The National Academies of

SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

Static and Seismic Design of Piles for Downdrag

Thursday, October 4, 2018
2:00-3:30 PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose

Discuss the fundamental behavior of piles subject to downdrag.

Learning Objectives

At the end of this webinar, you will be able to:

- Describe the current AASHTO downdrag specifications
- Discuss the differences between negative skin friction and downdrag
- Describe the fundamental physical response of piles subjected to downdrag forces
- Describe some of the current AASHTO code limitations of the neutral plane method

Static and Seismic Design of Piles for Downdrag

Timothy C. Siegel, P.E., G.E., D.GE
Dan Brown and Associates PC

TRB Webinar
October 4, 2018

- Aspects of Axial Resistance of Piles
- AASHTO Specifications
- Neutral Plane Concepts
- Conceptual Examples

Aspects of Axial Resistance of Piles

TIMELINE ON DOWNDRAG RESEARCH

1960s

BJERRUM, JOHANNESSEN AND EIDE (1969)

1962 – Bjerrum and Johannessen study the load distribution in test piles at the NGI Sorenga Site. They report drag force in a pile with two meters of recent fill and *about the same drag force in a pile without recent fill and no measurable ground settlement.*

Table 1 Results of previous tests on unprotected steel piles.

Site / Pile No.	Pile data: type	Pile data: length m	Time after driving years	Down-drag tons	Settlement during observation: ground	Settlement during observation: pile	K tan φ'
Sörenga							
B	I	53	5	≈400	≈ 200	10.0	0. 20
C	II	57	2	300	≈ 27	5.3	0. 18
G	II	41	2	250	1-2 mm/yr	3.2	0. 23
Heröya							
85	III	32	$1\frac{1}{2}$	300	≈ 30		0. 25
A	IV	≈30		120	≈ 20	3.3	0. 26
Alnabru							
F 6	III	32	1	≈300			

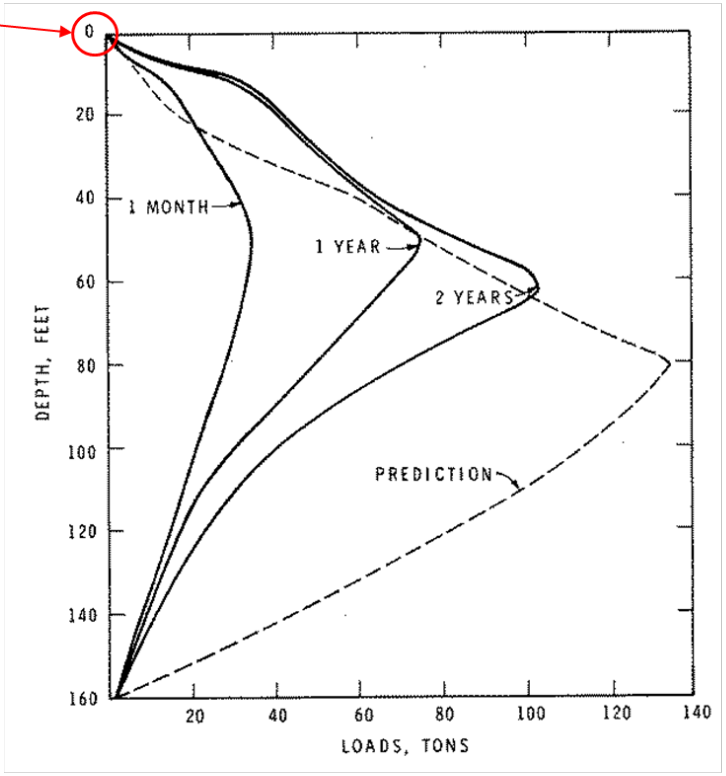
Pile type: I: KP 24, 47 cm, II: Tubular steel pile, Ø 50 cm, III: Tubular steel pile with concrete, Ø 50 cm; IV: Tubular steel pile, Ø 30 cm.

“Reduction of negative skin friction on steel piles to rock” *Proceedings, 7th International Conference on Soil Mechanics and Foundation Engineering*, 93-98.

CRAWFORD (1969)

1969 – Crawford published the results of a study in showing the development of the internal compression force of a "floating" steel pipe pile with time.

No top load



"Instrumentation and Downdrag" *Performance of Deep Foundations ASTM STP 444*, 223-226.

TIMELINE ON DOWNDRAG RESEARCH

1960s

early 1970s

BJERRUM, JOHANNESSEN AND EIDE (1969)

CRAWFORD (1969)

BOZOZUK (1972)

1969 – Bozozuk monitored a 'floating" pile in clay in Quebec, Canada and concluded that only a small relative movement between pile and soil was necessary to fully mobilize the side resistance and the drag force was balanced by the positive side resistance.

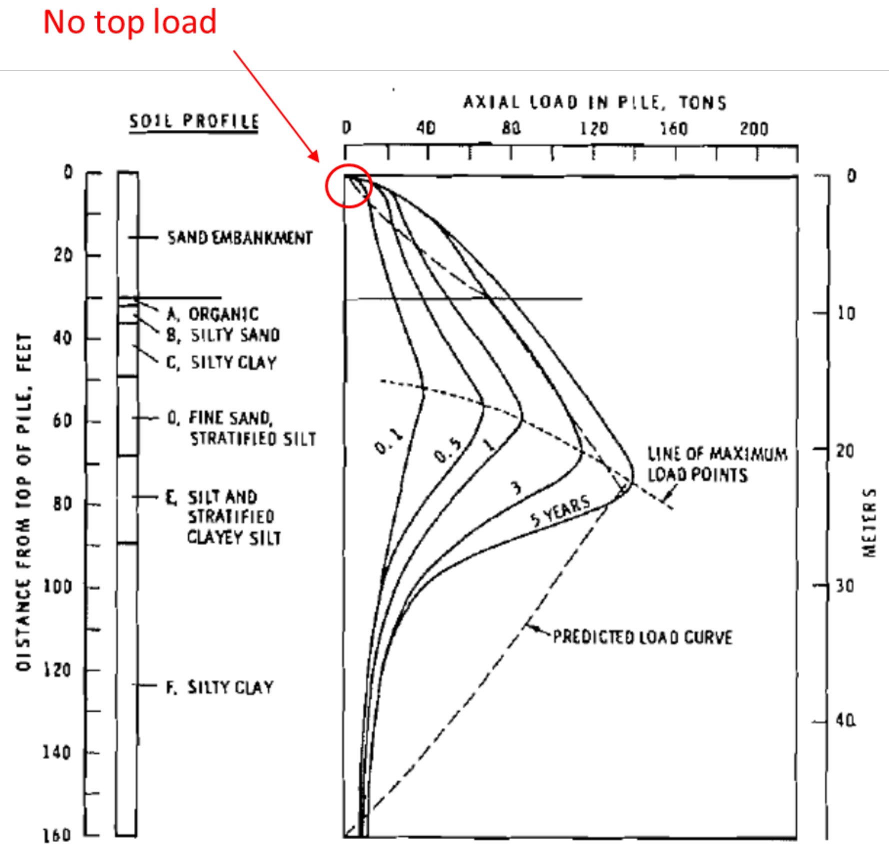


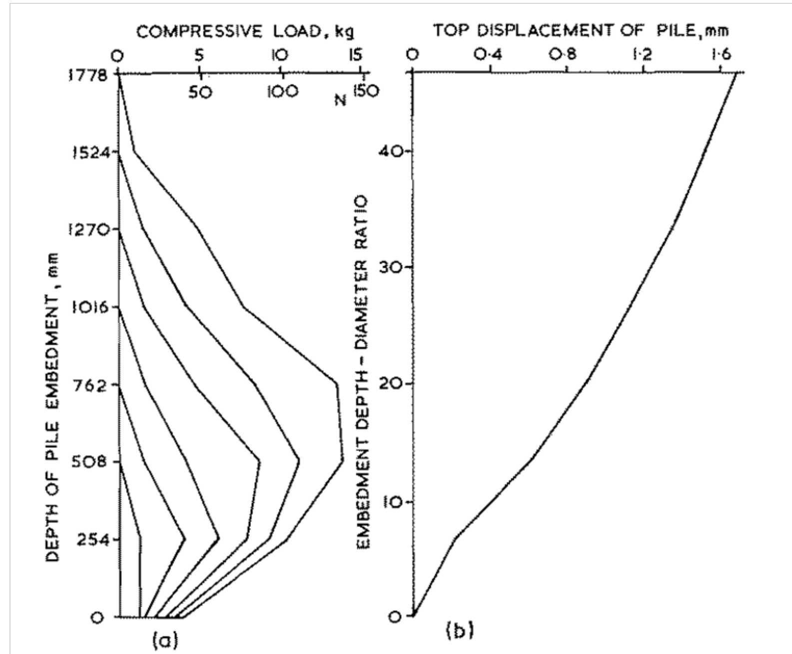
FIG. 7. Variation of skin friction load in 12-in. (30-cm) diameter steel pipe pile with time.

"Downdrag measurements on a 160-ft floating pile in marine clay." *Canadian Geotechnical Journal*, 9(2), 127-126.

HANNA AND TAN (1973)

1969 – Piles are not stress-free or strain-free even without top load.

Pile installation causes ground deformation, rotation of principle stresses, and volume changes that result in the development of an internal stress distribution.



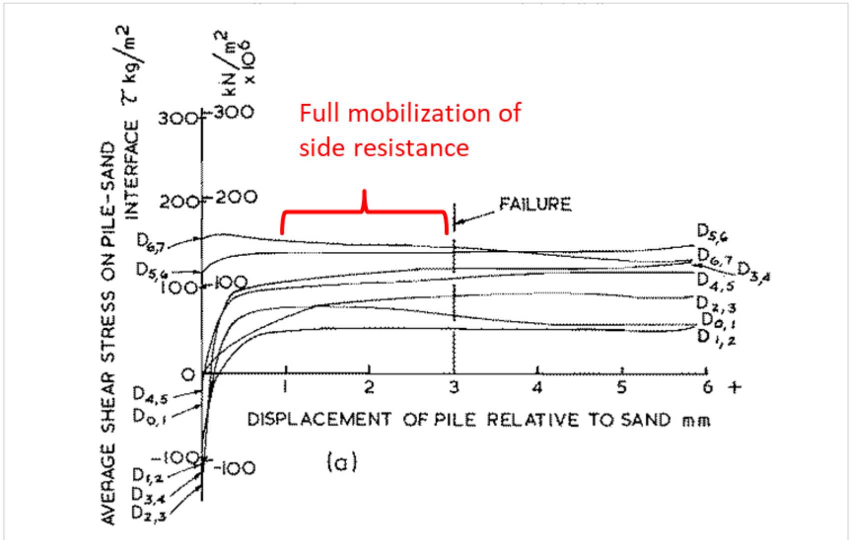
"The Behavior of Long Piles Under Compressive Loads in Sand." *Canadian Geotechnical Journal*, 9(2), 127-126.

HANNA AND TAN (1973)

1969 – Piles are not stress-free or strain-free even without top load.

Pile installation causes ground deformation, rotation of principle stresses, and volume changes that result in the development of an internal stress distribution.

Full mobilization of side resistance occurs at 1 to 3 mm of relative movement



“The Behavior of Long Piles Under Compressive Loads in Sand.” *Canadian Geotechnical Journal*, 9(2), 127-126.

TIMELINE ON DOWNDRAG RESEARCH

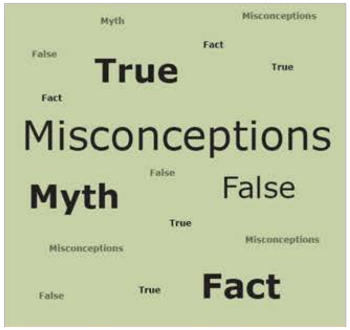
1960s

BJERRUM, JOHANNESSEN AND EIDE (1969)
CRAWFORD (1969)

early 1970s

BOZOZUK (1972)
HANNA AND TAN (1973)

mid 1970s – late 1980s



FELLENIUS (1988)

Unified Design of Piles and Pile Groups

BENGT H. FELLENIUS

A unified design of piles and pile groups is proposed wherein capacity, residual compression, negative skin friction, and settlement are related. First, the location of the neutral plane is determined. Then, the adequacy of the structural strength of the pile is checked and followed by an analysis of the settlement of the pile foundation, applying the concept of an equivalent footing placed at the neutral plane. Finally, the adequacy of the pile bearing capacity is verified. For structural capacity at the neutral plane, dead load and dragload are considered together, but live load is excluded. For settlement, all stress increase in the soil is considered, not just that of the dead load acting on the pile foundation. For bearing capacity, dead and live loads are considered, but dragload is excluded. The design is iterative, inasmuch as the choice of load and pile length will have an interactive influence on all aspects: location of neutral plane, dragload, structural capacity, and settlement, as well as bearing capacity.

Conventionally, or traditionally, when designing piles and pile groups, design for bearing capacity and design for settlement are considered separately and are not influenced by each other. In the simplest principle, design for bearing capacity consists of determining the allowable load—the service load—on the pile by dividing the capacity by a factor of safety. Settlement occurs when the service load on the piles stresses the soil, causing the soil to consolidate and compress. Usually, the methods of calculation are very simple. For instance, a common approach is to take the settlement of piles in sand to be equal to 1 percent of the diameter of the head of an individual pile plus the "elastic" compression of the pile under the load. For the case of an essentially shaft-bearing pile group in homogeneous clay soil, Terzaghi and Peck (*1*) recommended taking the settlement of the group as equal to that calculated for an equivalent footing located at the lower third point of the pile embedment length and loaded to the same stress and over the same area as the pile group plan area (Figure 1). For other approaches, see Meyerhof (*2*).

More complex methods for calculating settlement use elastic halfsphere analysis or finite element techniques. Vesic (*3*) and Poulos and Davis (*4*) presented several such analytical approaches toward calculating settlement on single piles and pile groups. Generally, it is assumed that before load is applied to the pile foundation, no stress is present in the pile or piles.

For the case of piles installed through a multilayered soil deposit, where upper layers settle because of, for instance, a surcharge on the ground surface or a general groundwater lowering, a settlement calculation of the pile group is often not performed. (The design practice seems to be to trust that the settlement will somehow be taken care of by including loads from downdrag in the bearing capacity analysis. Sometimes, on the other hand, the dragload is added to the service load and some settlement calculation is carried out for this combined load—a totally erroneous approach.)

Provided that the piles have been installed to reach well into competent soils and that no weaker soil layers exist below the pile toe elevation, this approach of including the dragloads in the bearing capacity and settlement analyses is mostly safe, albeit excessively costly. However, the problem of negative skin friction is one of settlement and not of bearing capacity (i.e., the magnitude of the dragload is of no relevance to the bearing capacity of the pile). Furthermore, the allowable load on the pile should be governed by a combined (unified) approach considering soil resistance and settlement inseparably acting together and each influencing the value of the other.

LONG-TERM MEASUREMENTS OF LOAD AND SETTLEMENT

Observations show that for piles bearing on very competent material, negative skin friction can result in very large dragloads. Bjerrum et al. (*5*) measured dragloads amounting to about 4,000 kN on 0.5-m-diameter steel test piles installed to bedrock through 55 m of clay soil settling under the influence of a recent surcharge.

If a pile is long enough or if the ratio of its unit circumferential area to its cross-sectional area is large enough, the induced stress could exceed the material strength (i.e., the structural capacity of the pile). In the field tests reported by Bjerrum et al. (*5*), the piles were driven to rock, and the induced dragload exceeded the available toe resistance, forcing the pile to penetrate into the rock. This effect is cyclic, as discussed by Fellenius (*6*). Obviously, the toe force developed during the pile driving must have been smaller than the dragload.

Immediately after a pile is installed in the soil, the soil begins to reconsolidate from the disturbance caused by the installation of the pile, whether the pile was driven or otherwise installed. Fellenius and Broms (*7*) and Fellenius (*6*) reported load measurements in 0.3-m-diameter concrete piles driven into a 40-m-thick clay deposit and into an underlying sand layer. Immediately after the driving, the load in the pile was small, about equal to the free-standing weight of the pile before the driving. The reconsolidation of the clay after the driving took about 5 months. During this time, negative skin friction developed and the dragload induced amounted to about 350 kN corresponding to about one-third of the maximum dragload, which developed during the following several years of observations (*6, 8*). The settlement of the ground surface

Department of Civil Engineering, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada.

"Unified Design of Piles and Pile Groups." *Geotechnical Instrumentation – Transportation Research Record 1169*, 75-82.

TIMELINE ON DOWNDRAG RESEARCH

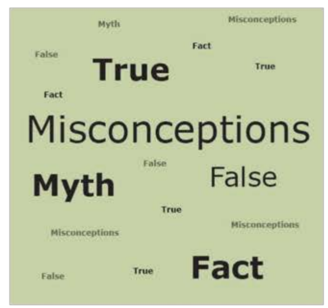
1960s

BJERRUM, JOHANNESSEN AND EIDE (1969)
CRAWFORD (1969)

early 1970s

BOZOZUK (1972)
HANNA AND TAN (1973)

mid 1970s – late 1980s



1988

FELLENIUS (1988)

Unified Design of Piles
(Neutral Plane Method)

Numerical analyses and other methods

AASHTO Bridge Design Specifications

Canadian Geotechnical Journal
FHWA Driven Pile Foundation Manual

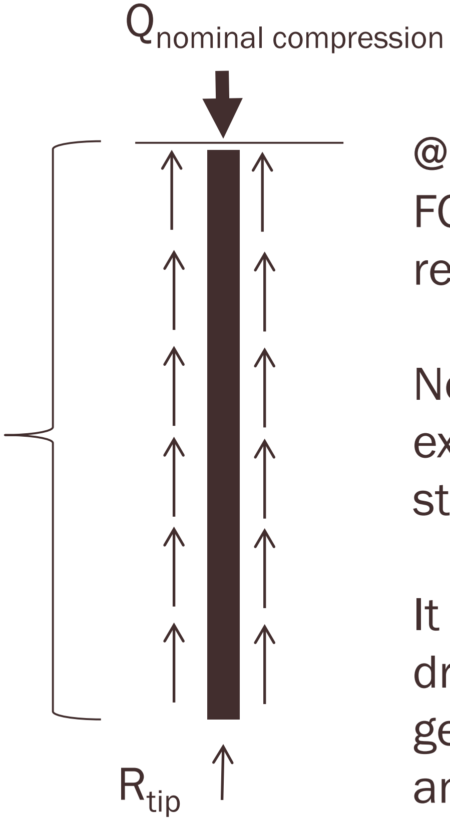
AXIAL RESISTANCE OF PILES

The axial resistance of deep foundations may be divided into two components:

1. Side resistance (unit value is f_{side})

Σ Area x $f_{side} = R_{side}$

2. Tip resistance



@ nominal compression (i.e., FOS = 1) the entire side resistance is positive/upward

Negative skin friction doesn't exist at the geotechnical strength limit state.

It is unrealistic to represent drag force as a top load for geotechnical strength limit analysis.

FUNDAMENTALS OF SIDE RESISTANCE

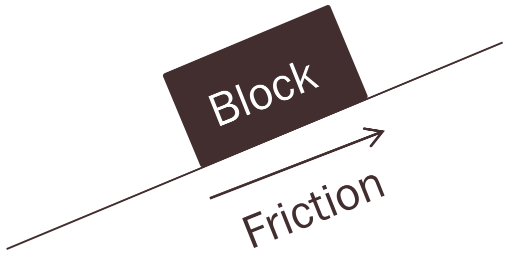
1. The shear is confined to a thin zone around the pile and drainage can take place. Therefore, the side resistance is frictional.

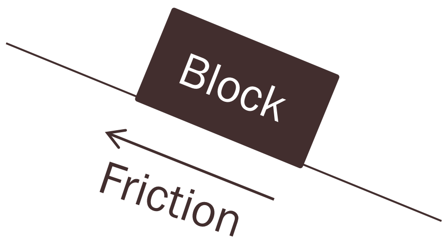
Burland, J.B. (1973) “Shaft friction in Piles in Clay – A Simple Fundamental Approach” *Ground Engineering*, 6(3), 30-42.

Meyerhoff, G.G. (1976) “Bearing Capacity and Settlement of Pile Foundations” Journal of the Geotechnical Engineering Division, American Society of Civil Engineers, 102, 195-228.

FUNDAMENTALS OF SIDE RESISTANCE

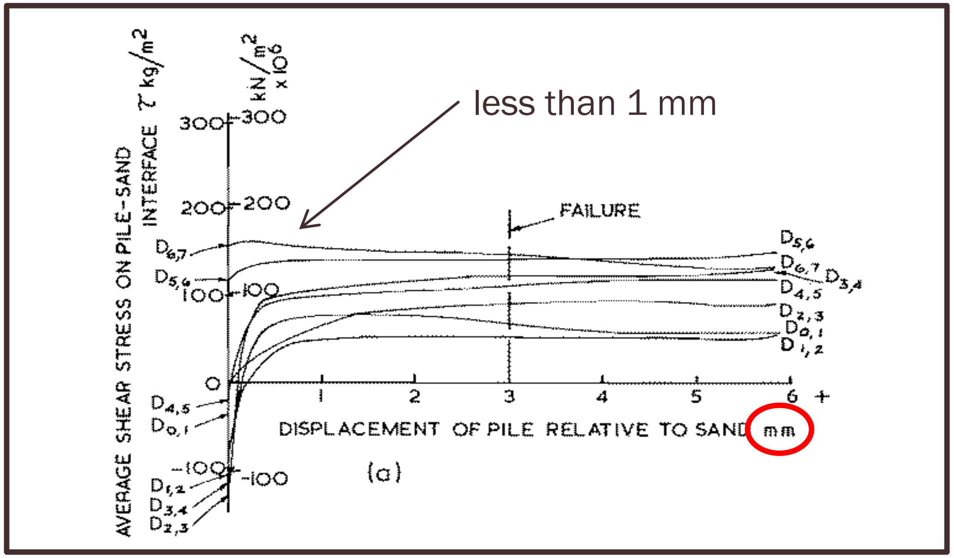
2. The direction of the (frictional) side resistance is always to resist the tendency for movement.





FUNDAMENTALS OF SIDE RESISTANCE

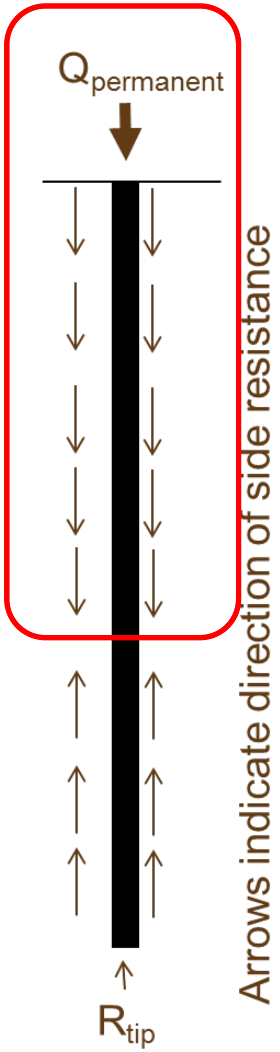
3. The side resistance is fully mobilized at very small relative movements between the pile and soil.



Hanna, T.H. and Tan, R.H.S. (1973) “The behavior of long piles under compressive loads in sand” Canadian Geotechnical Journal, 10(3), 311-340.

NEGATIVE SKIN FRICTION

.....is side resistance mobilized as the ground moves downward relative to the pile.

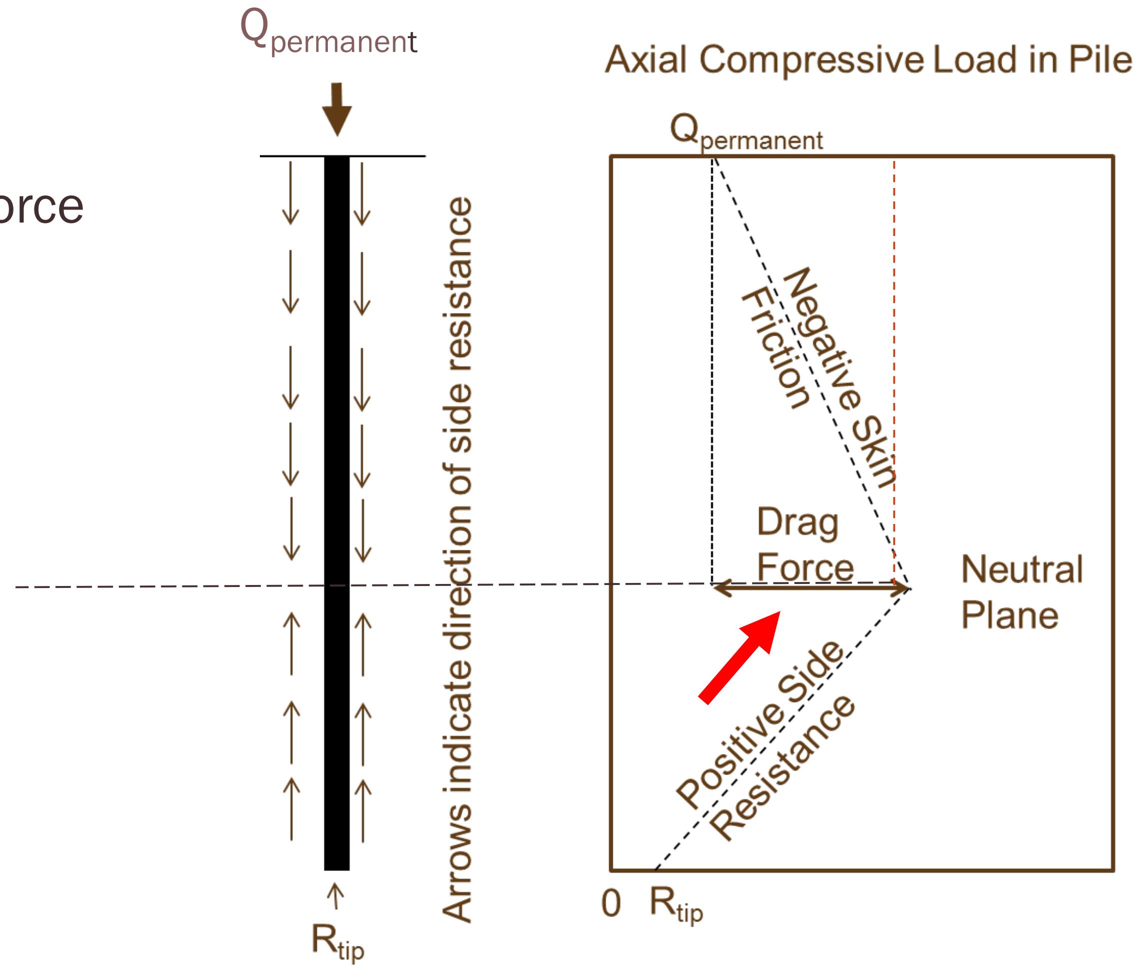


(The magnitude of ground settlement is irrelevant to the development of drag force. Essentially all piles will move relative to the soil as a result of differences in compressibility.*)

* Fellenius, B.H. Brusey, W.G., and Pepe, F. (2000) "Soil setup, variable concrete modulus and residual load", ASCE Proceedings, Specialty Conference on Performance Confirmation of Constructed Facilities, 16 p.

DRAG FORCE

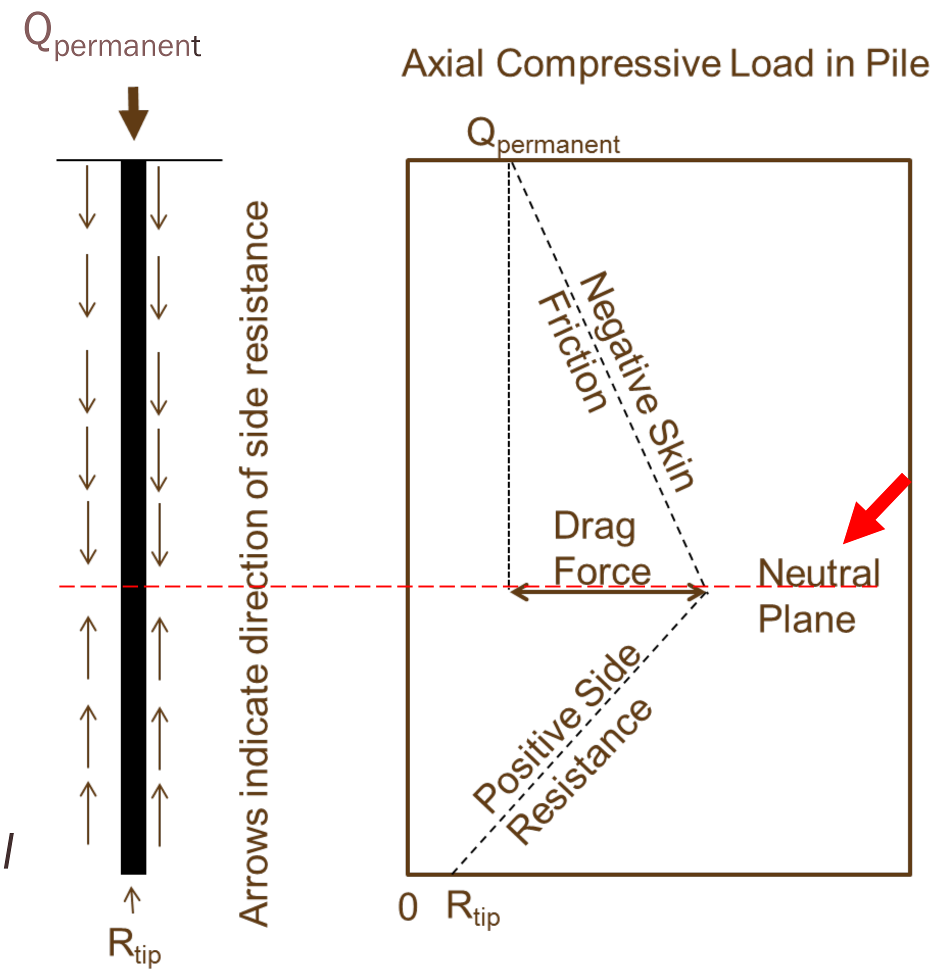
…..is the axial compressive force induced in a pile due to accumulated negative skin friction.



NEUTRAL PLANE

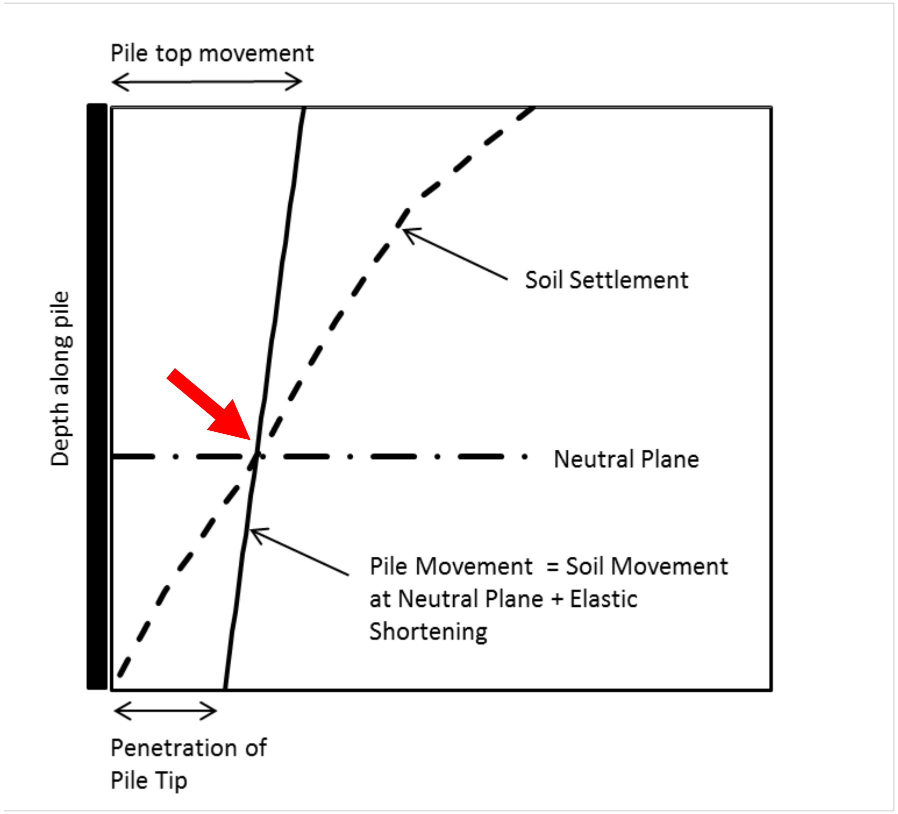
.....is the location along the pile where there is no relative movement between the pile and adjacent soil.

- *The side resistance is negative above the neutral plane.*
- *The side resistance is positive below the neutral plane.*
- *It is the location of the maximum axial compressive stress.*



DOWNDRAG

….. is the downward movement of the pile (S_{pile}) resulting from ground settlement.



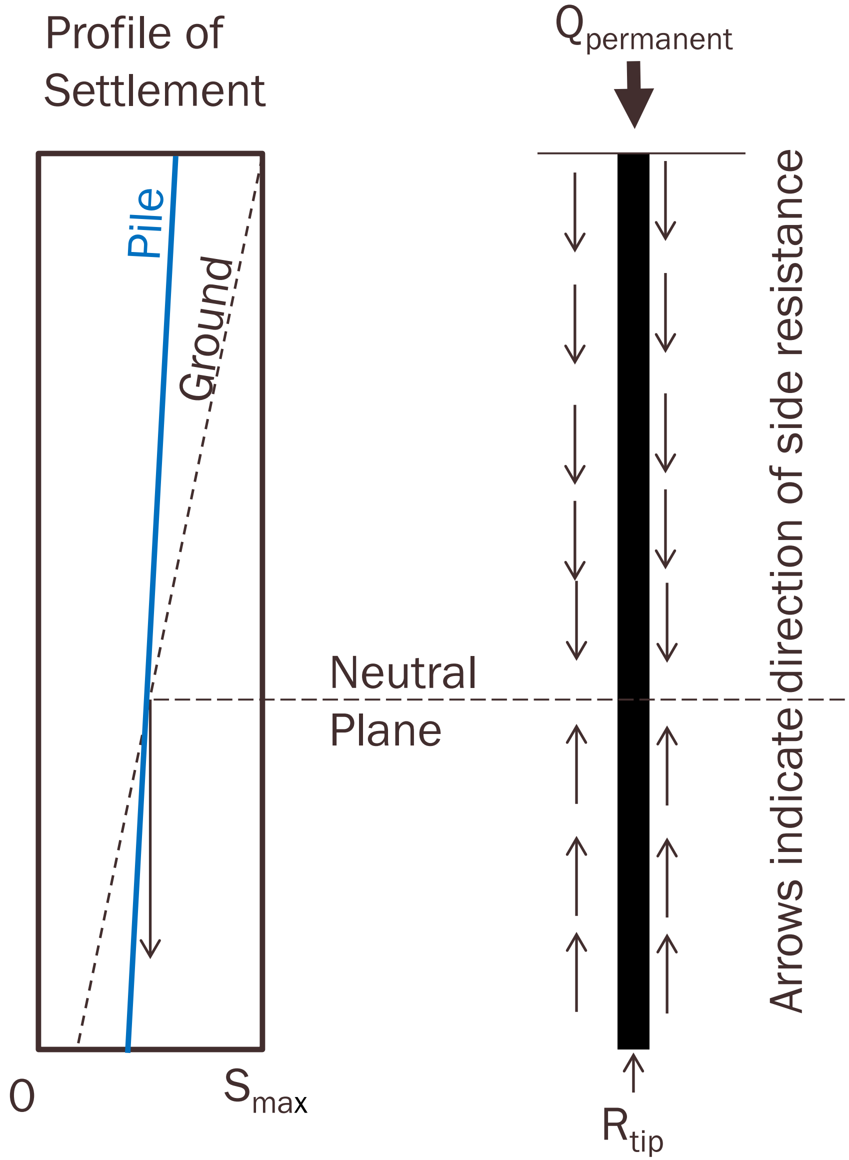
PERMANENT (OR SUSTAINED) LOADS

..... are constant over time (weight).

TRANSIENT LOADS

..... act only a short time (e.g., wind, seismic, traffic).

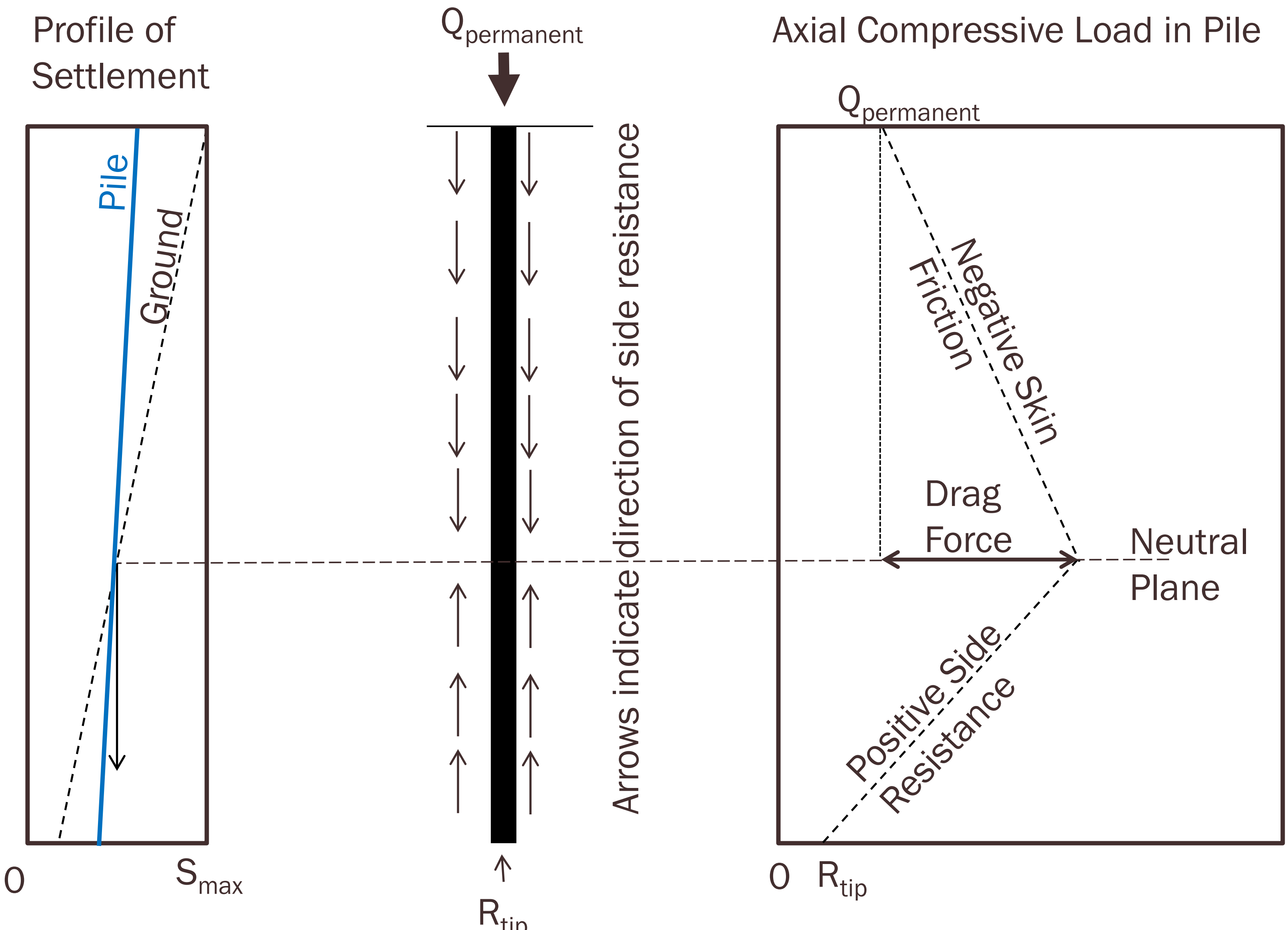
CONCEPTUAL PILE MODEL



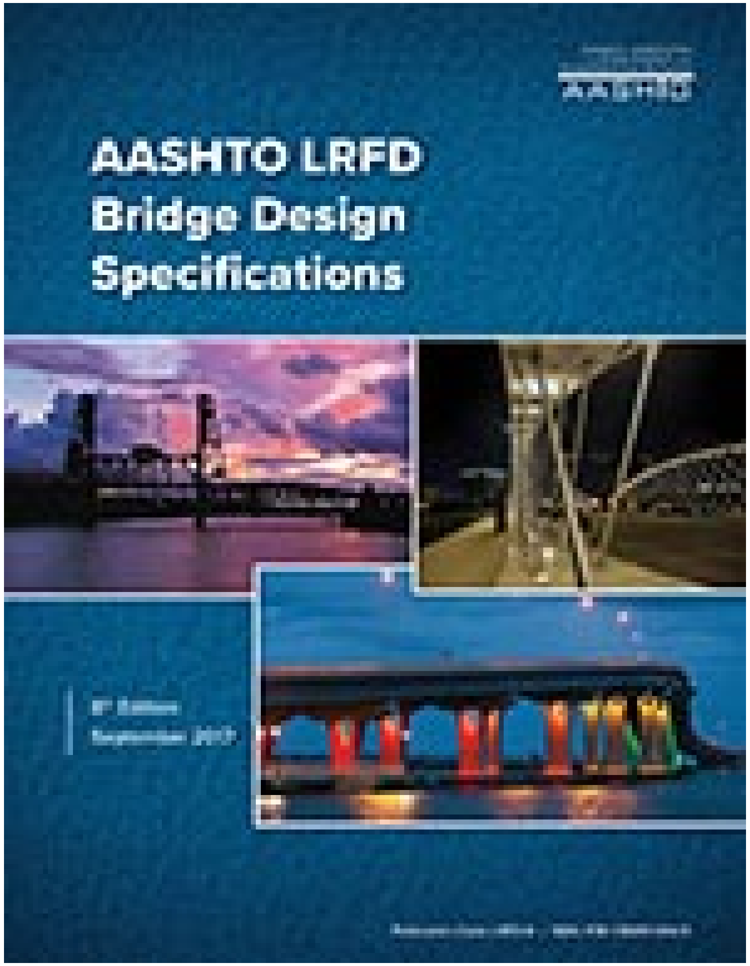
Soil moves downward relative to pile

Pile moves downward relative to soil

CONCEPTUAL PILE MODEL



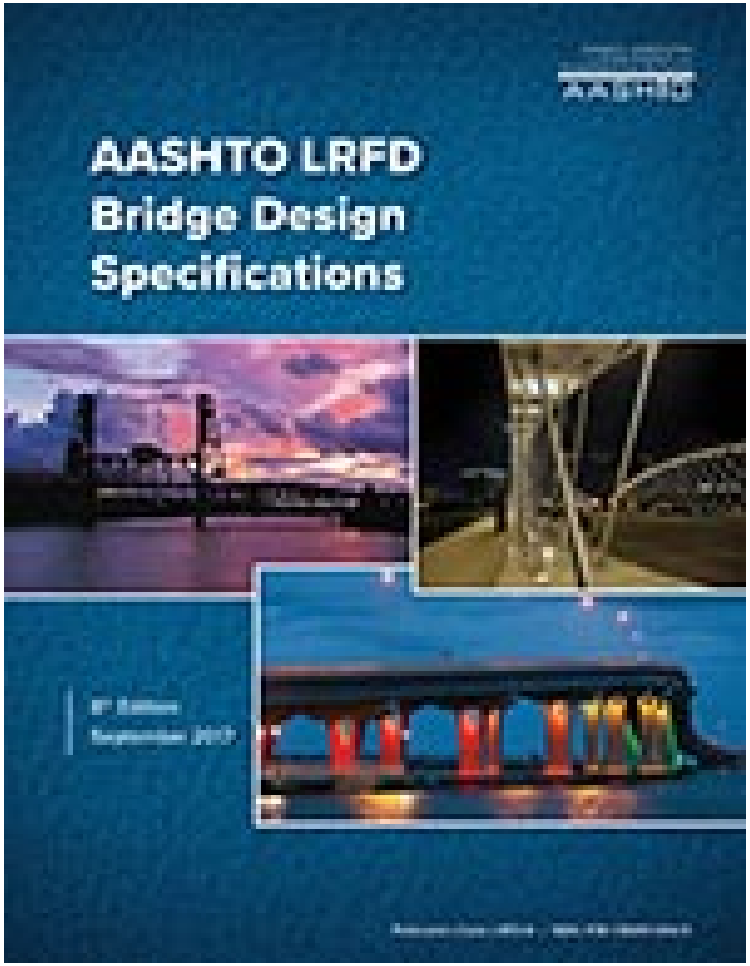
AASHTO Specifications

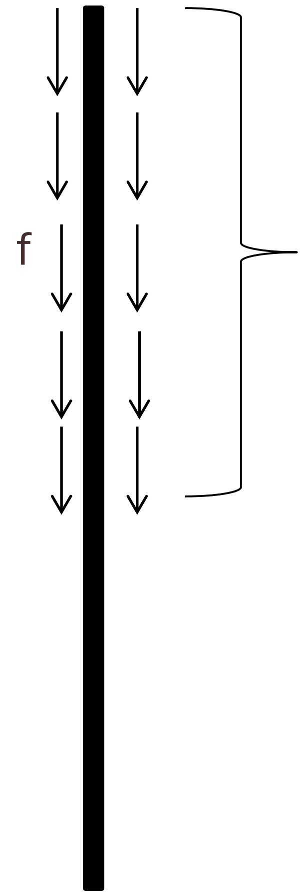


10.7.3.7—Downdrag

The foundation should be designed so that the available factored geotechnical resistance is greater than the factored loads applied to the pile, including the downdrag, at the strength limit state.

The nominal pile resistance available to support structure loads plus downdrag shall be estimated by considering only the positive side and tip resistance below the lowest layer contributing to the downdrag.

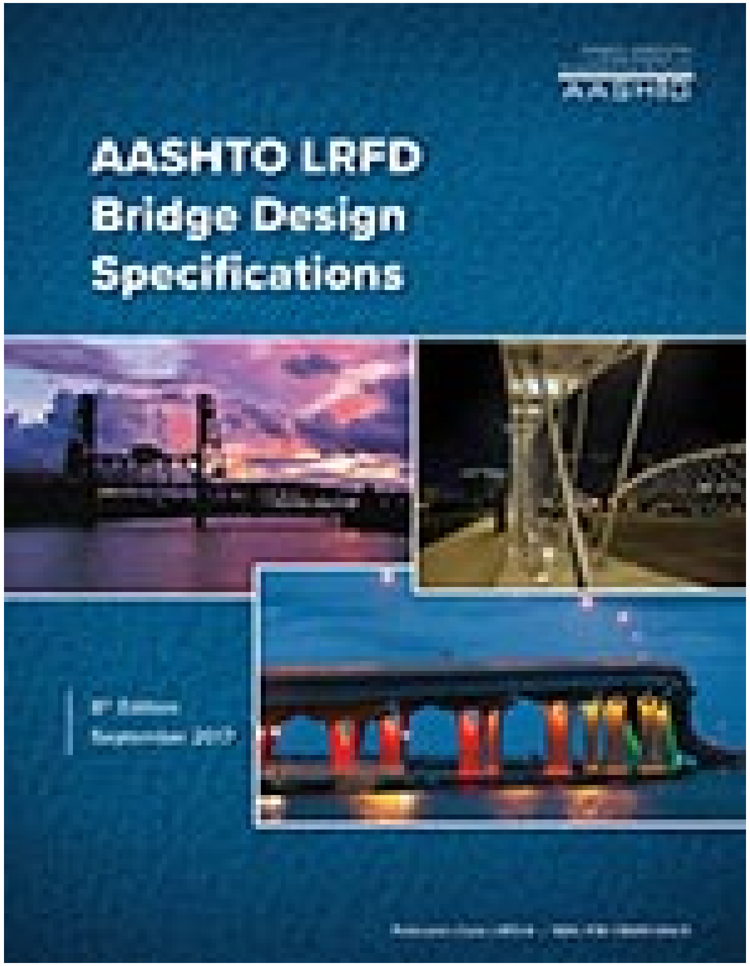


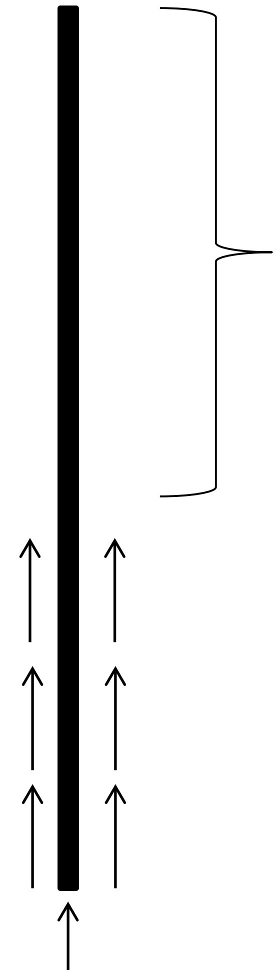


Soil contributing to downdrag....sometimes has been defined as a relative movement of 0.4 inches.

$$DD = \Sigma f^*A$$

DD included as a top load component





Zone of negative skin friction is assigned zero side resistance for the geotechnical limit state.

Neutral Plane Concepts
(a.k.a. Unified Design of Piles)

Fellenius, B.H. (1989) “Unified design of piles and pile groups”, Transportation Research Board, Washington, TRB Record, 1169, 75-82.

Fellenius, B.H. (1998) “Recent advances in the design of piles for axial loads, drag loads, downdrag, and settlement” Proceedings, Seminar by ASCE and Ports of New York and New Jersey, 19p.

NEUTRAL PLANE METHOD IN DESIGN

Important -

Ideally, the neutral plane should be determined using the actual, unfactored permanent load.

NEUTRAL PLANE METHOD IN DESIGN

Important -

Ideally, the neutral plane should be determined using the actual, unfactored permanent load.

The neutral plane should be determined using unfactored side/mobilized tip resistances.

NEUTRAL PLANE METHOD IN DESIGN

Important -

Ideally, the neutral plane should be determined using the actual, unfactored permanent load.

The neutral plane should be determined using unfactored side/mobilized tip resistances.

The mobilized tip resistance is unknown and must be assumed. Tip resistance versus displacement curves (or t-z curves) may be used in a more refined iterative approach.

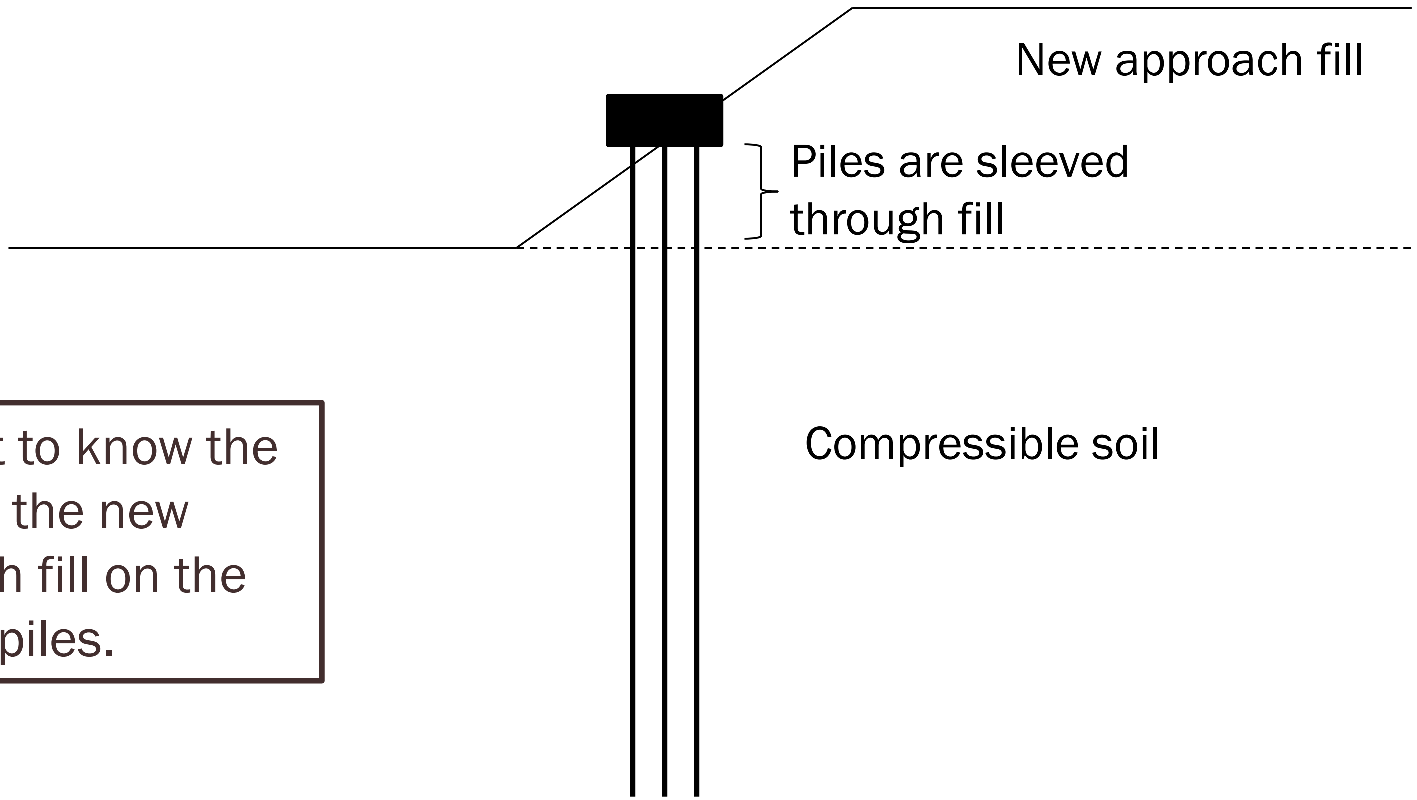
NEUTRAL PLANE METHOD IN DESIGN

Important -

Drag force is not considered when evaluating the geotechnical strength limit state. It is indirectly considered in settlement at the geotechnical service limit state and as an internal force/load at the structural limit state.

Conceptual Examples

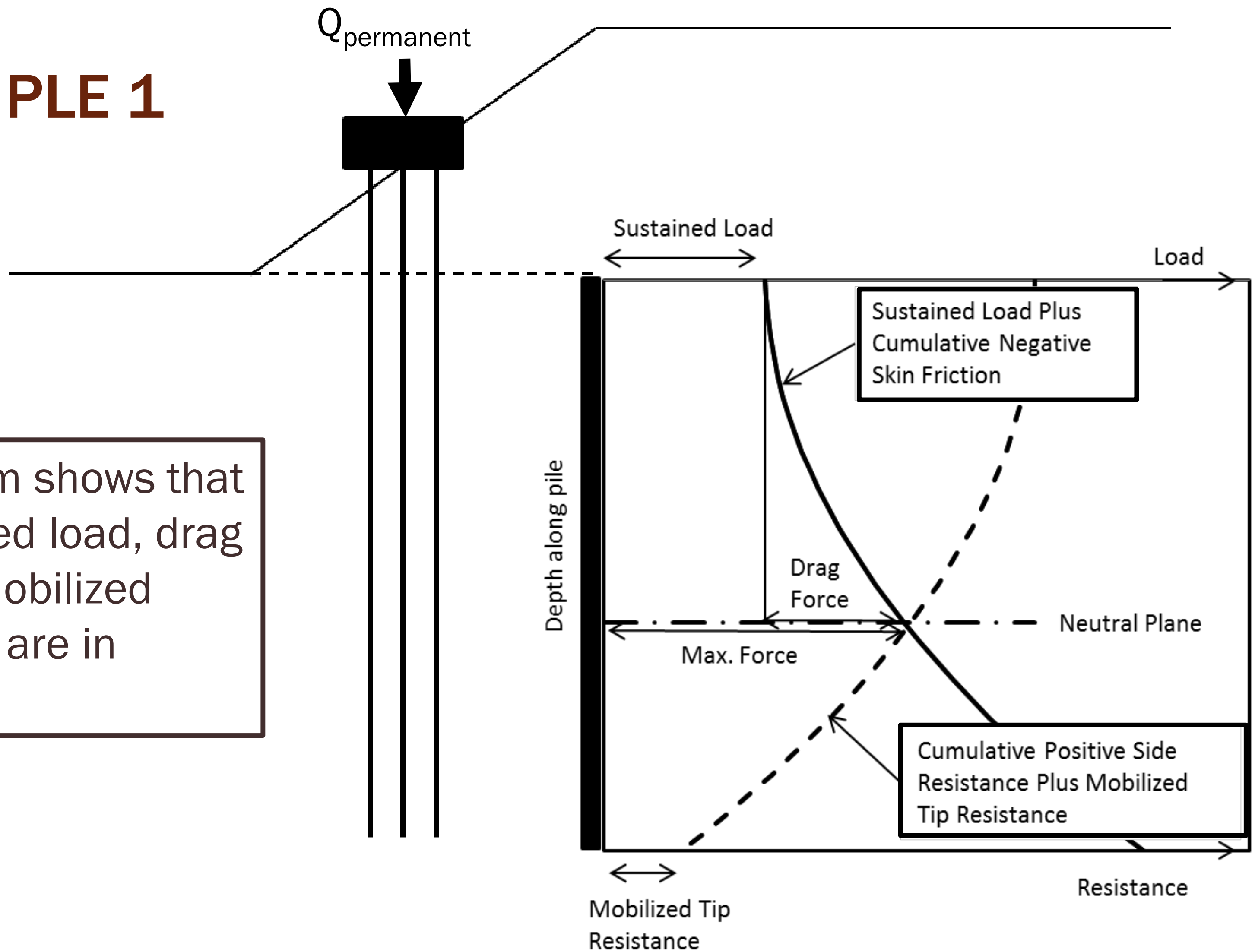
EXAMPLE 1



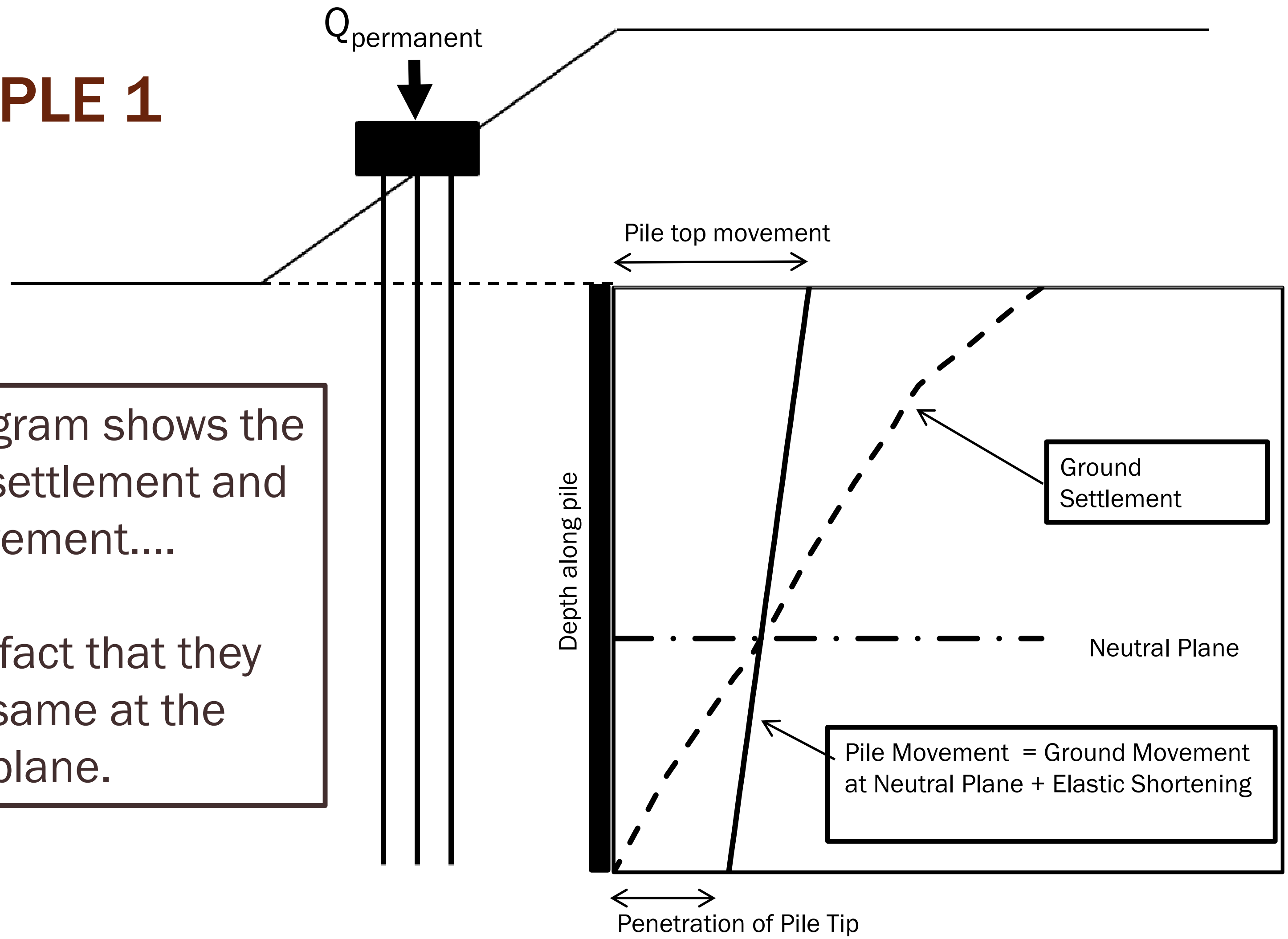
We want to know the effect of the new approach fill on the existing piles.

EXAMPLE 1

This diagram shows that the sustained load, drag force and mobilized resistances are in equilibrium.



EXAMPLE 1

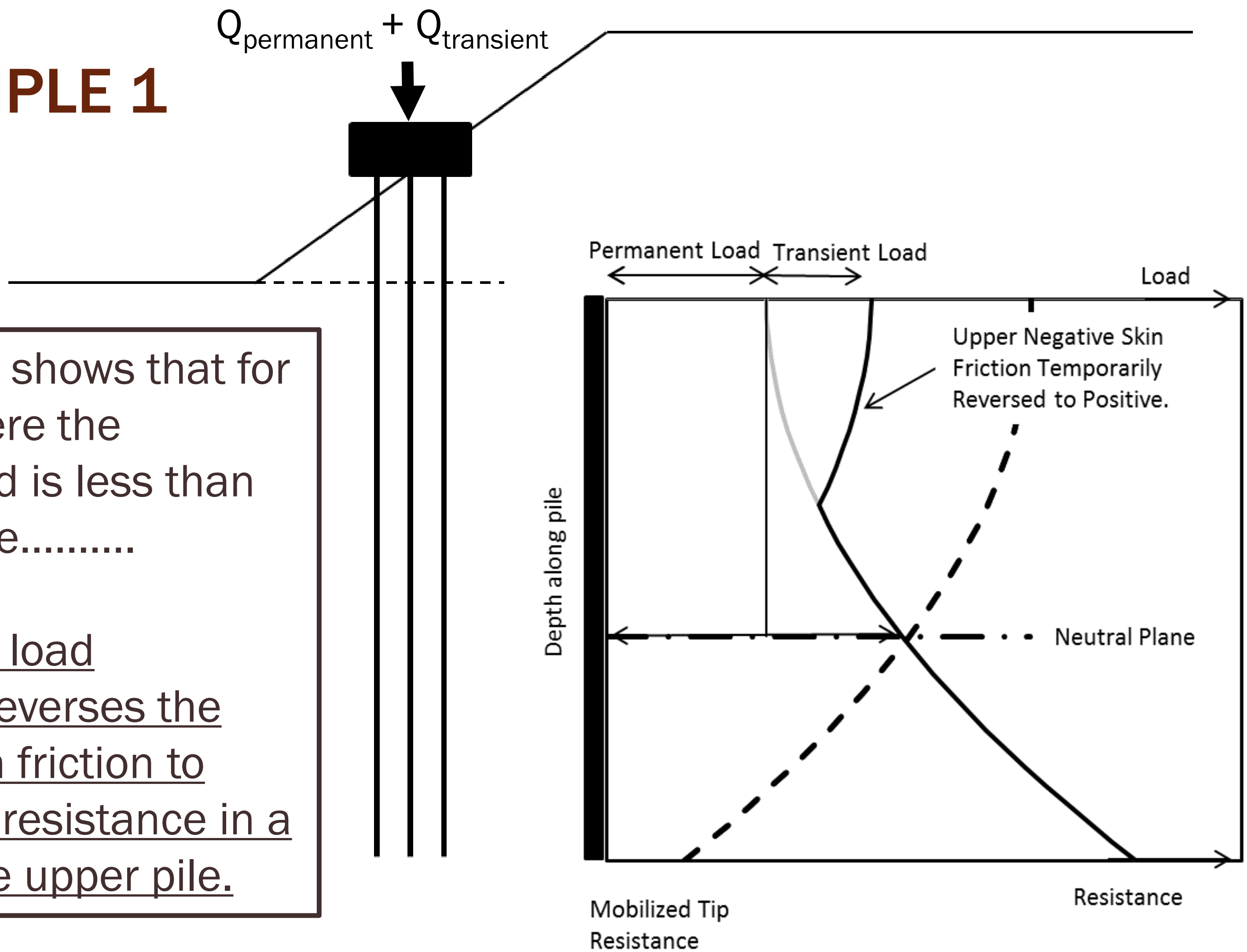


This diagram shows the ground settlement and pile movement....

and the fact that they are the same at the neutral plane.

Transient Load?

EXAMPLE 1

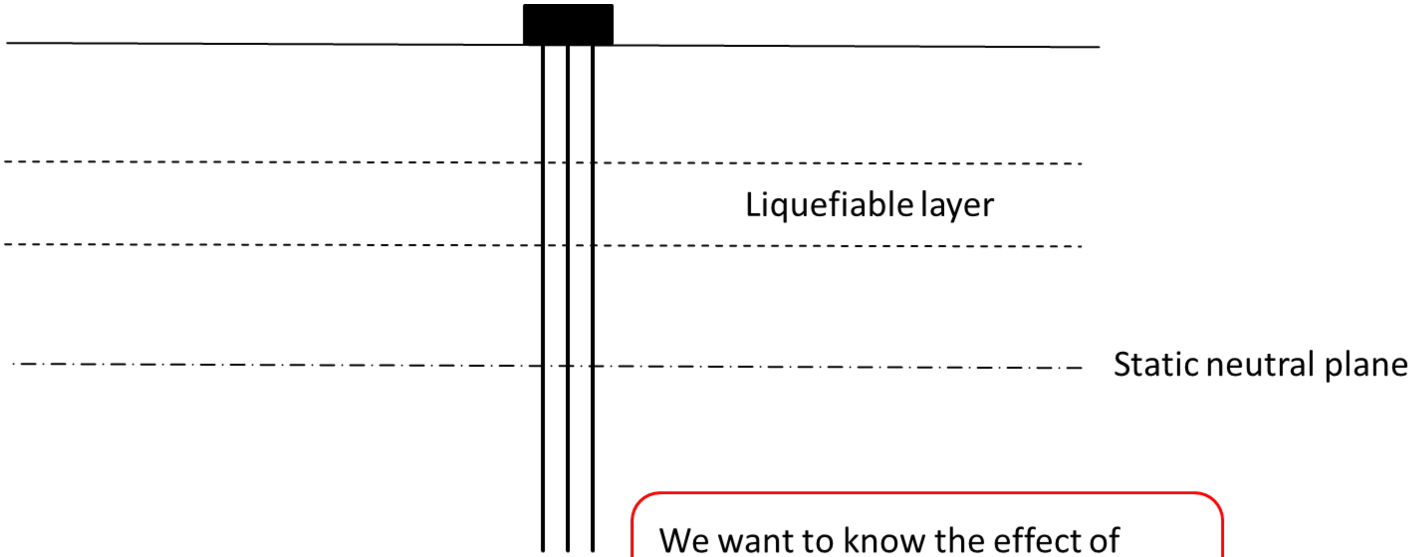


This diagram shows that for the case where the transient load is less than the drag force..........

<u>the transient load temporarily reverses the negative skin friction to positive side resistance in a portion of the upper pile.</u>

Seismic Liquefaction

EXAMPLE 2

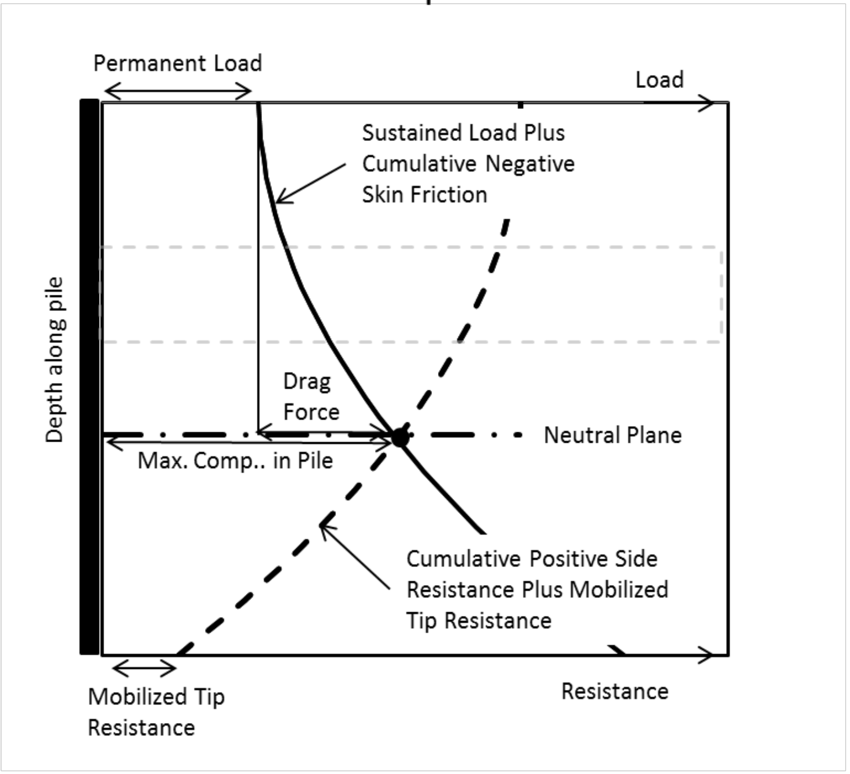


We want to know the effect of liquefaction on the existing piles.

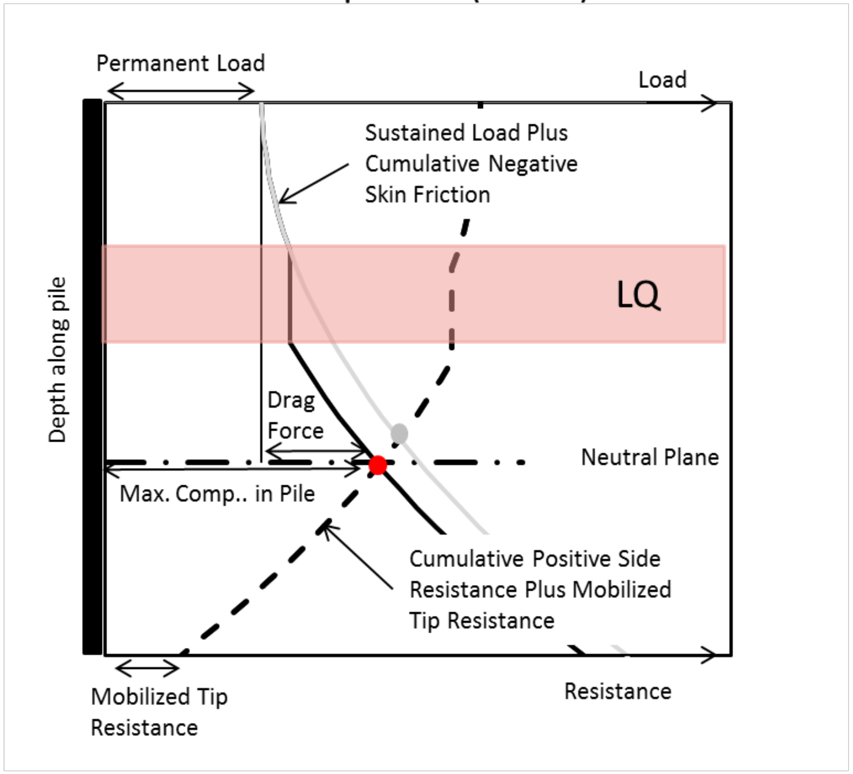
Fellenius and Siegel (2007)"Pile Drag Load and Downdrag in a Liquefaction Event." *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 132(2), 1412-1416.

EXAMPLE 2

Non-liquefied



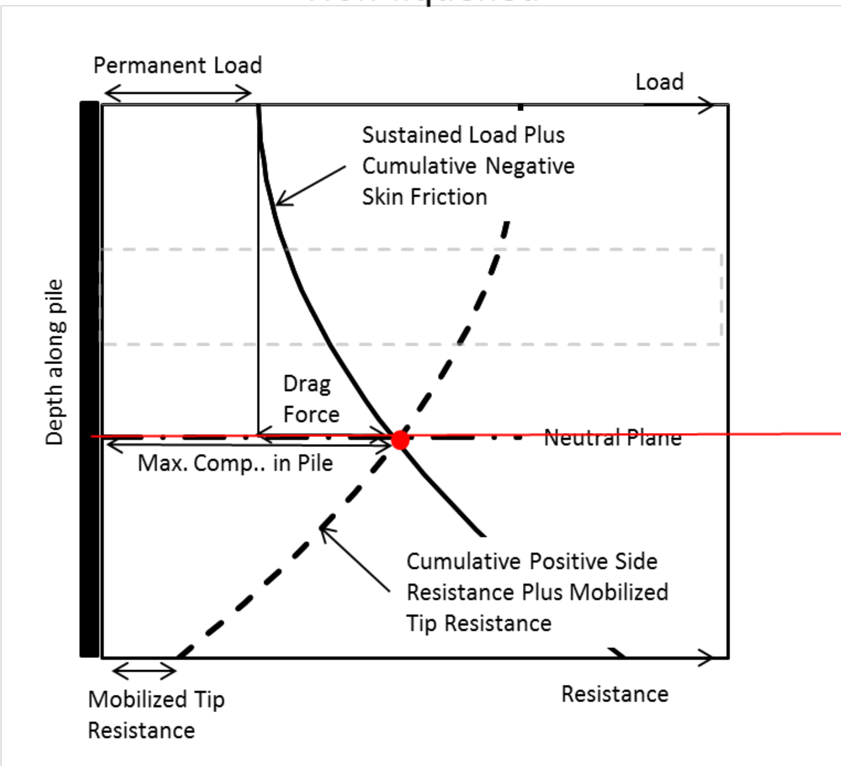
Liquefied (in red)



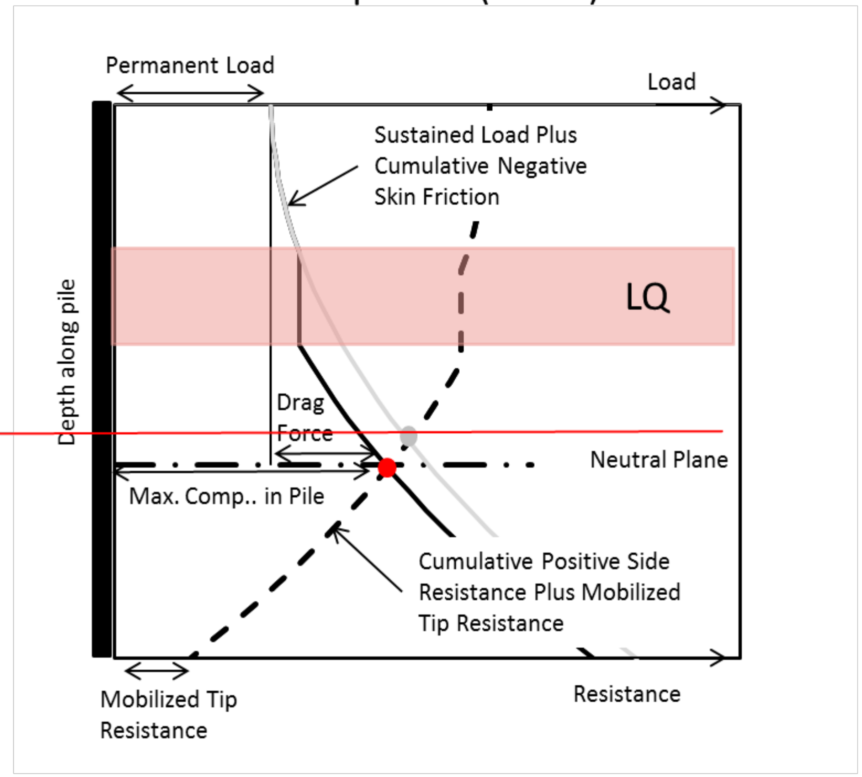
- Temporary reduction of geotechnical resistance

EXAMPLE 2

Non-liquefied

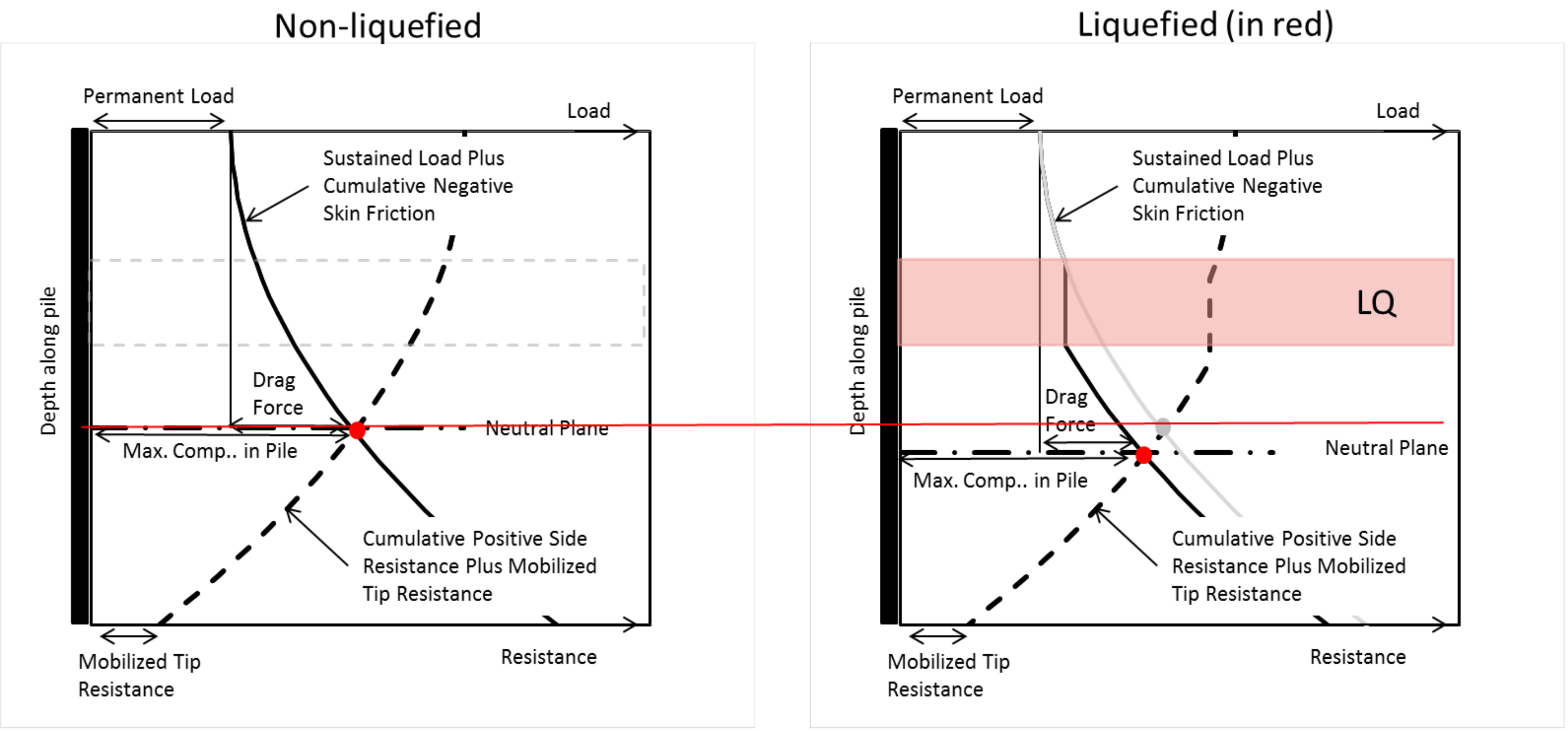


Liquefied (in red)



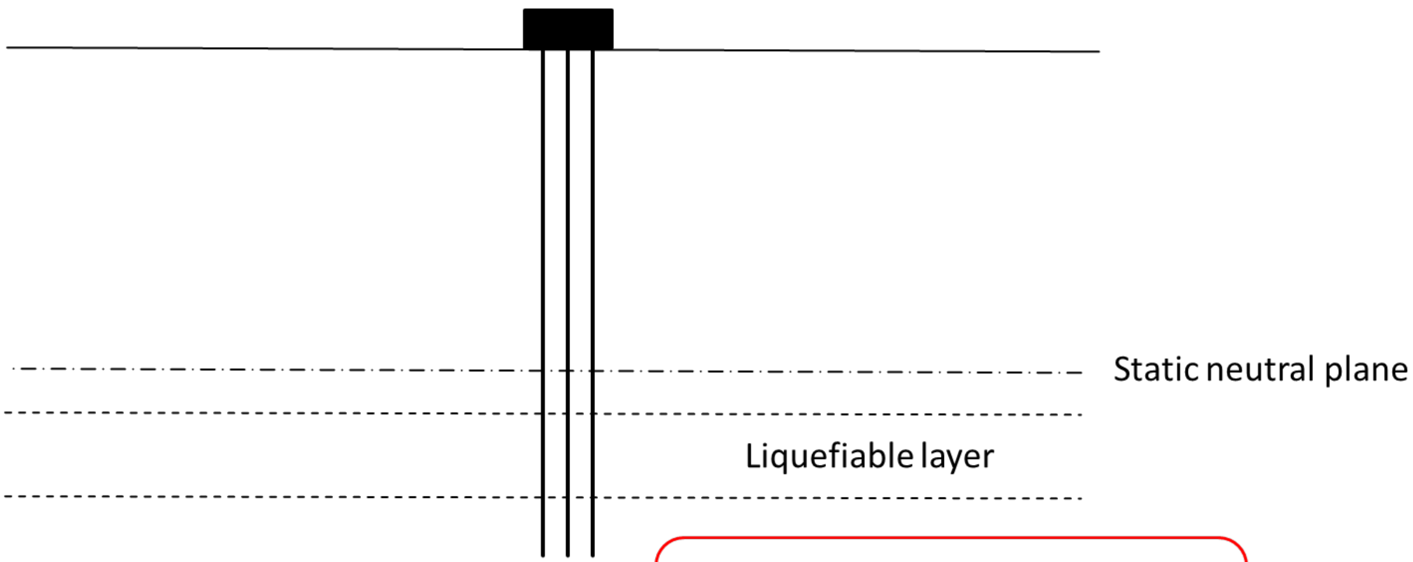
- Temporary reduction of geotechnical resistance
- Temporary reduction in drag force/reduction of max. comp. in pile

EXAMPLE 2



- Temporary reduction of geotechnical resistance
- Temporary reduction in drag force/reduction of max. comp. in pile
- Neutral plane temporarily deepens

EXAMPLE 3

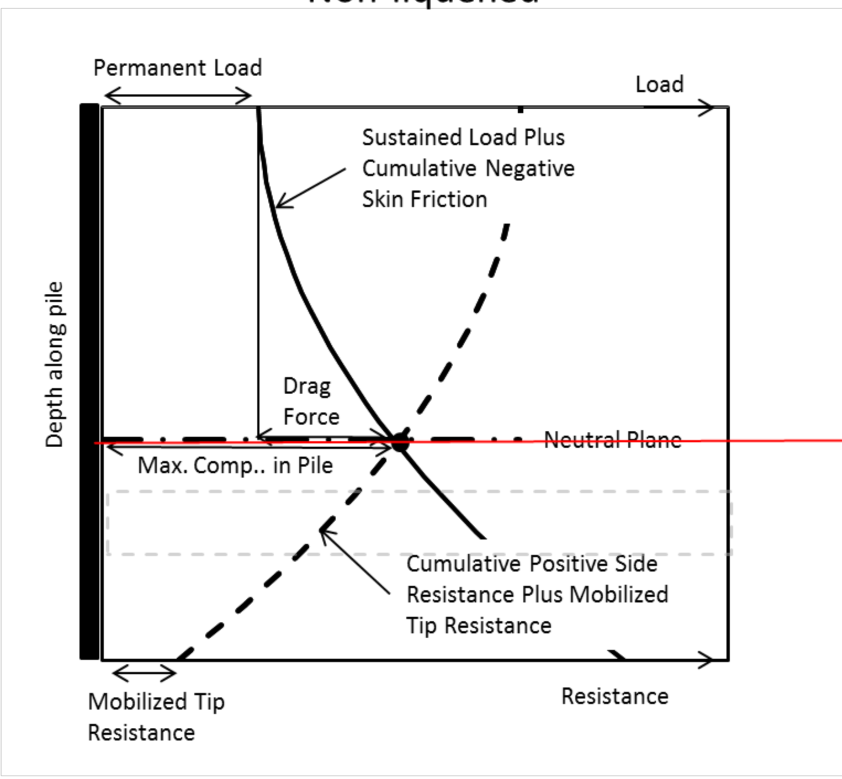


We want to know the effect of liquefaction on the existing piles.

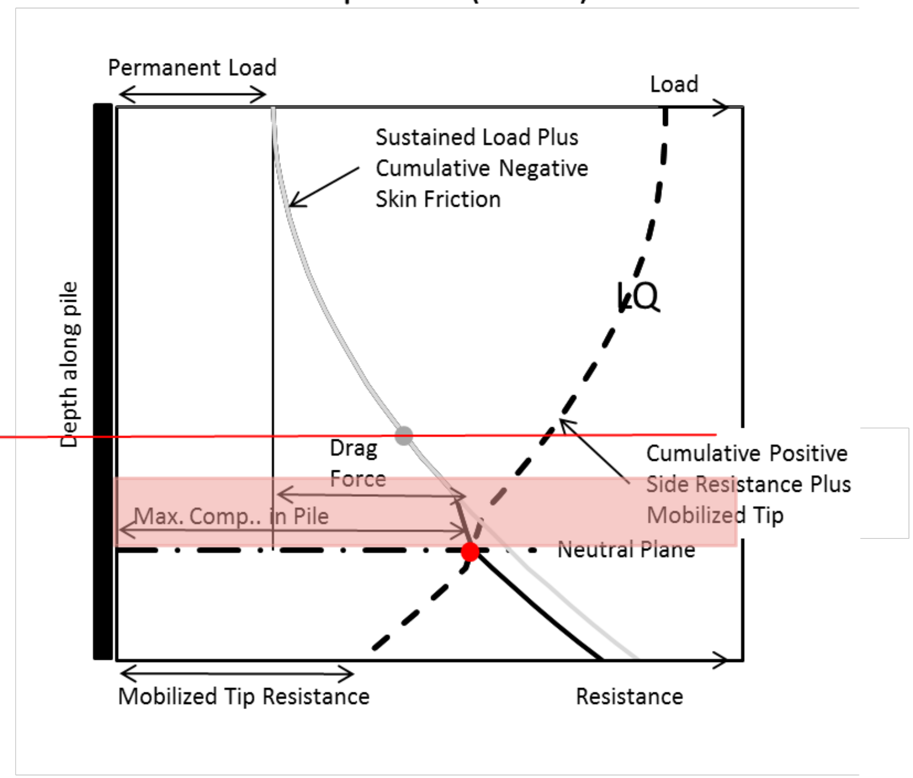
Fellenius and Siegel (2007)"Pile Drag Load and Downdrag in a Liquefaction Event." *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 132(2), 1412-1416.

EXAMPLE 3

Non-liquefied



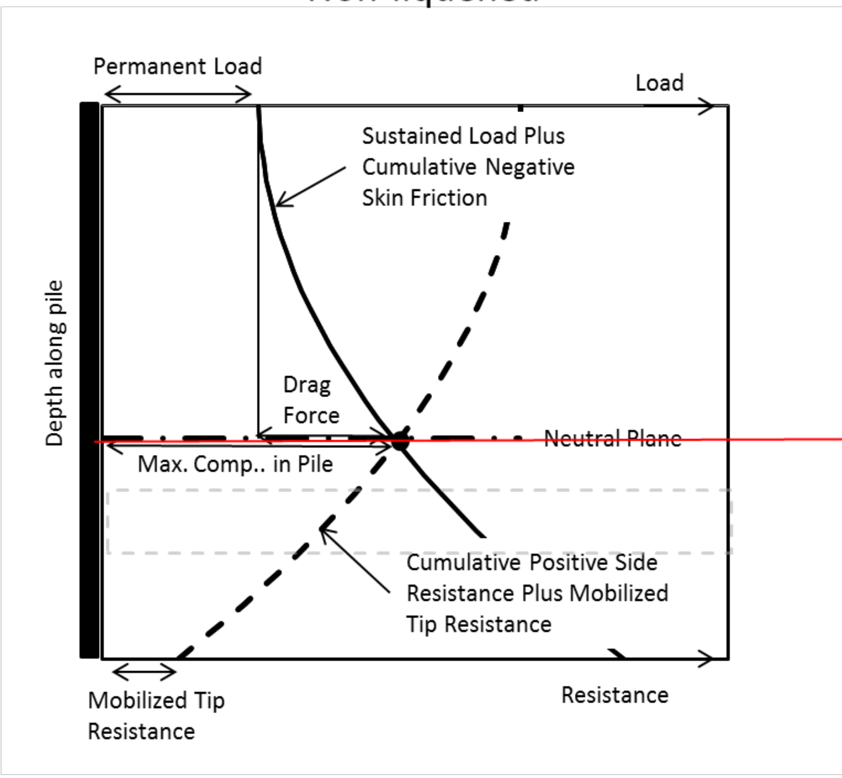
Liquefied (in red)



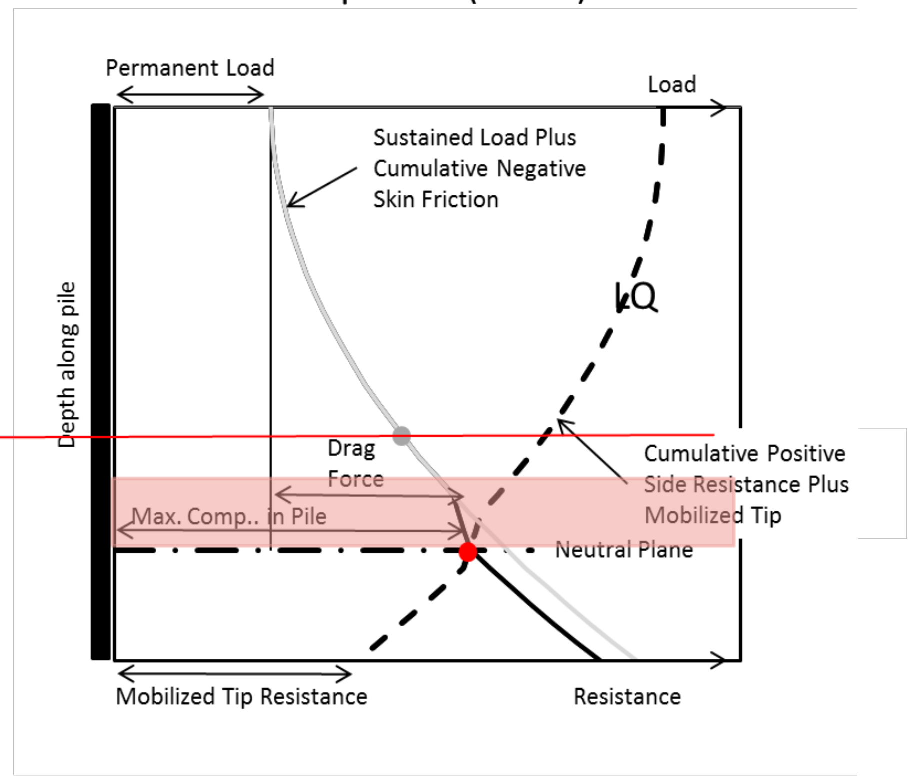
- Temporary reduction of geotechnical resistance

EXAMPLE 3

Non-liquefied

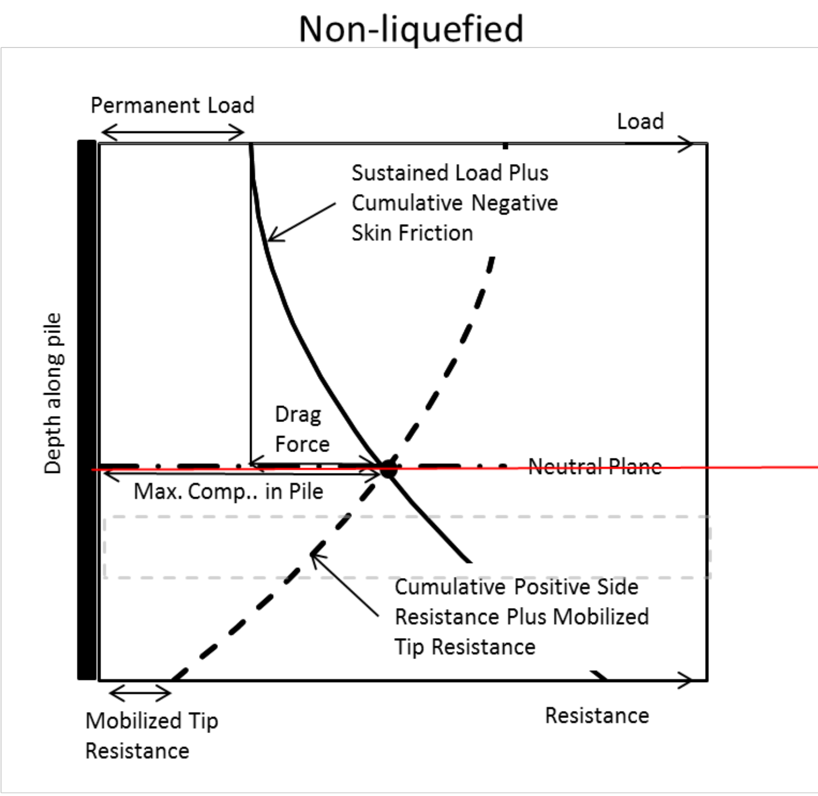


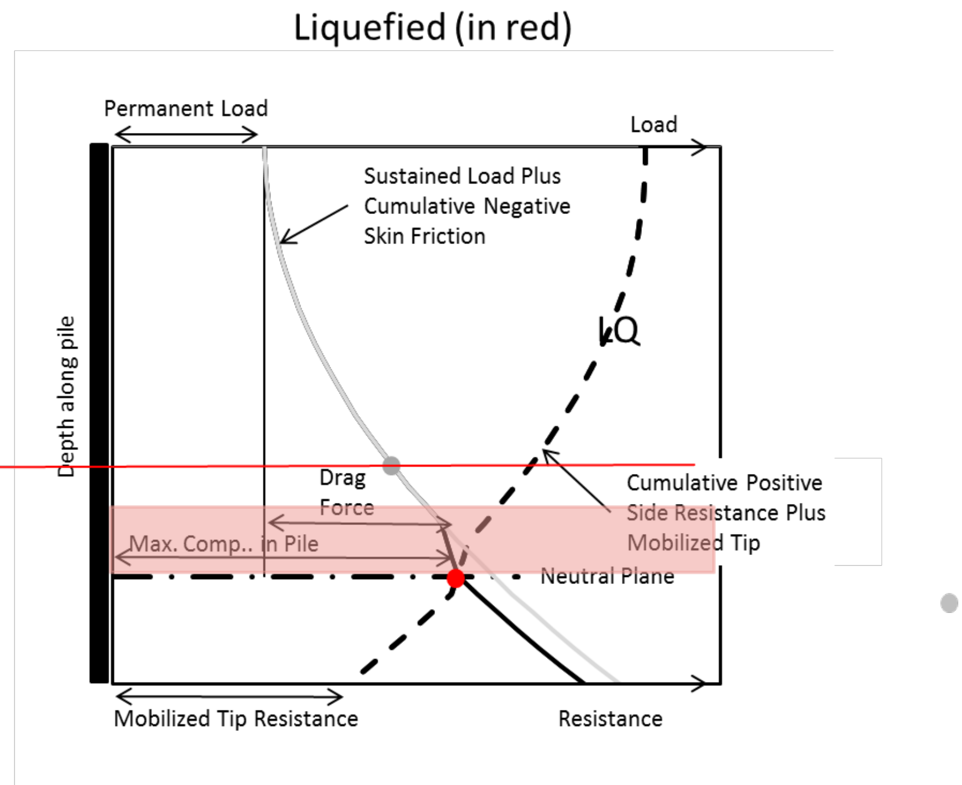
Liquefied (in red)



- Temporary reduction of geotechnical resistance
- Increase in drag force as soil above LQ moves downward relative to pile

EXAMPLE 3





- Temporary reduction of geotechnical resistance
- Increase in drag force as soil above LQ moves downward relative to pile
- Maximum compression of the pile increases

Review

REVIEW

- The “Neutral Plane Method” is accepted by AASHTO; however, the details of its implementation are unclear.

REVIEW

- The “Neutral Plane Method” is accepted by AASHTO; however, the details of its implementation are unclear.

- The neutral plane method provides a rational framework to consider negative skin friction, drag force, and downdrag (settlement).

REVIEW

- The “Neutral Plane Method” is accepted by AASHTO; however, the details of its implementation are unclear.
- The neutral plane method provides a rational framework to consider negative skin friction, drag force, and downdrag (settlement).
- Negative skin friction does not exist at the geotechnical strength limit state – so it is not realistic to add drag force when determining the required nominal geotechnical resistance.

REVIEW

- The “Neutral Plane Method” is accepted by AASHTO; however, the details of its implementation are unclear.

- The neutral plane method provides a rational framework to consider negative skin friction, drag force, and downdrag (settlement).

- Negative skin friction does not exist at the geotechnical strength limit state – so it is not realistic to add drag force when determining the required nominal geotechnical resistance.

- The location of the neutral plane may be the location of the maximum axial force and is appropriately used to check the nominal structural resistance of the deep foundation.

REVIEW

- The “Neutral Plane Method” is accepted by AASHTO; however, the details of its implementation are unclear.
- The neutral plane method provides a rational framework to consider negative skin friction, drag force, and downdrag (settlement).
- Negative skin friction does not exist at the geotechnical strength limit state – so it is not realistic to add drag force when determining the required nominal geotechnical resistance.
- The location of the neutral plane may be where the maximum axial force and is appropriately used to determine the required nominal structural resistance of the deep foundation.
- The location of the neutral plane is where the ground and pile move together – and so settlement of the ground at the neutral plane is equal to the settlement of the pile.

THANK YOU FOR YOUR ATTENTION

Today's Speakers

- Sharid Amiri, *California Department of Transportation,* sharid.amiri@dot.ca.gov
- Timothy Siegel, *Dan Brown and Associates,* tim@dba.world

Get Involved with TRB

- Getting involved is free!
- Join a Standing Committee (http://bit.ly/2jYRrF6)
- Become a Friend of a Committee (http://bit.ly/TRBcommittees)
  - Networking opportunities
  - May provide a path to become a Standing Committee member
- For more information: www.mytrb.org
  - Create your account
  - Update your profile

Receiving PDH credits

- Must register as an individual to receive credits (no group credits)
- Credits will be reported two to three business days after the webinar
- You will be able to retrieve your certificate from RCEP within one week of the webinar

TRB turns 100 on November 11, 2020

100 YEARS 2020

TRB

Help TRB:

- Promote the value of transportation research;
- Recognize, honor, and celebrate the TRB community; and
- Highlight 100 years of accomplishments.

Learn more at

www.TRB.org/Centennial

MOVING IDEAS: ADVANCING SOCIETY—100 YEARS OF TRANSPORTATION RESEARCH