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SIMULATION OF BORED PILE CONSTRUCTION

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ABSTRACT

The installation of pile foundations is complicated by an enormous number of problems. They include unseen subsurface obstacles, lack of contractor experience, and site planning. These major problems and other minor ones make it difficult for the estimator to evaluate the piling project productivity and cost. Therefore, this study is designed to assess these problems using simulation. Both piling process productivity and cycle time assessment are addressed. Data were collected for this study through designed questionnaires, site interviews, and telephone calls to experts in different construction companies. Many variables have been considered in the piling construction process. Two simulation models have been designed and validated to assess piling process productivity and cycle time. Consequently, two sets of charts have been developed based upon the validated models to provide the decision-maker with a solid planning, scheduling and control tool for piling projects.

1 INTRODUCTION

The installation or construction of pile foundations is complicated by an enormous number of problems relating to subsurface obstacles, lack of contractor experience, and site planning difficulties. These problems can be summarized in the following statements. The site pre-investigation usually consists of statistical samples around the foundation area that do not cover the entire area. Soil types differ from site to site due to cohesion or stiffness, natural obstacles, and subsurface infrastructure construction obstacles. Lack of experience in adjusting the pile axis, length, and size present a further complication. Piling machine mechanical and drilling problems must be considered. Problems due to site restrictions and disposal of excavated spoil have great effect on productivity. The rate of steel installation and pouring concrete is impacted by the experience of steel crew and method of pouring. All these problems, no doubt, greatly affect the production of concrete piles on site. There is a lack of research in this field. Therefore, the objective of this study is to analyze the piling process productivity factors and assess productivity considering most of the above factors.

It is difficult for the estimator to evaluate piling productivity. Therefore, it is necessary to use sophisticated techniques to analyze the problem and determine the closest optimal solution. This study highlights the problem features and solution. The objective of this study is to provide the piling process decision-maker with a solid tool for assessing piling process productivity using simulation technique.

2 FACTORS THAT AFFECT PILE INSTALLATION PRODUCTIVITY

Literature review, site interviews, telephone calls, and a questionnaire analysis were used to collect the factors that affect piling installation productivity. Based on studies of the construction process and literature, the following factors were identified (Peurifoy et al., 1996):

1. Soil type (i.e., sand, clay, stiff clay, …etc).
2. Drill type. (e.g., auger, bucket)
3. Method of spoil removal, the size of hauling units, and space considerations at the construction site.
4. Pile axis adjustment.
5. Equipment operator efficiency.
6. Weather conditions.
7. Concrete pouring method and efficiency.
8. Waiting time for other operations (i.e., pile axis adjustment).
9. Job and management conditions.
10. Cycle time.

3 ATTRIBUTES MATRIX FOR PRODUCTIVITY VARIABLES

This study concentrates on selected variables, such as pile size, soil type, pile depth, pouring system, and auger height as shown in Table 1. The pile size (ϕ) varies within the range of 18", 30", 48", and 60". Therefore, this study concentrates only on these four categories of pile sizes. The soil types that are included in this study are clay, middle, and sand. Middle soil type represents all the types between pure clay and sand. Different depths can be encountered in the field but the collected data were available only for the 30′, 40′, 50′, and 60′ depths. Two pouring systems or techniques are used: tremie and funnel. Tremie technique is used in the wet method; however, funnel is used in the dry method. Various auger heights have been investigated in this study, such as 3′, 4′, 5′, and 6′. This study considers only the above-mentioned factors according to the specified limits when estimating piling process productivity. There are five variables with seventeen attributes. Therefore, the collected data have been divided into several data sets to cope with the selected variables and their attributes. Data have been divided into four main sets based upon pile size; one set for each size. Within each set, data are classified into three categories according to soil type: clay, middle, and sand. The remaining variables such as pile depth, pouring method, and auger height are then considered.

Table 1: Piling Process Productivity Variables Attributes Matrix

Pile Size (ϕ)	18"	30"	48"	60"
Soil Type	Clay	Middle	Sand	
Pile Depth	30′	40′	50′	60′
Pouring Method	Tremie (Wet Method)	Funnel (Dry Method)		
Auger Length (Height)	3′	4′	5′	6′

4 DESIGN OF SIMULATION MODELS

To build the simulation models for the piling process, construction steps have to be defined in detail. Figure 2 depicts the detailed construction steps of the piling process starting from the axis adjustment to concrete pouring and finishing the pile. The construction steps can be summarized as follows:

1. Adjust the piling machine on the pile axis.
2. Haul with the auger to the drilling place.
3. Start drilling until the auger is filled.
4. Return from the drilling level to the top of the pile hole.
5. Swing to the unloading area.
6. Unload the dirt in the unloading area.
7. Swing back to the top of the hole.
8. Repeat steps 2 to 7 until the pile is completely drilled.
9. Relocate the machine and start steps 1 to 8.
10. Start erecting the rebar cage using a crane.
11. Erect the concrete pouring tool, either funnel or tremie, into the hole.
12. Use funnel for dry method and tremie for wet method.
13. Start pouring the concrete and finish the pile.

Simulation models are designed to determine the productivity of this process. Both piling machine and crane activities' times have to be assessed so that the time required to constructing the pile is defined. The drill rig is responsible for performing the activities: axis adjustment, drilling, and machine relocation. The crane is responsible for the rest of the activities.

Drilling has six main activities: hauling to the drilling location, loading the auger (drilling), returning to the top of the hole, swing to unload area, unload dirt, and swing back to the top of the hole. The pile has to be divided into equal small depth segments (d) to facilitate cycle time calculation. The cycle time at the beginning of the drill sequence is, of course, different from that as the hole increases in depth. To consider this concept, the segment depth (d) has to be tiny so that the cycle time difference between the upper and lower segment's edges is small. Therefore, it is assumed that the cycle time is the same throughout the depth of the hole. Hence, the cycle time at the center of each depth segment represents the cycle time through the entire segment. Figure 1 shows that the pile is divided into small equal depth segments to facilitate productivity determination. The current study proposes 10′ depth segments to be embedded in the simulation model building and activities duration determination.

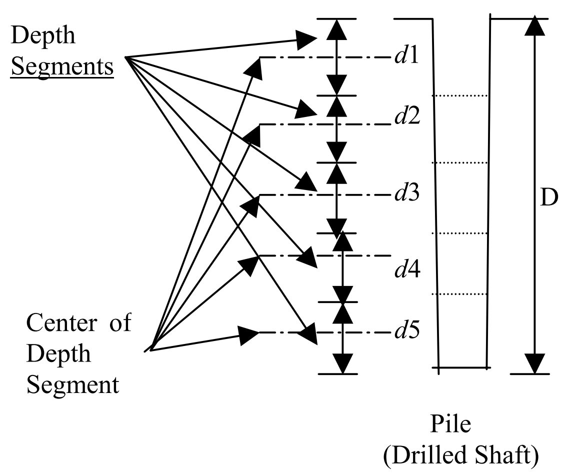


Figure 1: Pile Depth Segments

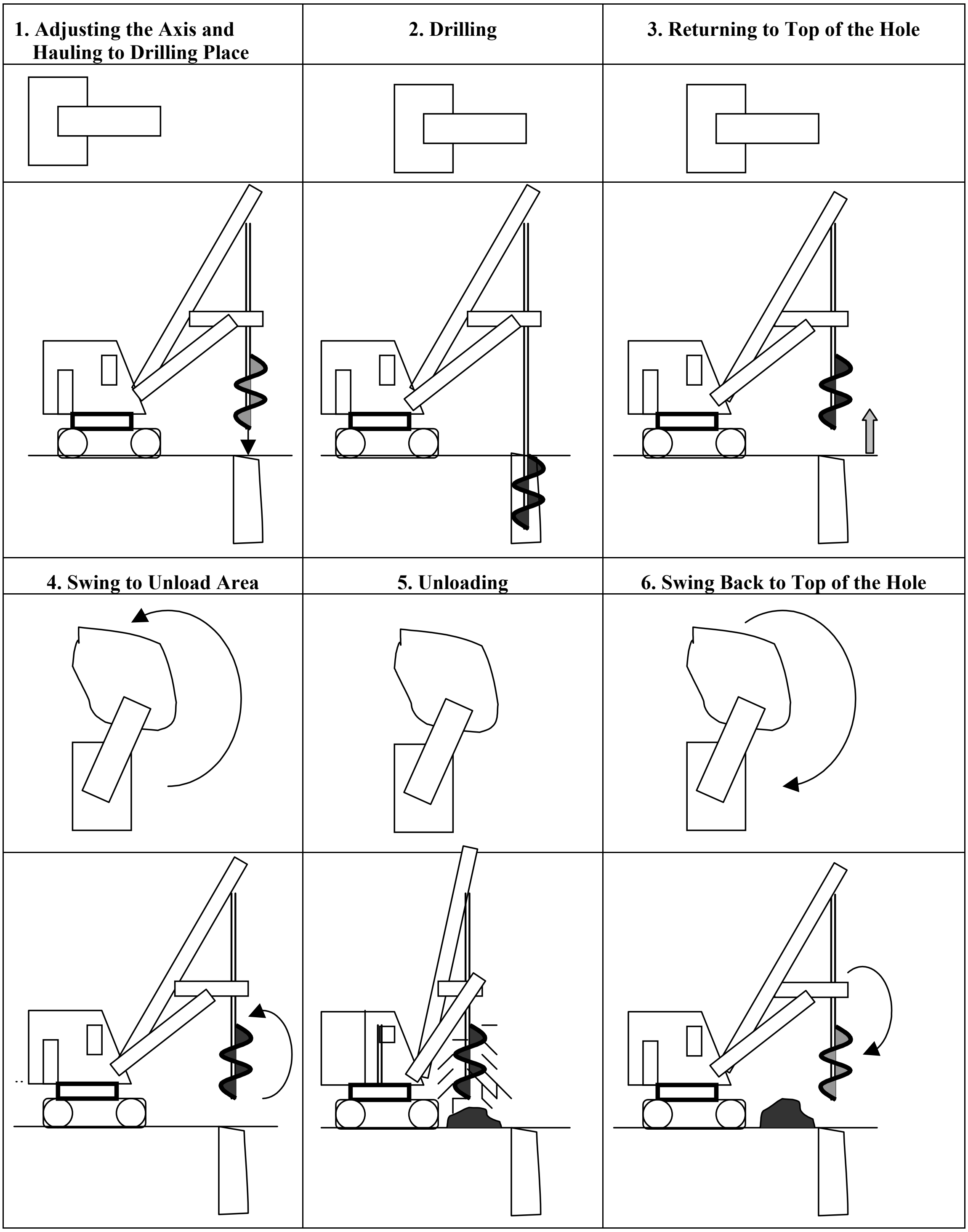


Figure 2: Flow Diagram for Pile Construction Steps

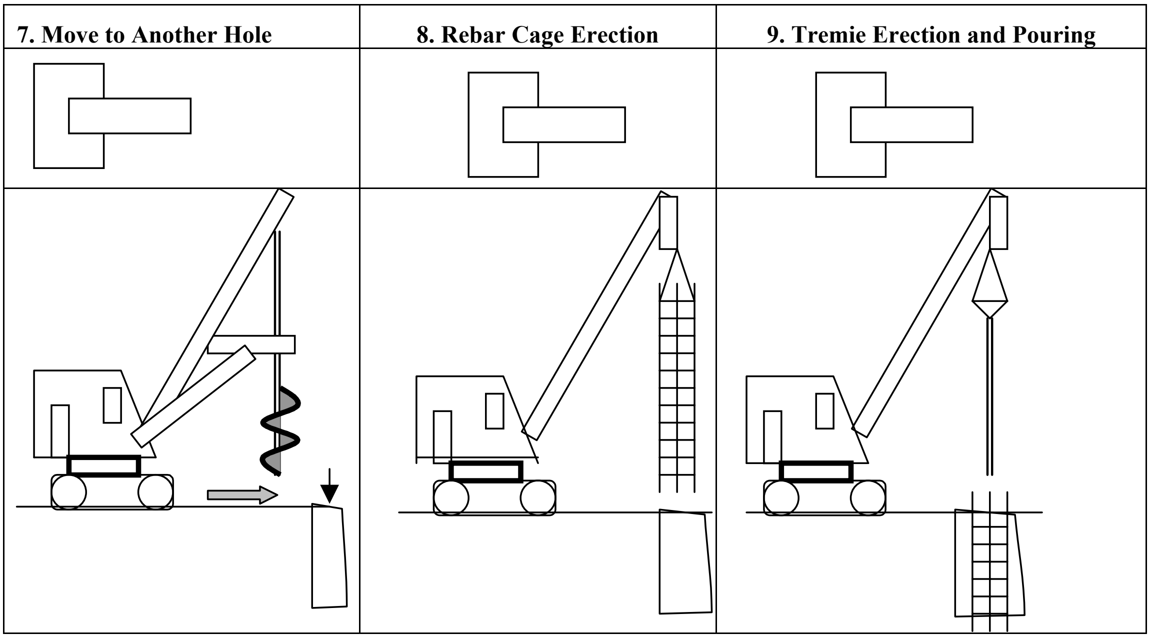


Figure 2: Flow Diagram for Pile Construction Steps (Cont.)

5 SIMULATION ENGINE (PROGRAM) SELECTION

Designing a simulation model for any process is dependent upon the simulation engine (program) that is used. Therefore, simulation modeling for the same process is different from one simulation one engine to the other according to its functions and code requirements. The simulation engine that has been used in this study is MicroCYCLONE version 2.7 developed by Daniel W. Halpin, 1990-1992. For more information regarding this program, the reader is referred to Halpin and Riggs (1992). This program uses different elements that represent each construction process activity. The elements of MicroCYCLONE that are used to model and simulate piling process activities are shown in Figure 3 (Halpin and Riggs, 1992). The piling process model design is shown and explained in detail in the following section.

6 MICROCYCLONE SIMULATION MODELS FOR PILING PROCESS

Based on MicroCYCLONE elements, two models have been developed to represent the piling construction process. First model shows the designed simulation model for the piling process dry and/or wet construction without linear sections methods while the other model shows the cased construction method. *Dry method* is the construction method that performs drilling in a soil that can stand-alone without caving when drilling the pile, (e.g. in clay, stiff clay, or any other cohesive soils). The *Wet method* is the piling process construction method that uses bentonite slurry or other materials to support the excavated soil because it cannot stand-alone without caving when drilling. Sometimes, the drilled shaft has more than one soil type in different layers. Most of the time, one of these layers is a caving soil. This type of soil will make it difficult to drill without using some means of support; however, this is the role of using a steel case. Whenever, a steel case is used to avoid soil caving in any layer, this method is called *Cased method*, whether it is used in dry or wet method. Accordingly, the piling construction steps (activities) are different from one method to the other. Dry and wet methods are mainly the same in the major activities, therefore, there is no need to separate them into two different simulation models. They are different only in the times required to erect the tremie and the funnel. The *tremie* is used in concrete pouring for wet method, where a *funnel* is used in case of concrete pouring in dry method. On the other hand, cased method for dry or wet techniques has to have its own simulation model because of the different process sequence. Hence, two main simulation models have been developed: one represents dry and wet uncased and the other represents dry and wet cased methods. Figure 4 shows the MicroCYCLONE simulation model for constructing a pile using dry and/or wet uncased method; however, Figure 5 shows the simulation model for dry and/or wet cased method. The MicroCYCLONE models are depicted in the following sections.

Name	Symbol	Function
Combination (COMBI) Activity		This element is always preceded by Queue Nodes. Before it can commence, units must be available at each of the preceding Queue Nodes. If units are available, they are combined and processed through the activity. If units are available at some but not all of the preceding Queue Nodes, these units are delayed until the condition for combination is met.
Normal Activity		This is an activity similar to the COMBI. However, units arriving at this element begin processing immediately and are not delayed.
Queue Node		This element precedes all COMBI activities and provides a location at which units are delayed pending combination. Delay statistics are measured at this element.
Function Node		It is inserted into the model to perform special functions such as counting, consolidation, marking, and statistic collection.
Accumulator		It is used to define the number of times of the system cycles.
Arc		Indicates the logical structure of the model and direction of entity flow.

Figure 3: MicroCYCLONE Elements Description

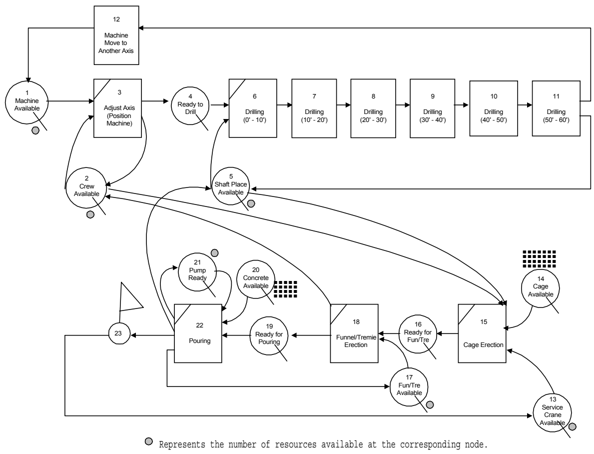


Figure 4: MicroCYCLONE Model for the Piling Process Using Dry/Wet Uncased Construction Method

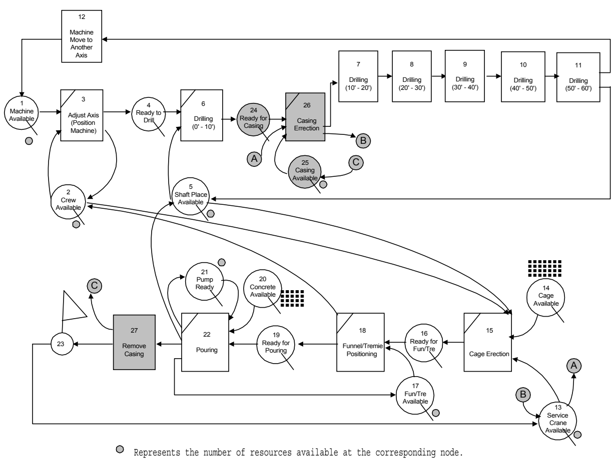


Figure 5: MicroCYCLONE Model for the Piling Process Using Dry/Wet Cased Construction Method

6.1 Dry/Wet Uncased Model Description (Figure 4)

- At the beginning of simulation, the piling machine and the labor crew have to be available as shown in Ques 1 and 2, respectively.
- Being available, the machine auger or bucket will be adjusted on the pile axis as shown in node number 3 (COMBI). The machine will be ready for drilling as shown in Que number 4.
- To start drilling, shaft space has to be available as in Que 5.
- Drilling will begin. Drilling activities have been divided into several sub-activities based on depth. Depth is divided into multiple 10' segments because time data were collected for every 10' depth. These segments will also be very beneficial in case of dry/wet cased method. It will enable the model to consider the caving layer and the construction of steel casing. Hence, the drilling activities will be in serial as shown in nodes number 6 – 11 until finishing drilling the shaft.
- The machine will move to another shaft location as shown in node 12 and the shaft hole will be ready to complete the pile construction.
- To start completing the pile construction, rebar cages have to be available for the crane to erect as shown in Que 14. At the same time, a service crane has to be available to complete the pile construction as in Que 13.
- The crane will erect the cage as in node 15 with the help of the labor crew and will be ready to erect the pouring mechanism as shown in Que 16.
- To erect the tremie or funnel in node 18, it has to be available as shown in Que 17.
- After erecting the tremie or funnel, the pile will be ready to pour concrete as in Que 19 and the labor crew will be free.
- Pump and concrete have to be ready prior to concrete pouring as in Ques 20 and 21.
- After pouring concrete as in node 22, the pump will be free, shaft space will be available for any other activities, and the simulation counter will register a cycle, which represents one pile.
- Finally, the service crane will be available for any other operations.
- *Available Process Resources*:

  - One machine is available at Que 1.
  - One labor crew (3-5) is available at Que 2.
  - One shaft place is available at Que 5.
  - One service crane is available at Que 13.
  - Several rebar cages are available at Que 14.
  - One funnel or tremie is available at Que 17.
  - Several cubic yards of concrete are available at Que 20.
  - One pump is available at Que 21.

6.2 Dry/Wet Cased Model Description (Figure 5)

- This model is similar to the first model except for the shaded activities.
- The modified activities to the first model are installation of the steel case and its removal.
- The steel case is ready to be erected as shown in Que 25.
- This case or linear section might be erected prior to the second 10' or any of the other segments. Its position in the process sequence will not affect time or productivity because its duration will be added to the process duration. In other words, If it is done after the first 10' segment, the duration and productivity will be similar if it is done after the fifth 10' segment. Therefore, the used model considers only the steel case after the first 10' segment as shown in node 26.
- After finishing pouring concrete, the steel casing can be removed using the service crane as in node 27.
- Then, the case will be free to be used in another shaft.
- The resources will be the same as in the first model as well as adding one casing available at Que 25.

Accordingly, the two designed models are simulated using the MicroCYCLONE program to get the productivity of the piling process in different cases using different process variables. This is explained in the following sub-sections.

7 DATA COLLECTION

A questionnaire was designed to collect data from contractors and consultants who are specialists in concrete bored pile construction and design, respectively. This questionnaire was used to collect the piling process cycle time, productivity, and soil characteristics. Reviewers were asked to provide information based on one of the most average projects that they have done or are currently doing. Accordingly, each questionnaire represents a full set of information about at least one project. Two types of data collection techniques were used in this study. The first technique was *direct data collection*, such as site interviews, site visits to fill data forms, and telephone calls. The second technique utilized a *questionnaire*. For more information, the reader is referred to Zayed (2001).

8 PREPARATION OF THE PILING PROCESS ACTIVITY DURATIONS

Time data were collected from the reviewers in three estimate format: minimum, most probable, and maximum. Three point estimates were used for each data point so that triangular distribution can be used in simulation to represent activities' duration. Triangular distributions have been chosen in simulation because of their easy estimation from reviewers' perspective. Statistical inference has been done to estimate one value for each data point that represents these data samples. Hence, statistical hypothesis tests were done to estimate the population's mean for each data point in each data sample. Therefore, three values were developed to represent each activity (data point): minimum, most probable, and maximum. These values constituted the triangular distribution (lower value, mode value, and higher value) that was used in simulation for the activities' duration.

9 SIMULATION OF PILING PROCESS MODELS

786 input files of MicroCYCLONE were prepared for simulation. The classification of these files is shown in Figure 6. It shows the first four major classifications according to size. Hence, four main input file groups are developed: 18", 30", 48", and 60". Within each group, two sub-groups are constituted for dry and wet uncased methods. These two sub-groups are divided into four categories relying on pile depth: 30', 40', 50', and 60'. Each depth category has 12 simulation-input files that cover three soil types using four different auger heights. Consequently, the number of computations using this classification is 384 input files. Similarly, the dry/wet cased method uses the same classification with 384 input files.

After preparing the simulation input files, the MicroCYCLONE program was used. The final outcome of the simulation process was productivity of the piling process considering the above-mentioned classification. For example, drilling an ϕ-18 pile using wet uncased method with 30' depth in clay soil using 3' auger height, the productivity is *1.6* holes/hr. Under the same conditions using wet cased method, productivity is *1.09* holes/hr. There is a clear difference between the two productivity figures because of installing the steel case and removing it.

10 PILING PROCESS PRODUCTIVITY MODEL USING SIMULATION

Simulation results are determined using 60 working minutes per hour of production (productive time). Factors which would reduce the effective number of minutes per hour are not considered in this simulation. Therefore, to adapt the simulation results to reflect real world practice, a productivity index has to be applied to simulation results to make it reasonable. A productivity index (PI) is applied to the simulation results as shown in model (1):

$$Productivity = S * WH * PI \quad \text{(holes/day)} \quad (1)$$

The model in equation (1) is applied to the piling process simulation results in both methods: dry/wet uncased and cased. The PI is assigned as 0.7 according to Zayed (2001). To guarantee that this model is reasonable, it has to be validated using real world data. The validation procedure is depicted in the following section.

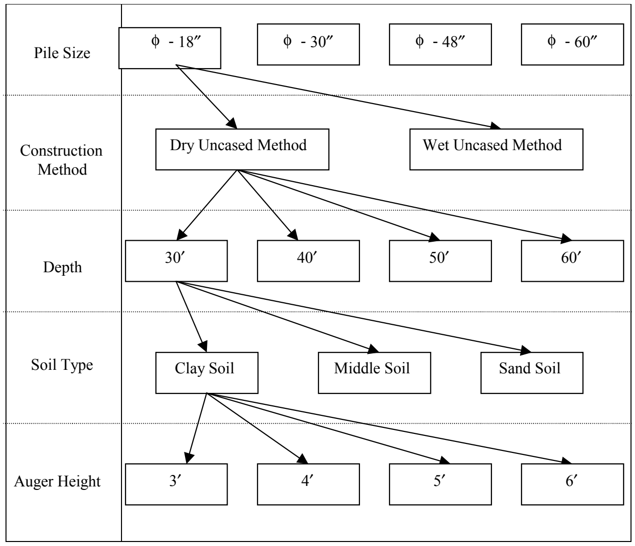


Figure 6: Simulation Input Files' Classification for Uncased Methods

10.1 Piling Process Model Simulation Results Validation

The results of the equation (1) model are compared with the collected productivity. To exactly determine how far the simulation productivity model results differ from the collected, a validation factor has to be calculated for each data point. The validation factor (VF) is calculated using equation (2) as follows:

Validation Factor (VF) = PMR / CP
Where PMR = Productivity Model Result
CP = Collected Productivity (2)

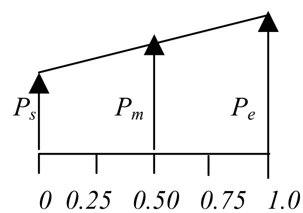
VF has been calculated for each data point by dividing the estimated productivity using simulation by the collected productivity. This has been done for different soil types: clay, middle, and sand. Table 2 shows the calculated VF for clay, middle, and sand soils using wet and dry methods. This table shows that the VF for ϕ-18 in clay soil with 30' depth using 3' auger and wet method is 1.0 while it is 0.97 for 4' auger. This indicates that the model of productivity for the 3' auger height reflects exactly the field data collected on site. For the 4' auger height the simulated production is 97% of the field productivity. This table is very informative in establishing behavior regarding different piling process variables.

The concept of validation factor (VF) has been developed to check the degree to which the designed models reflect field data. Based on Table 2, the value of VF for more than 36% of the model output exceeds 90%. About 30% of the outputs have VF values in the range of 80-90% fitness while 13% of them have VF in the range of 75-80% fitness. Consequently, 79% of the models outputs have been predicted with more than 75% validity, which is fairly good and acceptable.

10.2 Simulation Model Productivity Analysis

Simulation calculates productivity considering the following auger heights: 3', 4', 5', and 6'. Productivity has to be defined in between these heights. Linear interpolation has been used to calculate the process productivity for auger heights between the heights that have been used in the models. For example, more auger heights have been added to the analysis, such as 3.25', 3.50', 3.75', 4.25', 4.50', 4.75', 5.25', 5.50', and 5.75'. A linear function is assumed to be used between the two different productivity figures for each auger height's pair {(3', 4'), (4', 5'), and (5', 6')}. Hence, the productivity is calculated using the following model (3):

$$P_m = P_s + \{(P_e - P_s) * (A_m - A_s)/(A_e - A_s)\} \quad (3)$$



Based on the model in equation (3), productivities of all the cases for auger heights, (from 3' and ends at 6' with increments of 0.25') have been determined. Productivity charts are constructed for the use of piling process contractors. Figure 7 shows the productivity curves for ϕ-18 in clay soil using wet/dry methods for different auger heights and depths. It has eight curves: four represent the estimated productivity considering wet method and the other four considering dry method. For example, at auger height 3.75' with depth 60' in clay soil and ϕ-18, the estimated productivity is 4.89 holes/day using the wet method versus 5.7 holes/day using dry method. For further details about the charts, the reader is referred to Zayed (2001).

Table 2: Validation Factor (VF) for ϕ-18

	Construction Method at Various Auger Heights							
	Wet Method				**Dry Method**			
Pile Depth	***VF for Clay Soil***							
	Auger 3′	Auger 4′	Auger 5′	Auger 6′	Auger 3′	Auger 4′	Auger 5′	Auger 6′
30′	1.00	0.97	0.91	0.88	1.23	1.15	1.06	1.02
40′	1.13	1.10	1.05	1.01	1.42	1.34	1.24	1.18
50′	1.23	1.19	1.14	1.10	1.57	1.48	1.38	1.30
60′	1.31	1.27	1.21	1.18	1.71	1.59	1.49	1.40
	VF for Middle Soil							
30′	0.92	0.87	0.80	0.76	1.13	1.03	0.94	0.87
40′	1.04	0.98	0.91	0.86	1.31	1.19	1.09	1.00
50′	1.13	1.06	0.99	0.93	1.44	1.32	1.21	1.11
60′	1.19	1.13	1.05	0.99	1.56	1.41	1.30	1.19
	VF for Sand Soil							
30′	0.85	0.78	0.71	0.66	1.04	0.93	0.83	0.75
40′	0.96	0.88	0.81	0.74	1.21	1.08	0.97	0.87
50′	1.03	0.95	0.88	0.81	1.33	1.19	1.07	0.96
60′	1.09	1.01	0.93	0.86	1.43	1.28	1.15	1.03

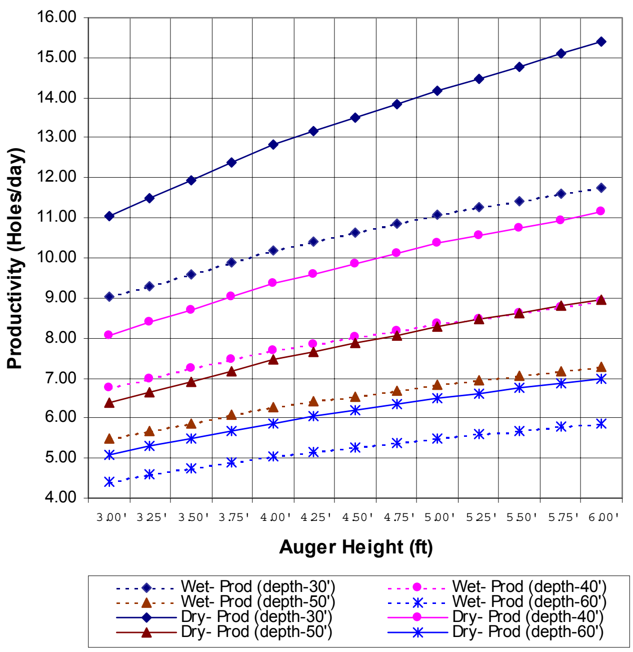


Figure 7: Estimated Productivity for ϕ-18 in Clay Soil

11 CONCLUSIONS

The simulation technique is used to assess piling process productivity and cost. Two simulation models have been designed to assess these items. Those models have been validated to assure their appropriateness for piling process analysis. The concept of validation factor (VF) has been designed to check the degree to which designed models reflect field data. The value of VF for more than 36 % of the model output exceeds 90% validity, which expresses an excellent fit of the available data sets. About 30% of the outputs have VF in the range of 80-90% fitness while 13% of them have VF value in the range of 75-80% fitness. Consequently, 79% of the models outputs have been predicted with more than 75% validity.

Several sets of charts that represent productivity and cycle times have been developed. A comprehensive discussion of the application of these simulation models to productivity, cycle time, and cost is available in Zayed (2001).

APPENDIX A: NOTATION

WH	= Working hours per day
PI	= Productivity index (qualitative variables effect)
S	= Productivity result using simulation (holes/hr)
VF	= Validation factor
PMR	= Productivity model result
CP	= Collected productivity
P_m	= Productivity in the middle points (holes/day)
P_s	= Productivity in the start point (first auger height limit) (holes/day)
P_e	= Productivity in the end point (last auger height limit) (holes/day)
A_m	= Auger height in the middle points with *0.25* increment (ft)
A_s	= Auger height in the start point (first height limit) = 3’, 4’, or 5’
A_e	=Auger height in the finish point (last height limit) = 4’, 5’, or 6’

Subscripts and Superscripts

m = middle point.
s = start point.
e = end point.

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