Neutral Plane Method for Drag Force of Deep Foundations and the AASHTO LRFD Bridge Design Specifications

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ABSTRACT: The axial resistance provided by deep foundations may be divided into two components: side resistance and tip resistance. The direction that the side resistance acts depends on the relative movement between the deep foundation and the adjacent soil. That is, when the pile or drilled shaft moves downward relative to the soil, then the side resistance is positive and acts upward. Conversely, when the soil moves downward relative to the deep foundation the side resistance is negative and acts downward. Research supports that both positive side resistance and negative skin friction develop in essentially all deep foundations. The side resistance distribution is a function of the soil strength and stiffness, the applied top load, and whether the top load is sustained, transient, or a combination of sustained and transient loads. Consideration of drag force has become more convoluted with the implementation of geotechnical aspects into the *AASHTO LRFD Bridge Design Specifications* and its use of load and resistance factors. This paper briefly reviews the explicit approach for considering drag force in AASHTO LRFD Specifications, describes the neutral plane method for drag load of deep foundations within the framework of the AASHTO LRFD Specifications and presents two hypothetical examples that illustrate the neutral plane method.

1 BACKGROUND

1.1 *Introduction*

The axial resistance provided by deep foundations may be divided into two components: side resistance and tip resistance. The direction that the side resistance acts depends on the relative movement between the deep foundation and the adjacent soil. That is, when the pile or drilled shaft moves downward relative to the soil, then the side resistance is positive and acts upward. Conversely, when the soil moves downward relative to the foundation the side resistance is negative and acts downward. Research supports that both positive side resistance and negative skin friction develop in essentially all deep foundations. The side resistance distribution is a function of the soil strength and stiffness, the applied top load, and whether the top load is sustained, transient, or a combination of sustained and transient.

The cumulative negative skin friction is the drag force. The drag force is an internal force associated with the development of static equilibrium of the pile-soil system. The magnitude and location of the drag force are a function of the relative ground movement and the soil behavior, and its representation as an applied top load is an oversimplification that is best avoided. The consideration of drag force has become more convoluted with the implementation of geotechnical aspects into the load factor resistance design (LRFD) and its use of load and resistance factors. This paper briefly reviews the consideration of drag force in deep foundation design in the

AASHTO LRFD Specifications, describes the implementation of the neutral plane method within the framework of the AASHTO LRFD Specifications and presents two hypothetical examples that illustrate the neutral plane method.

1.2 *Review of Terms*

Negative skin friction – Side resistance mobilized above the neutral plane as the ground moves downward relative to the pile or drilled shaft.

Drag force – Internal axial compressive load in a pile or drilled shaft due to the accumulated negative skin friction. The use of "force" instead of "load" is intentional to make a distinction that the drag force should not be represented as an applied top load in design.

Neutral plane – Location along a pile or drilled shaft 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 negative skin friction) is equal to the combination of the upward (positive) side resistance and the mobilized tip resistance.

Residual force – Internal axial force within a pile or drilled shaft that is neither due to a top load or associated with resisting a top load.

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.

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

Transient loads – Per AASHTO, these are assumed to vary over a short time interval relative to the lifetime of the structure.

1.3 *Literature Review*

One of the first to publish on the subject of negative skin friction was Crawford (1969) who monitored a 305 mm diameter, 49 m long "floating" steel pipe pile. Without any top load, the distribution of internal compressive force developed with time as shown in Figure 1. The time dependence and the distribution of the internal compressive force distribution are characteristic of negative skin friction.

In the 1960's, Bjerrum et al. (1969) monitored the compression of steel piles driven to bedrock in Norway. The data presented in their paper illustrated that the full magnitude of negative skin friction developed at very small relative movements between pile and soil. A conclusion also made by Crawford. Bozozuk (1972) monitored a friction (or "floating") pile in clay in Quebec, Canada over a five-year period and also concluded that only small relative movements between pile and soil would fully mobilize the side resistance. Also, the magnitudes of the unit side resistances – positive and negative - were essentially equal.

Hanna and Tan (1973) performed scale model laboratory tests in sand that showed piles that are not stress- and strain-free even when under zero top load. Their hypothesis is that pile installation (either driven or cast-in-place) causes deformations in the adjacent soil, rotation of the planes of principle stresses, and differential volume changes that result in development of an internal compressive force distribution within the pile as shown in Figure 3. Figure 3 illustrates that the tip resistance is progressively mobilized as the pile displacement increases. Hanna and Tan also measured the relative displacement between the pile and soil which is illustrated in Figure 4. For the conditions in their study, full mobilization of the side resistance generally developed at relative displacements between ground and pile of 1 to 3 mm.

The research on negative skin friction performed in the 1960's and early 1970's, led to efforts to incorporate the results into deep foundation analysis and design. In particular, the design-related issues included: (1) what conditions are conducive to the development of negative skin friction on piles, (2) how is the magnitude of negative skin friction predicted, (3) what are the important design aspects, and (4) how can it be reduced.

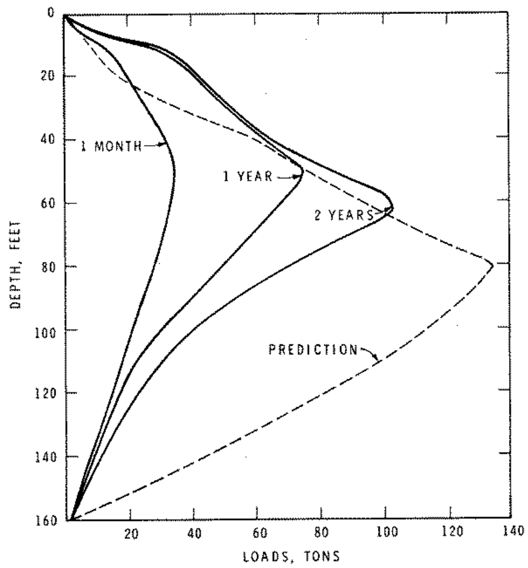

Figure 1. Compressive internal force distribution in 305mm dia. steel pipe pile (Crawford, 1969)

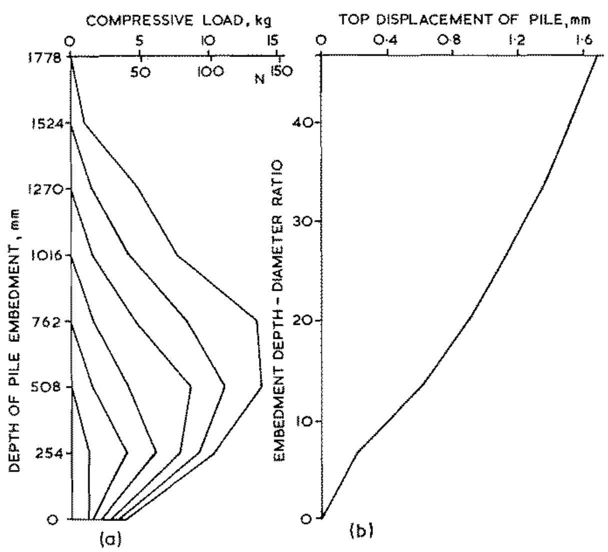

Figure 2. Compressive internal force distribution and pile top displacement during sand filling (Hanna and Tan, 1973)

The subject of negative skin friction is complex and it is expected that some of the early attempts to address the issues would prove insufficient. For example, some proposed that negative skin friction develops where large relative movements (e.g. 5 cm or more) occurred. In reality, the negative skin friction fully mobilizes at small relative movements (i.e., 1 and 3 mm). Others proposed that an effective approach was to attempt to prevent negative skin friction with a bituminous coating even though this also decreases the nominal geotechnical resistance.

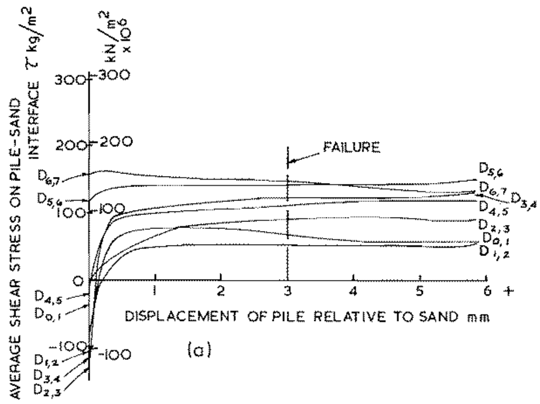

Figure 3. Development of shear stress along pile

In 1986 Fellenius published the neutral plane method (also known as the unified design approach) for pile design that provided a rational framework for the understanding of negative skin friction, its distribution along the pile, drag force, and how to consider it in pile design (1986; 1988). Fellenius and Siegel (2008) applied the neutral plane method to piles and drilled shafts in liquefied soil. The neutral plane method has been incorporated in the FHWA's Design and Construction of Driven Piles (Hannigan et al., 2006), the Canadian Foundation Engineering Manual (2006), the Australian Piling Standard (1995) and the Hong Kong Foundation Design and Construction Manual (2006). While the current *AASHTO LRFD Bridge Design Specifications* allow the application of the neutral plane method for the consideration of the drag force, it does not provide any instruction on how to do so. This paper briefly reviews the consideration of drag force in deep foundation design as explicitly described in the AASHTO LRFD Specifications, describes the implementation of the neutral plane method within the framework of the AASHTO LRFD Specifications and presents two hypothetical examples.

2 DRAG FORCE IN AASHTO

2.1 *Explicit Approach*

The explicit approach involves three steps: (1) the determination if drag force needs to be considered, (2) the estimation of the drag force, and (3) the inclusion of the drag force as a top load after applying the appropriate load factor.

The following criteria describe sites where drag force are required to be considered:

- Sites are underlain by compressible material such as clays, silts or organic soils;
- Fill will be or has recently been placed adjacent to the piles or shafts, such as is frequently the case in bridge approach fills;
- The groundwater is substantially lowered, and/or;
- Liquefaction of loose sand soil can occur.

For sites meeting any one of these criteria, then a settlement profile must be computed and soil that will experience a downward movement of 10 mm (0.4 in) relative to the pile is considered to cause negative skin friction. The negative skin friction is calculated based on conventional methods for estimating side resistance and the drag force is determined by multiplying the negative skin friction by the pile-soil contact area. The drag force is treated as a top load (designated DD for downdrag load). The downdrag load is included as a factored load in determining the required geotechnical resistance at the strength limit state. The nominal geotechnical resistance available to resist the structure load plus the downdrag load is estimated by considering only the positive side resistance and tip resistance below the lowest layer contributing to the downdrag. The explicit approach is conceptually illustrated in Figure 4 where a soil profile is shown on the left, a ground settlement profile is in the middle, and force conditions are shown on the right.

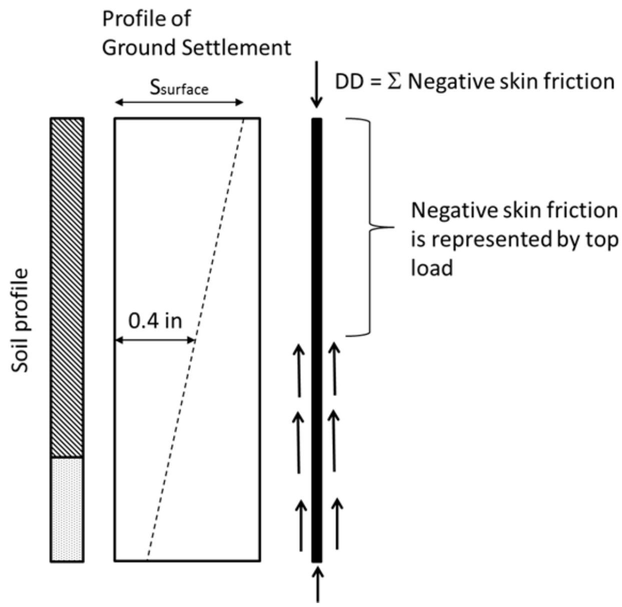

Figure 4. Conceptual illustration of the explicit approach currently included in AASHTO

2.2 *Neutral Plane Method*

For the neutral plane method, a plot is prepared that graphically shows two curves - one curve is the sustained top load ($Q_{sustained}$) combined with the negative skin friction – the other curve is the positive side resistance combined with the mobilized tip resistance (R_{tip}). A conceptual example of this plot is presented in Figure 5. The sustained load is the constant axial compressive load and therefore most closely associated with AASHTO's permanent load. Judgment is necessary to select the representative sustained load.

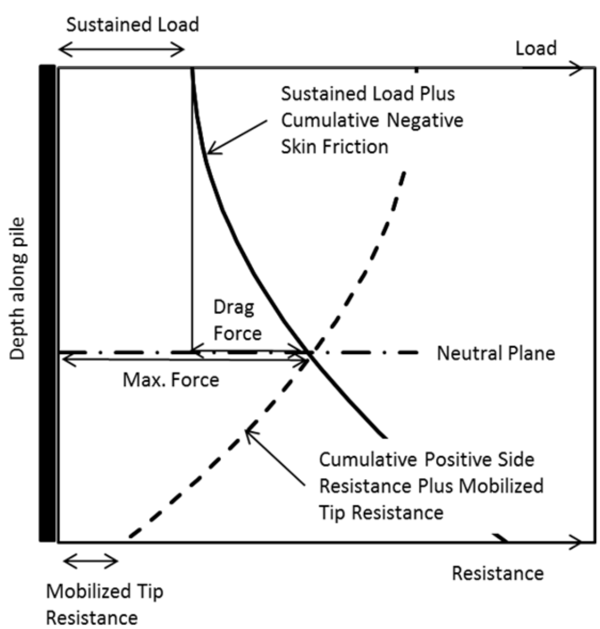

Figure 5. Neutral plane plot

The pile shown in Figure 5 is in static equilibrium where the sustained top load plus the cumulative negative skin friction is equal to the cumulative positive side resistance plus the mobilized tip resistance. The neutral plane is the location where the direction of the side resistance reverses from negative to positive. It is also the location of the maximum force in the pile and where there is no relative movement between the pile and surrounding soil. The loads and resistances should not be factored in preparing a neutral plane plot. The use of load and resistance factors will distort this plot and lead to erroneous results.

The negative skin friction is not part of the evaluation of the geotechnical strength limit state. At the geotechnical strength limit state, the entire pile is moving downward relative to the soil and therefore negative skin friction is not present. The nominal geotechnical resistance is the combination of the cumulative side resistance along the entire pile plus the end resistance.

The negative skin friction is indirectly part of the evaluation of the geotechnical service limit state. The neutral plane is a function of the negative skin friction. By definition, the ground settlement at the neutral plane is also the vertical movement of the pile. The total movement of the top of the pile is the vertical pile movement plus the elastic shortening that occurs in the section of pile above the neutral plane. For the equivalent raft approach (Peck et al., 1953; Meyerhoff, 1976) for determining the settlement of pile groups, the depth of the equivalent raft may conservatively located at the neutral plane. Figure 6 illustrates the relationship between ground settlement, pile movement and the neutral plane.

In most cases, a reasonable estimate of the neutral plane depth can be made using moderate mobilization of the tip resistance (e.g. 40 to 60% of the nominal tip resistance). A more sophisticated approach is to incorporate the pile tip stiffness. A generic (t-z) curve of tip penetration versus mobilized tip resistance is illustrated in Figure 7. An iterative process involves first constructing a neutral plane plot based on an assumed mobilized tip resistance and then determining its compatibility with the anticipated pile tip penetration using an appropriate t-z curve.

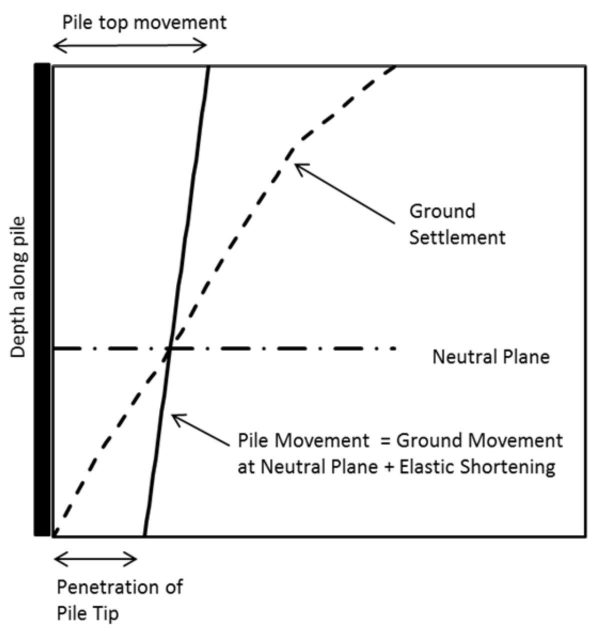

Figure 6. Ground settlement, pile movement, and neutral plane

The effect of the transient load on the forces in the pile will depend on its magnitude relative to the magnitude of the drag force. As illustrated in Figure 8, if the transient load is less than the drag force then the transient load essentially replaces part of the drag force temporarily. The transient load does not increase the maximum compressive force in the pile and the pile movement is only increased by the additional pile shortening where the axial stress is higher.

2.3 *Comparing the explicit approach and the neutral plane method*

A comparison of the explicit approach and the neutral plane method is summarized in Table 1. It may be debated whether negative skin friction develops in all piles and drilled shafts; however, the neutral plane method is relatively simple and is conservative if, in fact, negative skin friction does not develop. Perhaps the most important difference is that the neutral plane method excludes drag force at the geotechnical limit state. From a practical perspective, the neutral plane method is much less likely to result in a design controlled by the negative skin friction than the explicit approach.

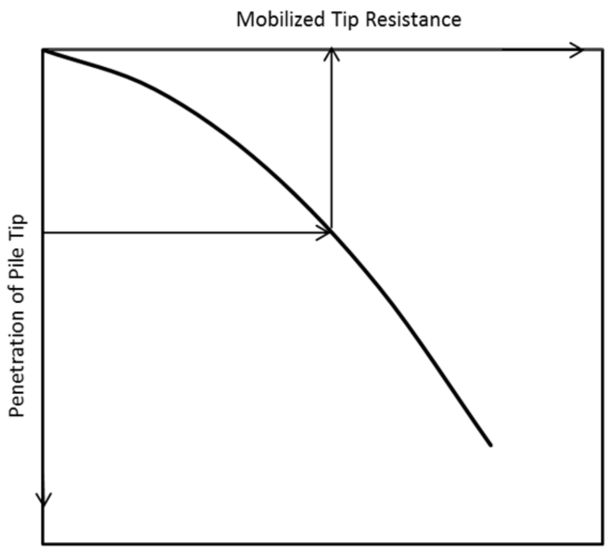

Figure 7. Pile tip penetration versus mobilized tip resistance

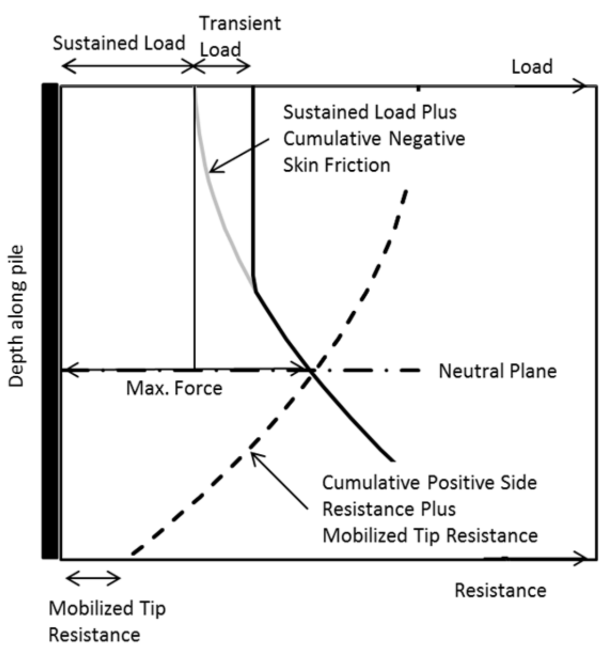

Figure 8. Neutral plane plot with transient load less than drag force

Table 1. Comparison of Explicit Approach and Neutral Plane Method

Explicit Approach	Neutral Plane (NP) Method
Applies to only certain pile/drilled shaft conditions	Applies to all piles/drilled shafts
Considers drag force as top load (downdrag load, DD)	Considers drag force as internal force
Includes DD at geotechnical strength limit state	Excludes drag force at geotechnical limit state
Includes DD for settlement	Excludes DD for settlement [settlement is f(NP)]
Includes DD at structural strength limit state	Includes DD at structural strength limit state

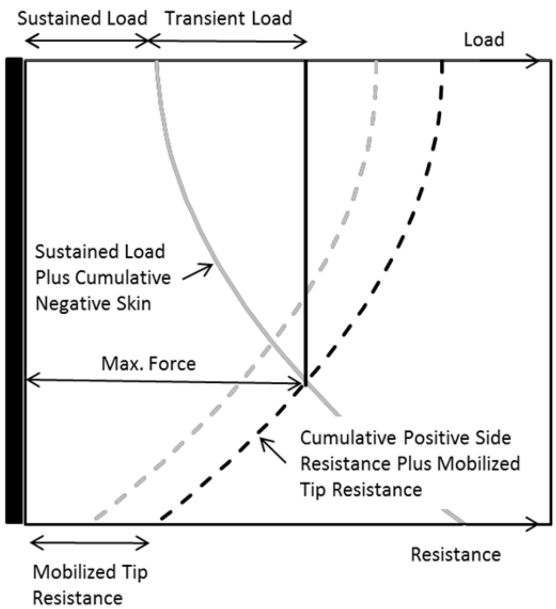

Figure 9. Neutral plane plot with transient load less than drag force

3 HYPOTHETICAL EXAMPLES USING THE NEUTRAL PLANE METHOD

3.1 *Piles through embankment supported in compressible soil*

A hypothetical example of piles through an embankment supported in compressible soil is shown in Figure 10. These piles are sleeved through the embankment fill as is common with bridge projects. As the embankment fill compresses the soil, negative skin friction, positive side resistance, and tip resistance are mobilized to achieve static equilibrium over time. The neutral plane plot, the ground settlement/pile movement plot, and a typical t-z curve are conceptually represented in figures 5, 6, and 7, respectively.

The downdrag load (DD) is set equal to the drag force determined from Figure 5 and adjusted by the appropriate load factor for the structural limit state analysis of the pile section. The top movement of the pile at the geotechnical service limit state is the vertical ground movement at the neutral plane plus the shortening of the pile between the top and the neutral plane. The downdrag load DD is not included as a top load for settlement analysis. And the negative skin friction is not involved in the geotechnical limit state analysis.

3.2 *Piles through embankment fill supported on incompressible material*

A hypothetic example of piles through an embankment supported on an incompressible material is shown in Figure 11. These piles are sleeved through the embankment fill. As the embankment fill compresses the soil, negative skin friction and tip resistance are mobilized to achieve static equilibrium over time. The neutral plane plot, ground settlement/pile movement plot are conceptually represented in figures 12 and 13. Because the pile tip is essentially fixed, the neutral plane develops at the top of the incompressible material and the entire thickness of overlying soil contributes to the negative skin friction. The downdrag load (DD) is set equal to the drag force determined in Figure 12 and adjusted by the appropriate load factor for the structural limit state analysis of the pile section. The top movement of the pile at the geotechnical service limit state is the shortening of the pile.

4 CONCLUDING REMARKS

The AASHTO LRFD Bridge Design Specifications present an explicit approach for considering negative skin friction but also allow the use of the neutral plane method. Research supports that the neutral plane method is more representative of the actual pile conditions. Experience has shown that the neutral plane method is less likely to result in a pile/drilled shaft design controlled by negative skin friction.

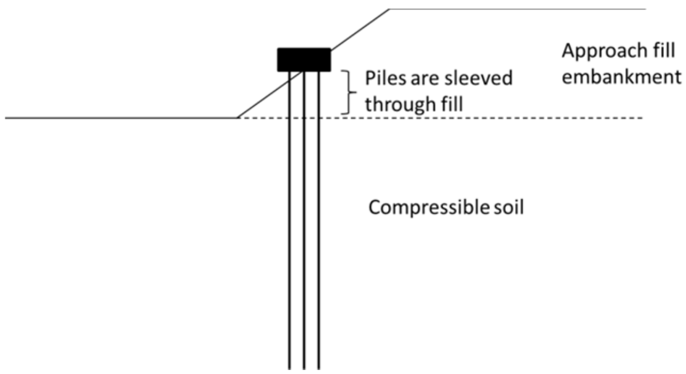

Figure 10. Piles through embankment fill supported in compressible soil

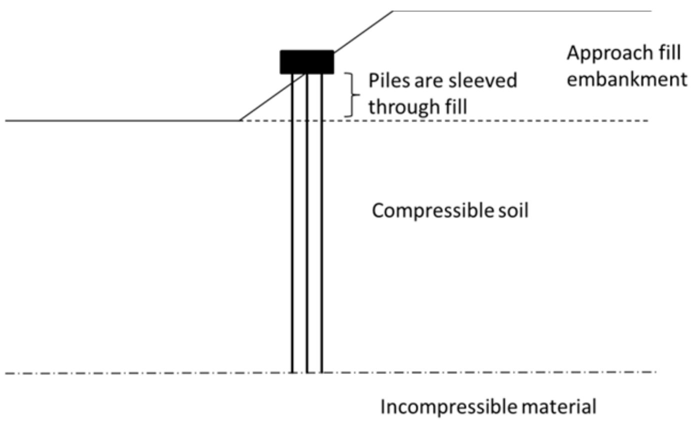

Figure 11. Piles through embankment fill supported on incompressible material

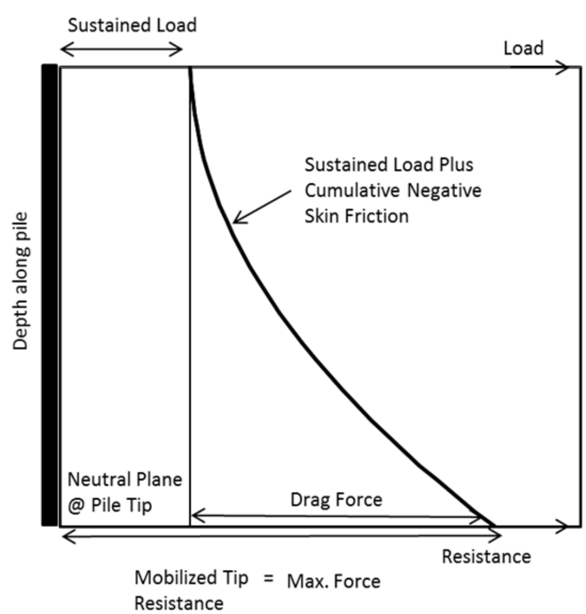

Figure 12. Neutral plane plot for example shown in Figure 11

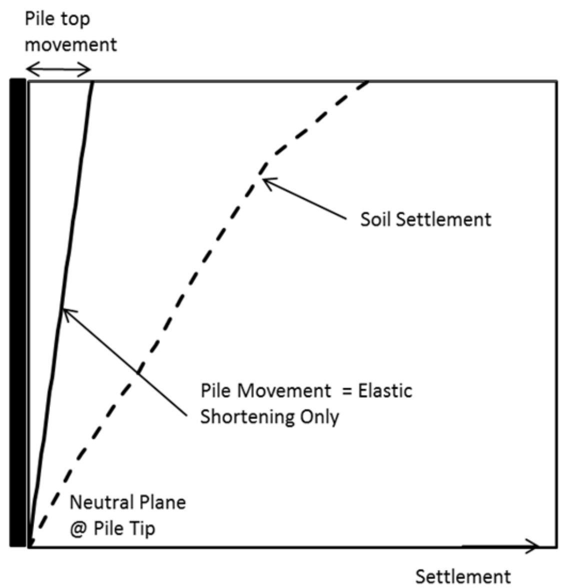

Figure 13. Ground settlement, pile movement, and neutral plane for example shown in Figure 11

Finally, it is recognized that the neutral plane method, as described herein, is a simplification to a complex pile-soil interaction. Residual forces may be present within piles as a result of driving and other factors that are not explicitly accounted for. It may also been argued that is more accurate to define the neutral plane where the pile velocity is equal to the soil velocity (Wang & Brandenberg, 2013).

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