Piled Foundation Design – Clarification of a Confusion

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A frequent confusion and lack of understanding exists with regard to the design of piles subjected to drag forces. Some will lump the drag force in with the dead and live loads when assessing pile bearing capacity. Also common is to disregard the root of the problem: settlement of the piled foundation. It must be realized that: dead and live loads applies to bearing capacity, dead load and drag force applies to structural strength, and downdrag is settlement.

A few weeks ago, I was once again asked if the allowable load for a pile should be reduced when considering drag force. Shortly thereafter, when I took a look at the discussions at www.Geoforum.com, I noticed a very similar question. Perhaps I should not be that taken aback by the lack of knowledge displayed by the questions. The persons asking may not have been taught better. The following is a quote from a textbook published in 2001 and assigned to 4th Year Civil Engineering students at several North American Universities:

Piles located in settling soil layers are subjected to negative skin friction called downdrag. The settlement of the soil layer causes the friction forces to act in the same direction as the loading on the pile. Rather than providing resistance, the negative skin friction imposes additional loads on the pile. The net effect is that the pile load capacity is reduced and pile settlement increases. The allowable load capacity is given as:

$$Q_{allow} = \frac{Q_{ult}}{F_S} - Q_{neg} \quad !$$

where

Q_{allow} = Allowable load capacity
Q_{ult} = Load capacity
F_s = Factor of safety
Q_{neg} = Drag force

First, "negative skin friction" is not "downdrag" but defines a downward directed shear force along the pile, while downdrag is the term for settlement of a pile (caused by the settling soil 'dragging a pile along'). Second, the term "load capacity" means different things to different people and "allowable load capacity" is an abominable concoction of words.

Third, and very important, the phrasing in the quoted paragraph confuses cause and effect. Drag force is not downdrag, and it does not cause settlement, but is caused by settlement of the surrounding soil and is mobilized when the pile resists this settlement. The worst boo-boo, however, lies in the quoted formula, which does not recognize that the factor of safety and the drag force are interconnected, i.e., changing the factor of safety changes the drag force. As this may not be immediately clear to all, the following example will try to clarify the interaction between the pile, the factor of safety, and the drag force.

Example

Consider the case of a 300 mm diameter pile installed to a depth 25 m through a surficial 2 m thick fill placed on a 20 m thick layer of soft clay deposited on a thick sand layer. The case is from a recent project in the real world. Let's assume that a static loading test has been performed and the evaluation of test data has established that the pile capacity is 1,400 KN. As is visually presented in Fig. 1, applying a factor of safety of 2.0 results in an allowable load of 700 KN (dead load 600 KN and live load 100 KN). Moreover, due to the fill and a lowering of the groundwater table, an almost 200 mm settlement of the ground surface will develop after the construction. How should the designer assess this case? Incidentally, as several full-scale case histories have shown, whether or not the soil at the site settles 200 mm or 2 mm, or for that matter 2,000 mm, the magnitude of the drag force will stay the same.

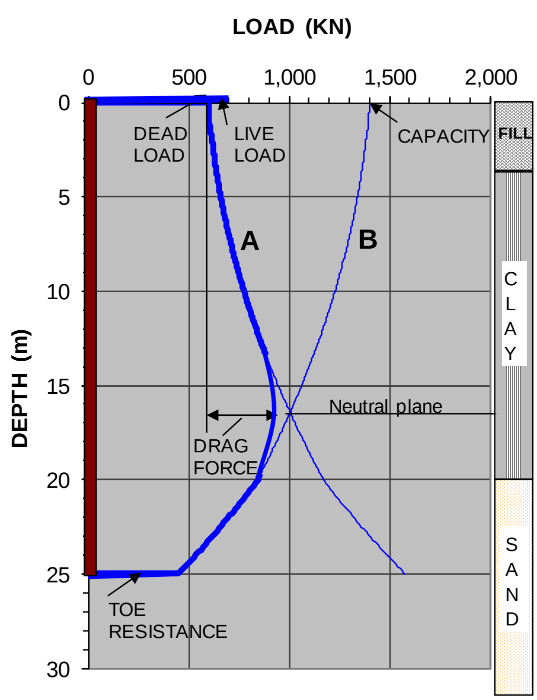

Fig. 1 Distribution of load in the pile.

*"**A**" is the long-term load-distribution and "**B**" is the resistance distribution measured at ultimate resistance (capacity) in a static loading test*

Comments and questions

Some practitioners believe that all is well because the foundations include piles with a capacity of twice the desired allowable load. Then, there are those who understand that, for the numbers indicated above, the pile will be affected by a drag force of about 300 KN, acting at a neutral plane located at 17 m depth (Fig. 1). A few of these practitioners will subtract the drag force from the pile capacity before applying the factor of safety and arrive at an amended allowable load of 550 KN (which is a violation of principles as this approach in effect has reduced the drag force by a factor of 2.0). Others will apply the quoted formula, and arrive at an allowable load of 400 KN. Yet others will realize that the latter approach means that the drag force is applied without a factor of safety, preferring to apply the formula with the drag force increased by a factor of safety, say 2.0. This results in an allowable load of (1,400/2 - 2x300) = 100 KN — don't laugh, I have seen it done several times and it was proposed for this project! So, which allowable load is right? Is it 100 KN, 400 KN, 550 KN, or 700 KN? (Similar diverging approaches abound in the load-and-resistance-factor-design, LRFD).

Suppose the structure supported on the piled foundation was built before the drag force conditions were recognized (no signs of distress are noticeable). Then, what factor of safety would a back-analysis show the piles to have? Would it be 1,400/700 = 2.0, or (1,400 - 300)/700 = 1.6, or 1,400/(700+300) = 1.4? And, I wonder how the fellows advocating the laughable approach would react when realizing that the piles are supporting seven times more load than the maximum load their approach would allow as safe.

Before answering, consider that the magnitude of the drag force depends on the magnitude of the dead load on the piles. Reduce the dead load and the drag force increases, and vice versa. For example, after reducing the allowable load by 150 KN to arrive at a 550 KN value (made up of a dead load of, say, 475 KN and a live load of 75 KN), the drag force is no longer 300 KN, it is 400 KN! If the allowable load is reduced by an additional 150 KN, say to 400 KN (made up of a dead load of, say, 325 KN and a live load of 75 KN), the drag force increases 500 KN!

Note, for the three values of dead load — 600 KN, 475 KN, and 325 KN — the neutral plane location changes from depths of 17.0 m to 18.0 m to 19.5 m, respectively. To simplify the example, no change of the toe resistance is included. In reality, however, the deeper down the neutral plane lies, the smaller the enforced penetration of the pile toe into the sand and the smaller the mobilized toe resistance, and when the toe resistance is reduced, the location of the neutral planes moves upward and the drag force changes. Altogether, the load at the neutral plane, that is, the maximum load in the pile, is essentially unchanged for the three alternative values of allowable load. In stark and important contrast, for each reduction of allowable load, the project foundation costs increase.

Clarification

Bewildering, ain't it? Many select one of the four approaches as the one that to be correct, ignoring the others thus avoiding having to make the small leap of understanding of what a proper design needs to include, as follows:**:**

First, the drag force does not affect the pile bearing capacity — the ultimate resistance. That is, the pile capacity is the same whatever the magnitude of the load from the structure. The factor of safety is applied to ensure that, should the load on the pile be inadvertently larger than intended and should the pile capacity be inadvertently smaller than thought, the pile might be close to failure, but it would not fail. No negative skin friction—no drag force—is present close to failure. Therefore, only the first approach, that with the 700 KN allowable load, is correct.

Second, the drag force has to be considered, of course, but not in the context of bearing capacity. The concern for the drag force only affects the pile structural strength at the location of the maximum load, i.e., at the neutral plane. For the example case, if the structural integrity of the pile is safe considering the sum of dead load and drag force, that is, 900 KN for the example case, the design for drag force is complete.

Third, with (A) the dead load plus live load safe considering the pile capacity, and (B) the dead load plus drag force safe considering pile structural strength, it remains to show that (C) the pile will not settle more than acceptable, that is, that downdrag is kept in check.

In checking the pile for downdrag, it must be realized that there are two different definitions of the neutral plane. Both give the same result, or location, rather. One defines the neutral plane as located at the force equilibrium in the pile, which is where the shaft resistance changes from negative to positive direction and where the sum of the dead load plus drag force is in equilibrium with the positive forces in the pile. The second defines the location to be where the pile and the soil move equally. (Note, the toe resistance is only as large as is needed to establish the equilibrium between forces and movements. Moreover, whatever the factor of safety chosen in the design, if the soil is settling at the neutral plane, the pile will settle too and as much as the soil settles at that location). The influence of varying dead load and toe resistance is illustrated in Fig. 2. The diagram to the left shows the load distributions and locations of the neutral plane for the dead loads associated with the mentioned different allowable loads on the pile (the 100 KN case is excluded). The diagram to the right shows the distribution of soil settlement and location of neutral planes for the three approaches. (More explanation and discussion is available in Fellenius, 2004).

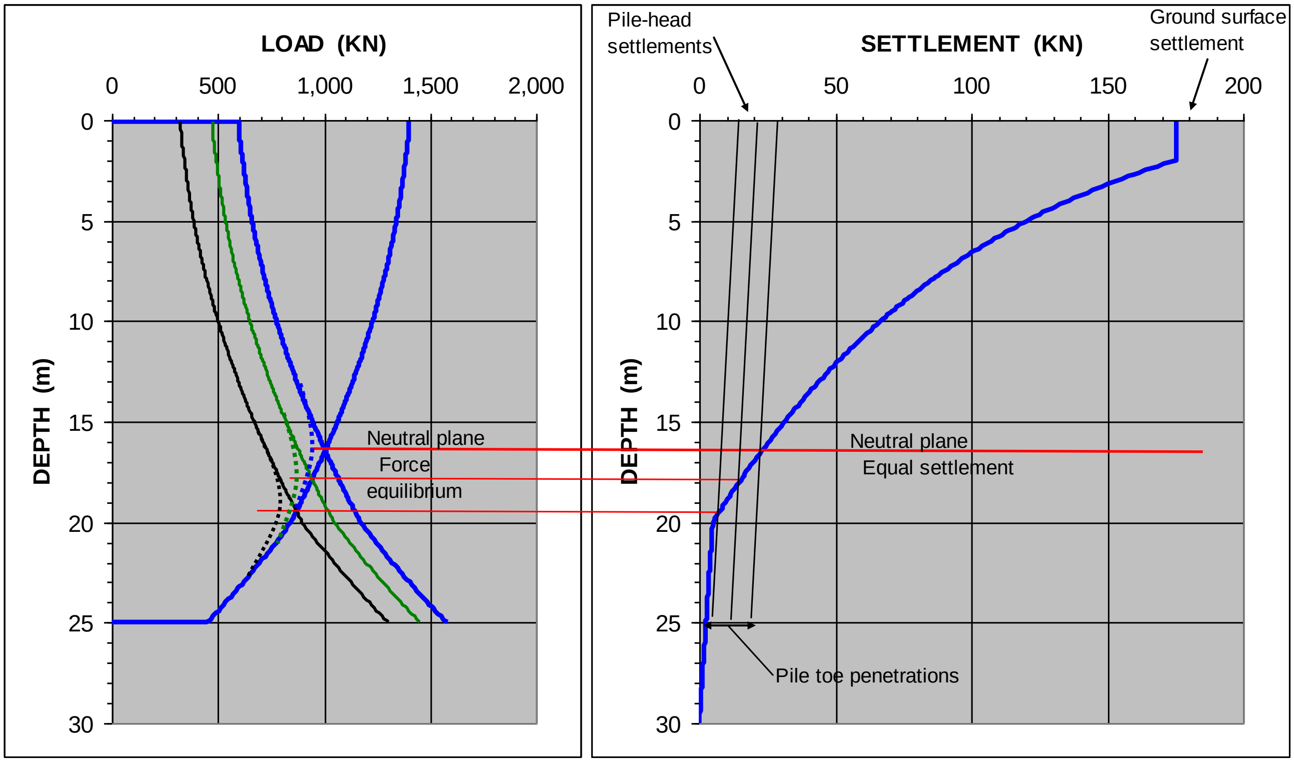

Fig. 2 Distribution of load in the pile and interaction with soil settlement. The dashed curves represent the gradual change in a transition zone from negative direction of shaft shear to positive direction.

The biggest problem

The foregoing appears to be news to many. It shouldn't. The long-term response of piles in settling soil was made known in several very accessible publications as early as some 40 years ago. How does one get the textbook writers and the teachers of foundation design to become aware of the knowledge and convey it in the teaching of future practitioners? How does one get practitioners to fill the voids in their professional education and to keep abreast with advances in the profession? The latter, unfortunately, may be the biggest problem of all, but discussing it lies outside this contribution.

References

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