# ***Pile-Soil Interaction Determined by Laterally Loaded Pile Groups***

By: Robbie Barton

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Advisor; Dr. Kevin Truman

It was once said that it is wise to build your house on a rock. However, what if the closest rock that is big enough is 30 feet under the soil? What happens when a structure much larger than a house needs to be built? It was these questions that guided engineers towards the concept of pile design. Piles are long, firm, column-like members that are embedded in the soil to provide axial as well as lateral support of structures such as buildings, piers, locks, and bridges. Often, piles are installed near each other to create groups to optimize the support of the structure. Both a single pile and groups of piles rely significantly upon the conditions of the surrounding soil. This study aims to take a closer look at the interaction of piles and soil to determine the optimal pile group design.

Piles are often the first members of a structure to be installed. They are also some of the most expensive members. Each pile can average a cost of $5000. Therefore, it is very important to analyze pile groups and discover the optimal and thus most economic group design. For example, currently the United States Army Corps of Engineers (U.S.A.C.E.) is constructing a lock and dam structure in Olmsted, Illinois. This billion-dollar project will replace two other locks along the Ohio River. To begin the project, 8,450 sheet piles were installed in the river to create a cofferdam so that dry construction could begin. Also, 11,000 steel 'H' piles were embedded 40 feet below the Ohio Riverbank to support this massive structure. This creates an approximate cost of $42,250,000 for the cofferdam and 55 million dollars for the lock piles for a total of almost 100 million dollars! If an efficient pile group design can eliminate only 200 piles, it could save one million dollars. This is why it is so important to understand pile group behavior, and how piles interact with the soil. This understanding can begin with a study of pile properties and how they are installed.

There are many materials that are used to create piles for different structures. For example, timber piles will typically support a pier in the ocean, but Olmsted Lock and Dam was built upon steel piles. In fact, there are also many different combinations of materials used for pile formation. Among these variations are concrete piles with steel reinforcement bars, concrete filled steel pipes with open or closed ends, and even plastic piles with fiberglass reinforcement bars. The three most common materials used for piles are timber, steel, and concrete. Each of these materials can also be fashioned into different shapes. Concrete piles are typically square, octagonal, or circular, and are characterized by a high load-carrying capacity, durability, and high column strength (U.S.A.C.E., K-83-1, 1983 A10). Timber piles are typically Douglas Fir, Southern Yellow Pine, Red Pine, or Oak, that are circular and tapered from one end to the other, and known best for their resilience and ease in replacement (K-83-1, 1983, A1). Finally, steel piles can be ‘H’ shaped, pipes, or countless other shapes, and are best known for carrying moderate to heavy loads, easier installation, and longer in length (K-83-1, 1983, A6). To determine which material and shape to use relies upon what type of structure is being constructed for load capacity, performance, cost, and the type of soil (U.S.A.C.E., EM 1110-2-2906, 1991, 2-6). For example, heavier structures such as skyscrapers or large apartment buildings could not use timber piles because they would not be able to support the axial load. However, steel piles would not typically be used for piers because they rust, corrode, and are economically inefficient for such a small structure. The soil characteristics also determine the pile type because of installation requirements.

Pile installation, more commonly known as pile driving, is a difficult and precise process that must be performed with utmost care so as not to damage the pile or the soil properties (EM 1110-2-2906, 1991, 5-2). Piles are typically installed by a driving force, such as a dropping hammer, to vertically power them through the soil to a specified depth and position. Driving utilizes many methods to penetrate the soil to achieve this desired position. Hammer driving will use impact hammers powered by gravity, steam, air, or diesel power to use kinetic energy to force the piles below the surface. Also electrically or hydraulically powered vibratory hammers will shake the pile at a certain frequency during impact hammering (EM 1110-2-2906, 1991, 5-6). Unfortunately, vibratory pile driving had the capability of affecting nearby structures. By driving the piles forcefully underground, the soil is changed form its original consistency. The driving process remolds the soil and will change the properties according to the type of soil being penetrated.

Cohesive soil, unsaturated or saturated clay, becomes more compressed around the area of the driven pile. This typically occurs within one pile diameter about the pile (USACE, EM 1110-1-1905, 1992, 5-45). In saturated clays, this compression increases pore water pressures, and this can lead to a temporary reduction in the soil's shear strength that also decreases the pile load capacity. However, after some time the pore pressures will lessen, and thus lead to an increase in shear strength and load capacity. This changing in pore pressures and load capacities is known as soil freeze (EM 1110-1-1905, 1992, 5-46). Unsaturated soils do not exhibit soil freeze due to driving. On the other hand, driving into cohesionless soil causes the relative density of soil to change. The driving process can increase the relative density and lateral displacement of the soil up to two pile diameters in length around the driven pile. Certain types of piles create greater soil displacements. For example, closed end steel pipe piles will create greater soil displacements than steel ‘H’ piles (EM 1110-1-1905, 1992, 5-46). Other types of soils such as dense sand and gravel, or silts can also affect the pore pressures. In fact, soil relaxation is a process caused by driving piles into dense sand or gravel which creates a temporary decrease in pore pressures and increased pile load capacity, but will eventually increase the pore pressures and decrease the load capacity. Cohesionless silts also produce a soil freeze effect, but can often do this much faster than saturated cohesive soils (EM 1110-2-1905, 1992, 5-46). Because there are many types of soils that exist in many different geographical regions, on-site pile testing is very common. Typically a few piles are driven into the soil at or near the construction site to determine the exact pile-soil interactions. However, this can be an extremely costly and time-consuming procedure. A more efficient manner of testing piles is through computer simulations using local soil conditions and pile types.

Although pile-testing programs already exist, I created a program using ABAQUS to test pile group behavior for Saint Louis soil conditions. I began by creating a single, two-dimensional pile in a surrounding soil mesh. I decided to use a square 2’ x 2’ concrete pile that is surrounded on all sides by three feet of soil. I then applied a 10 kip lateral load to one side of the pile to obtain the deformed mesh (Figure 1). Once I had achieved this mesh, I created a two-dimensional, three-pile line group with each pile four feet away from the next. Once again, I applied a 10 kip lateral force to each pile to obtain the deformed mesh (Figure 2). From this deformed mesh, I discovered that the two outer piles had moved slightly away from the middle pile so that the distance was greater than four feet away. The soil had reached the maximum point of consolidation and was now moving the piles away from each other. Now, I had to model these piles threedimensionally to get a real picture of what was happening. Once again, I started by creating a single pile in surrounding soil. I modeled a pile driven in the soil 15 feet below the surface. The results confirmed what I had seen in the two-dimensional picture. The soil was being consolidated on the side opposite of the lateral force, and it was creating a gap on the side of the force (Figures 3, 4). Finally I wanted to do a parametric study of a nine-pile group. The nine piles were arranged in a square fashion, three piles by three piles (Figure 5). I also added a rigid pile cap, bedrock, and a total of 30 feet to my mesh (Figure 6). My goal was to test pile group behavior with each pile 4, 6, 8, 10, 12, 14, and 16 feet away from the next closest pile. By using lateral loads, I could determine the ultimate lateral load capacity before the piles fail or buckle. I then could find the optimal spacing between piles in a group, and thus determine the most efficient and inexpensive pile group design. Unfortunately, my program still has some problems associated with it, and I was not able to finish the parametric study. On the other hand, I was able to analytically determine where the failure moment would occur, and what the ultimate lateral load for a single pile would be using Brom’s method.

Brom’s method uses equations with coefficients affiliated with both the pile and the soil to determine the ultimate lateral load for the system, and where a failure moment would be underground. However, it is imperative to understand how a pile will fail under a lateral load. First, a pile will fail differently if there is a pile cap attached to the pile head or if there is not one. It is common in most construction to use rigid pile cap to fix all the piles in their place. When a pile cap is attached, there are three failure modes that are determined by the length of the pile. If a pile is short, the critical lengths will be defined later, the entire pile and the cap will displace without a failure hinge. If a pile is of intermediate length, there will be a failure hinge where the pile and the cap interact. Finally, if the pile is long there will be two failure hinges. One hinge will occur at the pile to pile cap junction, and the other will occur at some distance below the surface (Figure 7).

Brom's method will define the critical lengths for short, intermediate, and long piles, it will determine the ultimate lateral load for the specified length, and it will determine where, if at all, the failure moment exists. An entire listing of Brom's method can be found in the United States Army Corps of Engineers Manual EM 1110-1-1905, Bearing Capacity of Soils, 1992, 5-34 to 5-37, but I will give an example of this method. In this process, a fixed pile head in cohesive soil has three separate sets of equations for the three different lengths. Short piles are described as $L \leq L_{cs}$ where;

$$L_{cs} = 2 \left[ M_y / (18\ C_u\ B_s) + (9/16)\ B_s^2 \right] .$$

Here, L represents the chosen length of the pile (ft.), $L_{cs}$ is the critical length for short piles (ft.), $M_y$ is the ultimate resisting bending moment of the entire cross-section of the piles (kips ft.), $C_u$ reflects the undrained shear strength of the soil (kips ft$^2$), and finally $B_s$ is the diameter of the pile shaft (ft.). The intermediate sized piles have a length greater than or equal to $L_{cs}$, but a length less than or equal to $L_{cl}$;

$$L_{cl} = \left[ 2.25\ B_s^2 + (4/9)\ M_y / (\ 9\ C_u\ B_s) \right]^{1/2} + \left[ M_y / (2.25\ C_u\ B_s) \right]^{1/2}$$

Finally, the length of a long pile is greater than or equal to $L_{cs}$. Each pile length also has its own ultimate lateral load equation, $T_u$ (kips), that involves these values. For my analysis, I tried to match the Brom's method model to my ABAQUS model to compare results. First the undrained shear strength, $C_u$, of the soil is 1.5 kips / ft$^2$, the diameter of the pile shaft is 2.0 ft., and the ultimate resisting bending moment is 699.79 kips ft. (Soil

Mechanics, Lambe, Whitmann, 1969, 453) (Mechanics of.., Beer, Johnston, 1992, 702). From these measurements, I determined $L_{cs}$ to be 7.8 ft., and $L_{cl}$ to be 16.1 ft. Therefore, the 30-ft. model I used will be considered a long pile. For a long pile, the ultimate lateral load can be calculated by the following equation;

$$T_u = 9\ C_u\ B_s\ [\ (2.25\ B_s^2 + (4/9)\ M_y\ )^{1/2} - 1.5\ B_s\ ]$$

Therefore, I calculated the ultimate lateral load to be 402 kips. This may seem extremely high, but the ultimate lateral load is not used for building design. Another term, the allowable lateral load, is used for pile designs. The allowable lateral load for concrete piles is 15 kips, for steel piles is 20 kips, and for timber piles is 10 kips (EM 1110-1-1905, 1992, 5-68). Now that the ultimate lateral load has been determined, it can be used to discover where the failure moment underground is located. The following equation is used to find this distance;

$$\text{Distance} = 1.5\ B_s + T_u\ /\ (9\ C_u\ B_s)$$

According to this equation, the failure moment distance will be 20.9 ft. beneath the surface of the soil. This is a valid distance because the length of the pile is 30 feet. Unfortunately, this method only gives the forces and distances for individual piles. Therefore, I have still not been able to analyze soil to pile group behavior to determine the optimal design.

Fortunately, through some research I have been able to discover what the optimal pile design specifications should be. The United States Army Corps of Engineers suggests that piles in a group should not be placed less than 2.5 times the pile diameter apart, and not greater than 7 times the pile diameter away from the next closest pile. Also the optimal design can be found when piles are spaced between 3 and 3.5 times the pile diameter, or greater than 0.02 times pile length + 2.5 times the pile diameter (1110-1-1905, 1992, 5-68). Chen and Poulos also found similar results to the U.S.A.C.E.. They stated that piles are typically not installed less than 2.5 times the pile width away, and the optimal spacing should be 3 to 4 times the width of the pile for a 3-pile group. The normalized ultimate soil resistance will change according to the pile spacing distance (Analysis of Pile-Soil.., Chen and Poulos, 1993, 212-213).

By using techniques such as computer model analysis and Brom's method, it is possible to determine the optimal pile design without costly on-site testing. Also, it is possible to change parameters quickly and obtain new results without re-installing more piles during construction. Every type of pile in different soil conditions embedded by diverse pile drivers to any depth can be fully modeled by computer programs to obtain the optimal design. It is extremely important to create the most advantageous design not only for economic incentives, but also for structural integrity. So, now it is practical to build your house on a rock, even if the rock is beneath 30 feet of soil.

# Appendix A: Figures

Figure 1: One-dimensional model of a pile under a 10 kip lateral load with soil displacement

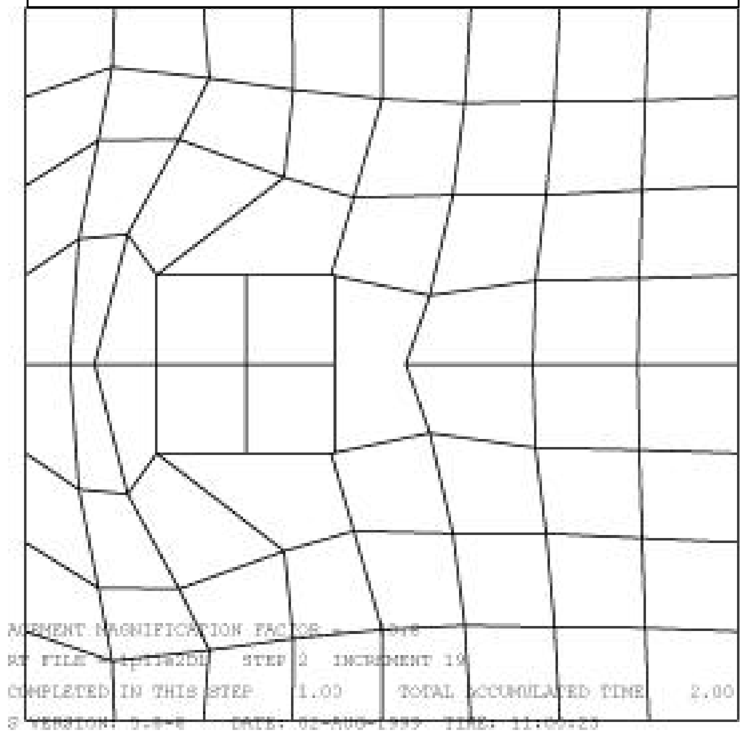



Figure 2: Two-dimensional model of 3 piles under lateral load with no gap created.

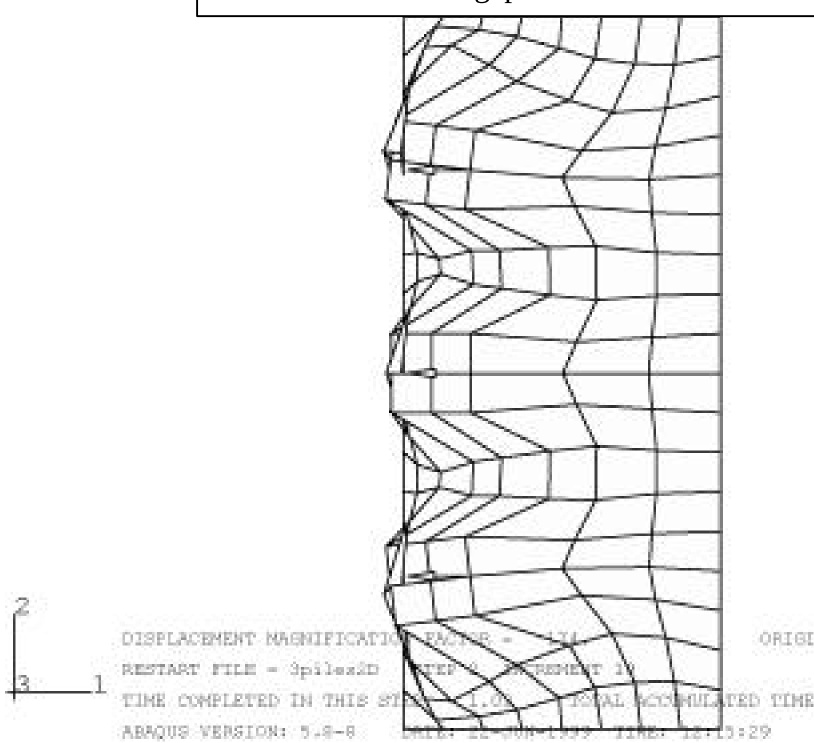


Figure 3: 3-dimensional model of a single pile being displaced from a lateral load.


Figure 4: 3-dimensional contour model of the soil after a 10 kip force was applied to the pile. Note: the pile has been removed from this picture

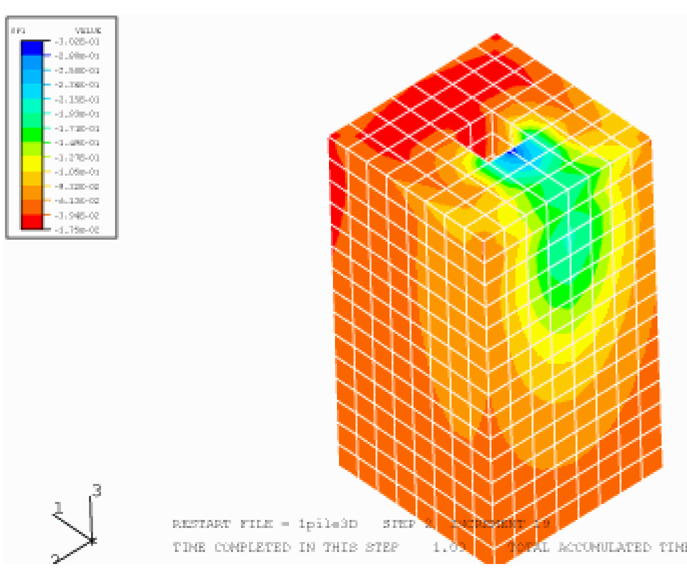
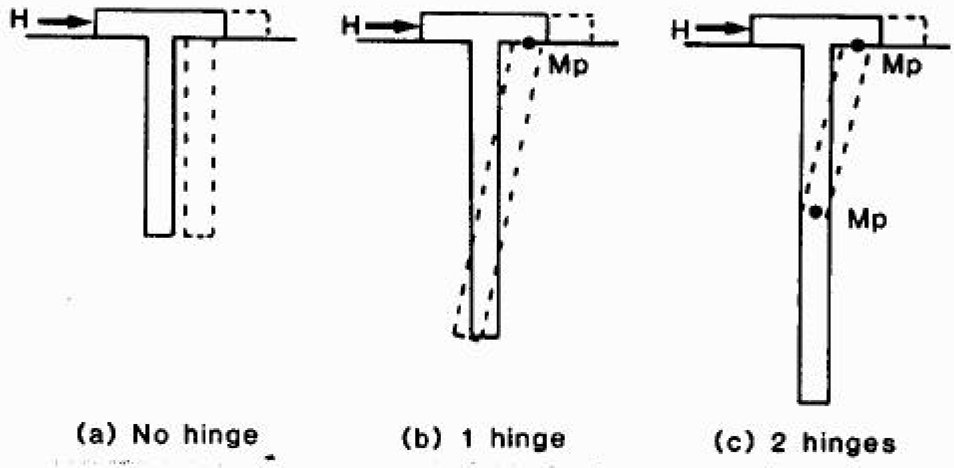


Figure 7: Failure moments of short, intermediate, and long piles with a rigid pile cap attached.



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