Honors Capstone Report

Investigating the Behavior of Pile Foundations Experiencing Downdrag

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1. ABSTRACT

In foundation piles, the friction between the soil and the pile in most cases resists the downward weight of the building until equilibrium is achieved. However, in many cases a surcharge load is placed under the structure after initial loading, causing the soil to compress and cause a downward force on the pile which causes further settling of the structure. In this project, the behavior of friction forces under reversal of direction was studied in a laboratory environment for many different materials. An existing hyperbolic model was modified to fit the data, and a linear relationship was found between the roughness of a material and the behavior of the friction force development.

2. INTRODUCTION

When constructing a structure, foundation piles are used to support the weight of the building and eliminate the risk of settlement. The resisting force is supplied by both the force of the soil on the end of the pile (known as toe resistance), as well as the friction between the pile and the surrounding soil along the length of the pile. The pile will sink into the soil until these resisting forces equal the weight of the structure.

Often, the settlement of the structure will leave an undesirable gap between the structure and the soil. To remedy this, the gap will be filled with a material such as sand. This is known as a surcharge load, and will apply a load on the soil surrounding the pile. The resulting compression in the soil will cause a reversal of displacement of the soil relative to the pile, and the skin friction will begin to pull the pile further down rather than support it as intended. This is a very dangerous behavior as it can cause additional settlement in the pile, but can also cause compressive failure in the pile when the downward skin friction is opposed by the upward toe resistance. As a whole this phenomenon is referred to as downdrag.

This behavior develops at a very low rate of displacement, so a good understanding of the behavior of the skin friction during downdrag is crucial to being able to accurately predict the forces and settlement that occur as a result of downdrag. The mobilization of skin friction during regular loading has been shown to follow a hyperbolic model with parameters governing the shape of the curve and the final asymptote. This hyperbolic model can be algebraically rearranged in order to describe the reverse friction in the case of downdrag. The original and modified formulae are shown in Figure 1 below.

$$f(x) = (k - y_0)\frac{x - x_0}{M_s B + (x - x_0)} + y_0 \qquad f_2(x) = (k_2 - y_1)\frac{(x - x_1)}{M_{s2} B + (x - x_1)} + y_1$$

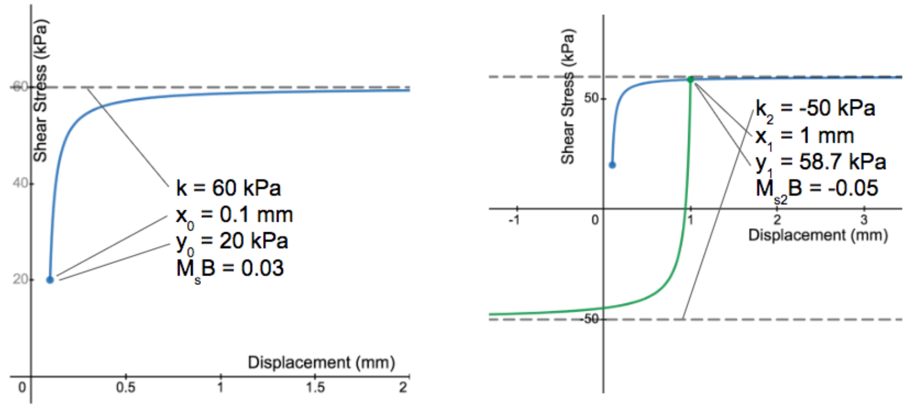

Figure 1: Original and Modified Hyperbolic Formulae

This model predicts the mobilized friction force as a function of the pile displacement. As the pile is loaded initially, the displacement is downward, and the friction begins to be mobilized upward against the load on the pile. During downdrag, the displacement of the pile relative to the soil is upwards, mobilizing a downwards force on the pile. For the rest of the paper, downwards displacement and upwards friction forces will be referred to as positive, while upward displacement and downwards friction force will be referred to as negative.

In order to make useful conclusions about the behavior of actual piles during downdrag, the findings must be generalizable for both many different pile materials, as well as different lateral soil pressure. To simplify data collection, a laboratory test was devised to measure the relationship between skin friction and displacement for many different materials. The hypothesis is that the behavior under downdrag will follow a similar hyperbolic curve to the behavior under positive displacement.

3. METHODS

A Geocomp ShearTrac machine was used to measure the skin friction behavior. Small pucks (shown in Figure 2 below) were made out of 7 different possible pile materials to precisely fit into the shear machine. These materials were smooth and rough concrete, smooth and rough steel, and wood parallel to, against, and normal to the grain. All soil used in testing was #25-30 2NS obtained from a sieving machine.

Figure 2: Different Pile Materials

The soil was placed on one side of the apparatus, and the puck of material was placed on the other side. The machine applied a normal force of 100 kPa to the system to simulate lateral soil pressure. The puck was dragged across the soil at a constant speed of 1 mm/min until it reached absolute displacement of 2 mm. Then, the puck was dragged in the reverse direction until it reached an absolute displacement of -2mm. This cycle was repeated 3 times, and the shear stress was recorded by the machine every 0.01 mm.

One test was also run on with #25-30 2NS instead of a puck so the material behavior could be compared with soil shear stress behavior.

Once the data was collected for each material, MATLAB was used to fit the hyperbolic model to the observed behavior. Two fitting algorithms were used; the Single Parameter model solved for the final asymptote based on an average of the data and solved for the shape parameter using curve fitting, while the Double Parameter model solved for both parameters using curve fitting.

4. RESULTS

4.1 Single vs Double Parameter Model

Pictured in Figures 3 and 4 are the Single and Double Parameter Model results for rough steel.

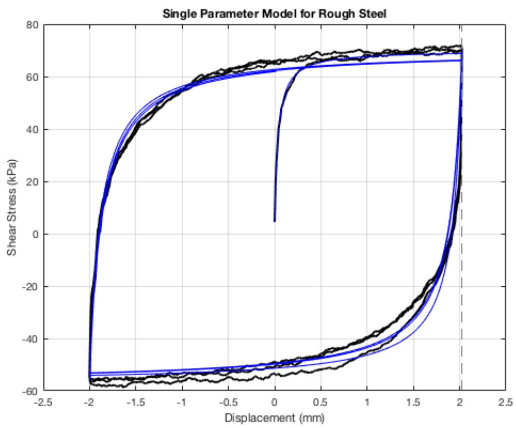

Figure 3: Single Parameter Model

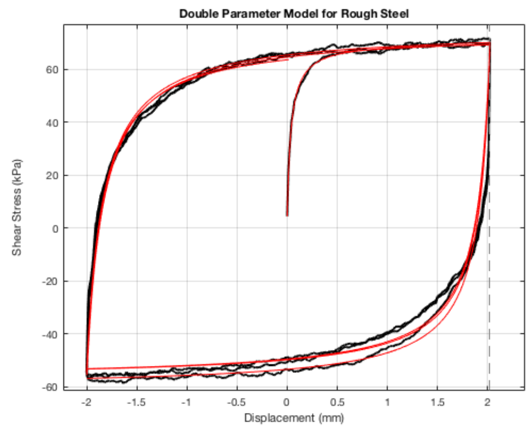

Figure 4: Double Parameter Model

In general, both models fit the curve very well. While the Single Parameter model tended to underestimate asymptotes, the difference between the solved parameters is negligible for the purposes of this research. Due to this, for the rest of the paper only the Double Parameter model will be used as it is generally slightly more accurate and less prone to error.

4.2 Variation of Parameters

The shape parameters (MsB) for each material are summarized in Figure 5 below. For each material, the first bar is the first machine cycle, and so on. Blue bars represent forward cycles while green bars represent reverse cycles.

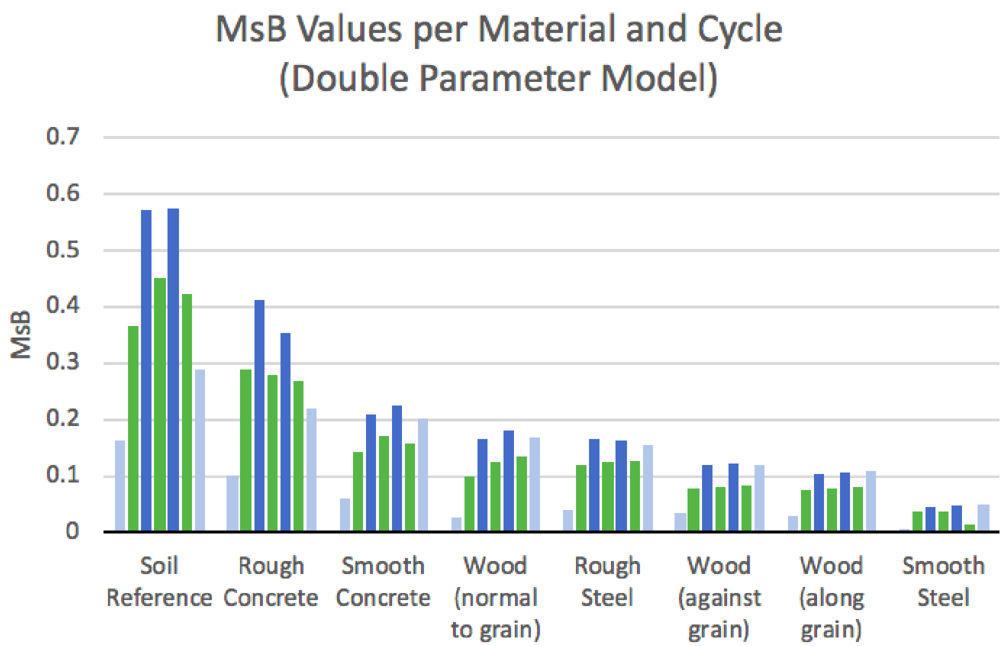

Figure 5: MsB Values Per Material and Cycle

A higher MsB value indicates that the mobilization of friction happens gradually, while a low MsB value indicates that the friction is mobilized very quickly. This graph shows that at first glance rougher materials such as rough concrete mobilize friction much more gradually than smooth materials like smooth steel.

Another thing that the graphs make clear is the difference between the forward and reverse cycles, as well as the observation that the first and last cycles are often much less than cycles 2-6. This discrepancy was also seen in the asymptote parameter.

5. DISCUSSION

5.1 Difference between Forward and Reverse Cycles

As seen in Figure #, there is a noticeable difference between the forward and reverse cycles, as well as the first and last cycles. The first and last cycles make sense, since the cycles only run 2mm during the first and last cycles as opposed to the 4mm displacement of the rest of the cycles. This means that the discrepancy is likely algebraic, and could reasonably be corrected.

The difference in the asymptote parameter is likely due to machine error, as there is no theoretical reason that the forward and reverse cycles should exhibit different maximum shear stress. The cause could be a screw that is overtightened and causes constant stress in one direction. This is not a huge issue for this project, as a constant offset will not affect the ability of MATLAB to correctly determine a shape parameter.

The difference between the shape parameter is more complex, as it is not affected by the difference in the asymptote parameter. Theoretically, this could be due to the soil holding a resistive pattern based on the direction of the first displacement, but tests in the reverse direction disprove this possibility. Currently the issue is dealt with by taking the average MsB value from all of the cycles, but this is a problem for future research

4.1 Difference in Shape Due to Roughness

As observed qualitatively in Figure 5, the MsB value decreases as roughness decreases. To express this quantitatively, the maximum shear stress can be used as a value to represent the roughness of the material. Figure 6 shows the relationship between maximum shear stress and average MsB.

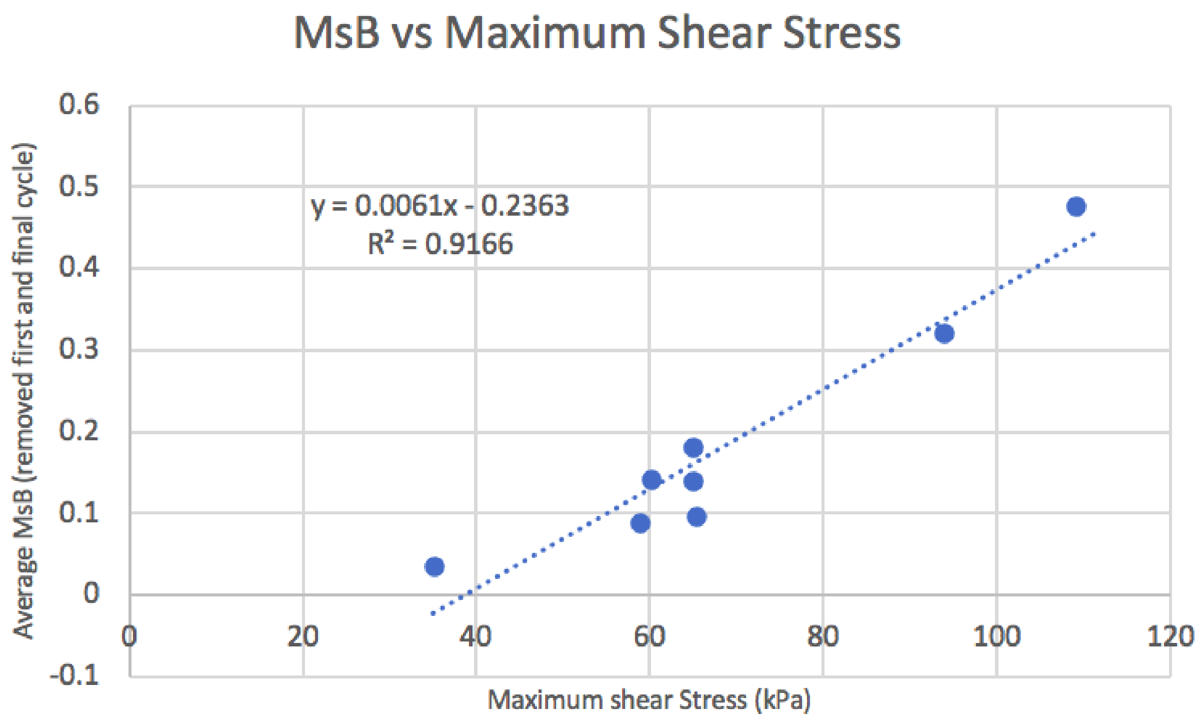

Figure 6: Relationship Between MsB and Maximum Shear Stress

As shown, there is a linear relationship between the maximum shear stress and the MsB value. If the MsB value could be written in terms of the maximum shear stress, that means that the entire friction development behavior could be determined by the maximum shear stress, which is easily determined for any material, and easily tabulated.

To make this relationship more rigorous, additional testing would need to be done under different normal stresses to understand how the relationship is affected by different soil conditions.

CONCLUSION

The main finding of this report is that the behavior of pile skin friction under both forward and reverse motion can be described solely by the maximum shear stress of a material. However, there is much more testing that can be done to improve the validity and generalizability of the model.

Firstly, more testing needs to be done under different soil conditions. The tests run in this project were all conducted under 100 kPa normal stress and were all tested against #25-30 2NS. Observing the relationship between maximum shear stress and MsB for different normal stresses and soil sizes will determine how applicable the model is for actual construction.

Secondly, there are numerous issues with the testing itself that need to be addressed before continuation. Most importantly, the discrepancies between forward and reverse cycles should be fixed or explained theoretically. This will have the added benefit of constructing a more accurate relationship and improving the precision of the model.

Finally, once these are addressed, then larger scale tests would be done. One large assumption with this laboratory testing is that the pucks of material are more generalizable to full scale piles. In reality, full scale piles are purposefully much rougher, and additionally are often coated to improve performance. Large scale tests would validate the model and provide more trustworthy values for construction purposes.