate, or large) and the required structural top loading and
(2) To ensure that loading is properly modeled for deformation assessment to ensure that excessive settlement (downdrag) does not cause a performance problem for the structure.

All assumptions must be clearly noted in the geotechnical analysis.

APPENDIX F-8: Special Considerations for Risk-Based Evaluation of Dragload

It has been noted that the critical locations associated with driven pile elements are near the base of the pile and near the top of the pile. At these locations installation damage, corrosion, or other loading effects (such as shear or bending) are likely to have larger performance impacts as compared to the mid-length of piles, where the neutral plane is generally located at service conditions. Near the neutral plane, while actual mobilized forces are small, total axial pile stresses may be locally higher due to the combination of pile top load and accumulated dragload. At the neutral plane loads are likely to be axial with relatively fewer effects that could adversely impact pile integrity.

In addition, driven piles (particularly displacement piles) are likely to be well confined due to the displacement of materials and compaction from the installation process. Surrounding soil likely provides additional confinement to improve pile capacity, as compared to free-standing columns.

While there are no changes to current practice, or accommodations for additional loading, within the central length of driven piles [acknowledging this is the critical location where added dragload accrues along a pile], beyond what codes allow, it is possible that risk-based evaluations may be used in the future to justify accepting larger pile stresses at non-critical locations within pile elements. This may occur through the adoption of different load factors for use when considering dragload.

APPENDIX F-9: Dragload Definitions and Terms

Base resistance – The soil resistance contributed at the pile toe or tip in end bearing. The amount of base resistance will depend on factors related to the pile and soil stiffnesses and the settlement/deformation of the pile. Generally, side resistance is mobilized more quickly (at smaller strains) than base resistance. The stiffness of the soil at the base will play a role in how quickly load accumulates at the base.

At service limits, given the load and resistance factors currently in use, unless the pile is a completely toe/end bearing pile, the contribution of the base to the pile resistance at service loadings is relatively small.

Downdrag Load, Dragload, Drag force, Negative Skin Friction (NSF), Negative Side Resistance – The side resistance force (stress * perimeter area) accrued along the pile element above the neutral plane as adjacent ground moves downward relative to the pile. This load is imparted into the pile and will cause an increase in stress within the pile and also result in additional pile deformation (related to the pile stiffness). It may consist of either frictional or cohesive/ (adhesion) components.

This load is imparted along a length of the pile, below the pile head and above the neutral plane, and should not be combined or represented by any equivalent ‘structural’ top loads imparted such as dead load or live load.

The use of “load” in the term “dragload” is intentional [and similarly “force” in “drag force”] to make a distinction that this force acting on the pile (and subsequently transferred into the pile element) should not be confused with the deformation or movement of the pile.

This load can vary depending on a variety of factors including:

- The magnitude of the structural top loads
- The length of the pile
- The time at which loads are applied
- The relative movement of the pile with respect to the surrounding soil
- The relative difference in stiffness between the soil and the pile along the pile and at the pile toe

Downdrag – The deflection or downward movement associated with the application of the Downdrag Load (DD) component of the structural loading. In cases where the pile toe is fixed, this may be only elastic shortening within the pile element; in cases where the toe may move, it is a combination of elastic shortening and pile settlement.

Geotechnical axial nominal resistance – Top load at which the pile or drilled shaft will no longer satisfy static equilibrium and will experience continued downward movement. It is equal to the sum of the fully mobilized side and tip resistances. Because the entire pile/drilled shaft is moving downward relative to the surrounding soil at this condition, the side resistance is entirely positive and, by definition, there will be no negative skin friction (NSF) and all side resistance is positive skin friction (PSF).

Illustration of this condition supports not considering dragload as an equivalent top load or using other techniques where dragload continues to exist at the strength limit state.

Load factors – Applied per AASHTO as the Downdrag Load (DD) is a load applied to the pile when evaluating the geotechnical service limit state and the structural strength limit state.

Mobilized base resistance – The fraction of the total available soil base resistance activated as a result of pile movement at the toe.

Mobilized side resistance – The fraction of the total available soil resistance activated along the pile length local soil-pile movement.

Mobilized soil resistance – The fraction of the total available soil resistance activated based on local soil-pile movement.

Generally, this term is applied to positive skin friction and base resistance acting to resist the downward acting structural loads, however it may also apply to dragload accruing above the neutral plane. Given a steady state condition, at small strains/deformations, only a portion of full soil friction/resistance may be available to either impart or resist loading due to the nonlinearity associated with soil friction.

At geotechnical failure, all available soil resistance (side and base) is mobilized. At loading conditions less severe than the geotechnical strength limit, only a % of the available resistance may contribute to resisting the applied loading depending on the location along the pile and the in-situ stress state.

At non-failure conditions soils will, locally, be in different states of mobilized strength (in both magnitude and direction along the pile length and in some % of mobilization at the pile toe).

Negative skin friction (NSF) – Side resistance which acts opposite to Positive Skin Friction (PSF) which adds load into a pile and needs to be accounted for in design. NSF will act in a region of a pile above a region of PSF and the pile toe. NSF does not exist at the geotechnical strength limit. The region of a pile where NSF exists depends on a large variety of factors.

Neutral plane (NP) – Location along a pile in static equilibrium where the direction of the side resistance reverses from negative to positive. For static equilibrium, the sustained load (i.e. the sustained top load plus the mobilized negative skin friction, NSF) is equal to the combination of the upward (positive) mobilized side resistance, PSF, [acting below the neutral plane] and the mobilized tip resistance. Calculations for the location of the neutral plane must use unfactored (service) loads.

Permanent loads – Per AASHTO, these are assumed to be either constant upon completion of construction or varying only over a long time interval.

Permanent top loads – A structural load applied at the pile head, generally, Dead Load (DL) which does not vary considerably (unlike transient loads). Note that if a transient load is in place for a long period, it may tend to act like a permanent load (e.g. added concrete railing or pavement structure).

Positive skin friction (PSF) – The side resistance available to support a pile in combination with the base resistance.

Residual force – Internal axial force within a pile that is neither due to a top load or associated with resisting a top load. Residual forces may be present in pile materials for a number of reasons including:

- Metal fabrication, forming, casting, and production
- Pre or post tensioning of materials (e.g. concrete piles)
- Driving and installation
- Static load testing or other pre-loading conditions

Top load – A structural load applied at the pile head.

Transient loads – Per AASHTO, these are assumed to vary over a short time interval relative to the lifetime of the structure. Generally, Live Load (LL) for governing design cases.

While transient loading may reduce the pile dragload over a small increment of the pile, it is important to note that the load within the pile will still be increased (and measurable) as the load is applied. The exchange of some amount of negative skin friction (NSF) for positive skin friction (PSF) occurs in the immediate vicinity of the neutral plane, shifting its location slightly. Transient loads will distribute across the length of the pile depending on their time of application, consolidation effects at that time, and system stiffness relationships.

Depending on how steady-state soil conditions are, prolonged top loads could result in additive dragload if the pile is deflected and soil consolidation is allowed to continue or re-engage.

Transition Zone – Soil forces act along a continuum and are associated with strain, deflection, and material properties (strength/stiffness). When soil forces transition from positive skin friction to negative skin friction, there are regions where relative soil movements become small. Relative movement is zero at the neutral plane. Where movements and strains are small, corresponding stresses (loading) is also relatively small- as an example, at the neutral plane there is “0” added or reduced load due to soil/pile interaction. The transition zone is the region where, along the pile length soil is neither 100% mobilized in PSF nor 100% mobilized in NSF but exists somewhere between these values.