Fellenius, B. H., 1997. Piles subjected to negative friction: a procedure for design. Discussion. Geotechnical Engineering, Vol. 28, No. 2, pp. 277 - 281.

Discussion

Bengt H. Fellenius, Ottawa, Canada

on "Piles subjected to negative friction: a procedure for design"
authored by H. G. Poulos
Published in Geotechnical Engineering,
Vol. 28, No. 1, pp. 23 - 44.

The author made reference to the discusser's 25 years old paper (Fellenius, 1972). The case history presented in that paper has value, still, but the also included recommendation for how to consider negative skin friction in pile foundation design is not correct, and the discusser has long since abandoned it. The old paper makes the mistake of separating the calculation of the settlement of the pile (pile group) from the transfer of the load applied to the pile head when determining the location of the neutral plane. The author's paper appears to have fallen into the same rut.

The location of the neutral plane is a function of equilibrium between the shear forces along the pile shaft. These can be considered fully mobilized. Also present is a more or less mobilized toe resistance. The forces and resistances are a consequence of soil settlement, small or large, and of the vast difference in stiffness between pile and soil. The absolute need for satisfying force equilibrium means that shear develops along the upper portion of the pile in the negative direction, hence "***negative*** skin friction", and along the lower portion in the positive direction. The location of the transition from negative to positive direction is termed "the neutral plane". Circumstances in the individual case can cause the neutral plane to be in the settling soil, or in the more competent "non-settling" or "much-less-settling" soil at depth. Change the load applied to the pile head and the location of the neutral plane will change as dictated by the resulting new equilibrium of forces.

The neutral plane is also where the pile and the soil move equally, or, phrased differently, where there is no relative movement between the pile and the soil. That is, the solution to the problem of pile group settlement lies with finding the magnitude of the soil settlement at the neutral plane, not with the negative skin friction per se. In addressing the phenomenon of piles that settle with the soil, the term to use is "downdrag", not "negative skin friction". Negative skin friction causes a dragload and regardless of the magnitude of the dragload, if the settlement at the neutral plane is small, there is no downdrag. (As the author indicates, the pile structural strength must be sufficient to resist the load applied to the pile head plus the dragload). To emphasize the point: the larger the **dragload**, the stiffer, stronger, and better the foundation, while, in contrast, the larger the **downdrag**, the worse the foundation. A pile that experiences no negative skin friction has a neutral plane at the ground surface and maximum downdrag—the foundation settles with the settling ground surface—usually a most undesirable situation.

Thus, the author's third conclusion, to be clear, should refer to "downdrag" and not to "negative skin friction".

The author proposes a partial-factor-of-safety method for the design, it appears, in reference to the determination of the location of the neutral plane. For considering the aspects of structural strength, a limit states method or partial factor method can be applied, of course, if one so prefers or is so forced by the governing code. However, for downdrag, which is a serviceability limit states, no factors shall be used, be they resistance factors, partial factors, or factors of safety.

When designing a pile group to counter settlement, the location of the neutral plane must be determined in an all-inclusive analysis: an analysis that incorporates:

- the load applied to the pile head
- all outside-the-pile-group aspects such as fills and groundwater table lowering
- the distribution of shaft resistance along the pile
- the load-movement characteristics of the pile toe.

The discusser has published detailed recommendations for the analysis of piles and pile groups considering capacity and settlement, and dragloads and downdrag (Fellenius, 1984; 1989; 1996, and Goudreault and Fellenius 1995). The principles are summarized in three diagrams shown in Fig. 16, illustrating the conditions for a pile in a homogeneous soil.

The first diagram of the three indicates the distribution of unit shaft resistance, r_s, and unit negative skin friction q_n. The diagram assumes, which is a reasonably correct assumption, that the magnitude of the unit shear force between the pile and the soil is the same in either negative or positive direction. The linearity is only for illustration and the distribution in an actual case would be according to the soil type(s) and prevailing effective stress. There is no need for assuming an average soil shear.

The middle diagram shows two curves. The right side curve is the distribution of ultimate resistances: ultimate toe resistance, R_t^{ult}, and total ultimate resistance, R^u (or, ultimate load, Q^u). In long-term service, the distribution of axial load in the pile follows the left side curve, starting from the dead load applied to the pile head and increasing with depth due to negative skin friction until the neutral plane, below which the load in the pile reduces due to positive shaft resistance and mobilized toe resistance, R_t. The neutral plane is the point of equilibrium between the downward and upward acting forces. Nearest the neutral plane, the transition between negative skin friction and positive shaft resistance occurs in a zone as indicated. The height of this zone is a function of the magnitude of relative movement between the pile and the soil, and of the soil type. The height in an actual case can range from a few though many pile diameters.

The last diagram shows the distribution of settlement. Above the neutral plane, the settlement is caused by stresses imposed on the soil from fills, groundwater table lowering, footing loads at the site, etc. (excavations will also affect the settlement distribution). No part of the pile load will be transferred to the soil above the neutral plane. Below the neutral plane, the pile load will start to go out into the soil introducing stress that causes additional soil settlement. However, within the pile embedment zone, the piles will have a soil reinforcing effect and settlement will be small. A simple approach to calculating the settlement is to assume an equivalent footing loaded with the total dead load on the pile group and to perform a conventional settlement analysis for this footing including in the analysis all outside factors also affecting the change of effective stress in the soil. A typical settlement distribution is indicated in the diagram. The settlement of the pile head is indicated by s_P and the settlement of the soil by s_S. The settlement of the soil just outside the edge of a pile group, $s_{S,\ edge}$, will be greater, as opposed to inside the pile group. This will have some effect on the magnitude of the load in the piles, but if the pile cap is stiff, all piles will have essentially the same depth to the neutral plane. (Depending on details such as the pile spacing and number of piles, the inside piles will have a transition zone of greater height as opposed to the outer piles ("edge" piles), which will result in a smaller dragload on the inside piles).

The location of the neutral plane is a result of interaction between the shear forces and the pile toe resistance. Both the negative skin friction and the positive shaft resistance can be considered to require only a negligible amount of movement to mobilize fully. However, this is not true for the toe resistance, which is a function of the net pile toe movement. The values are difficult to determine. In an actual design case, when determining the maximum load in the pile (dead load plus dragload) one should assume a fully mobilized toe resistance. When determining the settlement of the pile, one should assume a less than fully mobilized toe resistance, which results in a higher location of the neutral plane and a larger calculated settlement.

The analysis illustrated in the three diagrams, can be performed by "hand" using a conventional effective stress analysis in simple spreadsheet approach or by commercially available software, e.g., the UniPile program (Goudreault and Fellenius 1995)

Finally, in an actual design case, when the site and the pile conditions have been determined, the design proceeds in three steps:

1. The allowable load (dead load plus live load) is equal to the pile capacity, Q^u (ultimate resistance R^u) divided by the factor of safety.
2. The load — dead load plus dragload — at the neutral plane must be smaller than the axial structural strength of the pile divided by a factor of safety (or by similar approach to the allowable structural load)
3. The settlement calculated at the pile toe level or at the neutral plane must be smaller than the maximum tolerable value.

References (not in the author's list)

Fellenius, B. H., 1984. Negative skin friction and settlement of piles. Proceedings of the Second International Seminar, Pile Foundations, Nanyang Technological Institute, Singapore, 18 p.

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

Fellenius, B. H., 1996. Basics of foundation design and background to the UniSoft programs. BiTech Publishers, Vancouver, 140 p.

Goudreault and Fellenius, B. H., , P. A., 1995. Design of piles and pile groups considering capacity, settlement and negative skin friction. Background and User Manual to Unipile, Users Manual, Unisoft Ltd., www.UnisoftLtd.com, 64 p.

Reference (published after the Discussion was written)

Fellenius, B. H., 1998. Recent advances in the design of piles for axial loads, dragloads, downdrag, and settlement. Proceedings of a Seminar by American Society of Civil Engineers, ASCE, and Port of New York and New Jersey, April 1998, 19 p.

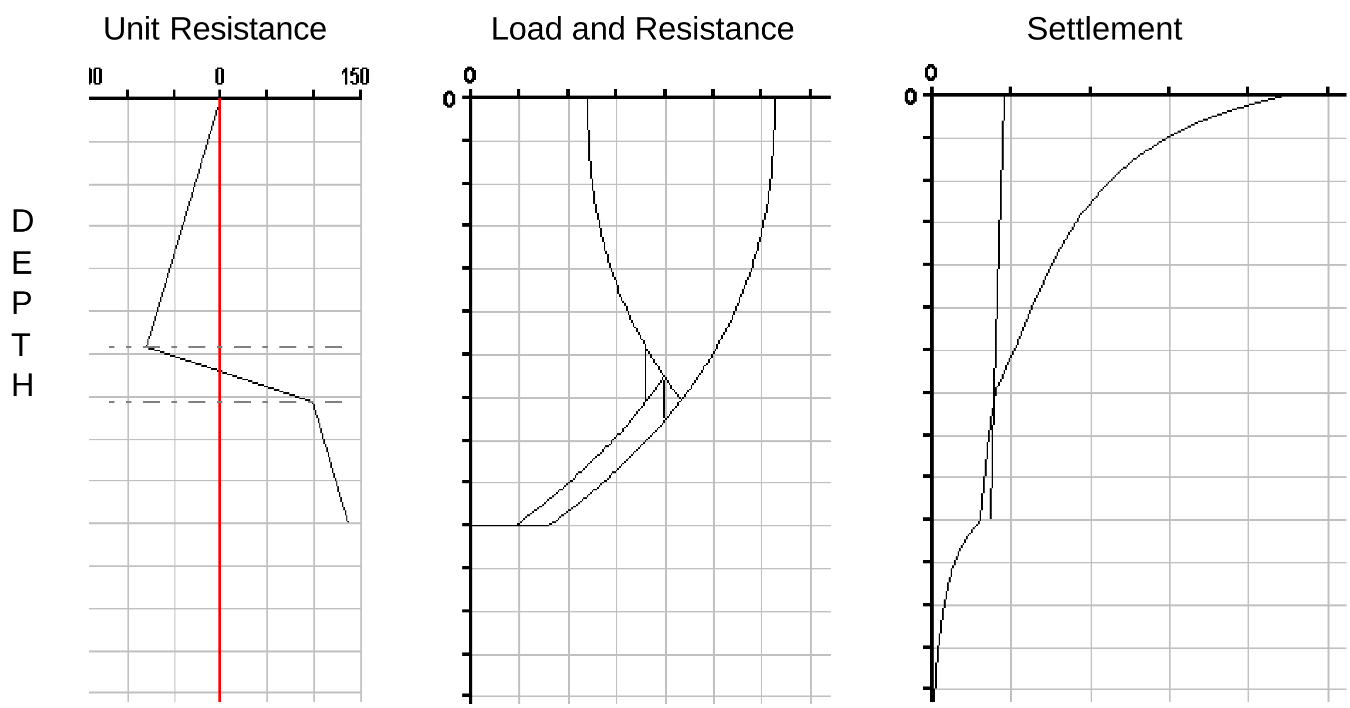

Fig. 16

Illustration of the analysis procedure
for a pile subjected to dragload and downdrag in a settling soil