First International Conference on Construction in the 21st Century (CITC2002)
"Challenge and Opportunities in Management and Technology"
25-26 April, 2002, Miami, Florida, USA

CONCRETE BORED PILES CONSTRUCTION PRODUCTIVITY INDEX

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ABSTRACT

The decision-making process is a very essential part of any construction operation. Estimating the productivity of the piling process is a core step that helps decision-makers bid, plan, and organize the piling project. To schedule the piling equipment operation among different projects and within the same project, productivity analysis is a necessity. To assess productivity properly, piling process quantitative and qualitative factors have to be considered. This paper focuses on the effects of qualitative factors on productivity assessment. A Productivity Index (PI) model is developed to represent this subjective effect in refining productivity assessment using deterministic and simulation techniques. Analytic Hierarchy Process (AHP) is used to develop the proposed PI model that relies on the actual performance of ten main piling process qualitative factors. Subjective data are collected from drilled shaft contractors considering these factors. The developed PI model implementation to piling process resulted in PI = 0.7. It has been validated using simulation model outputs.

KEYWORDS

Pile, Construction, Productivity Index, Qualitative, Analytic Hierarchy Process (AHP), Model

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, this study aims at analyzing these factors and determining the piling process productivity considering most of the above-mentioned factors.

2. STUDY OBJECTIVE

The objective of this study is to provide the piling process decision-maker with a tool for adjusting productivity estimates through a productivity index (PI). It is basically constructed to translate the subjectivity of productivity factors into quantitatively measured values using the Analytical Hierarchy Process (AHP) (Saaty, 1980). The PI is used to adjust the outcome of process-oriented models (e.g. deterministic and simulation) so that they consider the effect of qualitative factors.

3. FACTORS AFFECTING PILING PROCESS PRODUCTIVITY

Peurifoy, Ledbetter, and Schexnayder (1996) have identified a number of factors that affect drilling in rock, such as: type of drill and size of bit, hardness of the rock, depth of holes, drilling pattern, terrain, and time lost waiting for other operations. If pneumatic drills are used, the rate of drilling varies with the pressure of the air. Another item that influences the rate of drilling is the machine availability factor. Drills are subjected to severe vibration and wear, which may result in frequent failure of critical parts, or deterioration of the whole unit, entailing mechanical delays. The portion of time that a drill is operative is defined as the *availability factor*, which is usually expressed as a percent of the total time that the drill is expected to work.

Based on the previous discussion for the factors that influence the rates of drilling rock, the factors of drilling soft soils can be determined. The same machine could be used for drilling both types of soils. Drilling in a rocky soil is considered a special case of drilling in soft soils. Therefore, the factors that influence drilling soils containing boulders and rocks might be the same as those, which influence any other types of soil. These factors are summarized as shown in Table 1.

4. QUALITATIVE FACTORS WORTH (QFW) MODEL

The Qualitative Factors Worth (QFW) model is designed to address and assess qualitative factors that impact piling process productivity. It provides a logical, reliable, and consistent method of evaluating potential projects based on ten qualitative factors that are viewed as affecting project productivity. Therefore, this model addresses the fundamental questions of how much effect do these factors have on productivity and how can QFW be included in the productivity model calculation. The QFW model is beneficial in assessing productivity using the deterministic and simulation techniques. Both techniques provide optimistic productivity without considering qualitative factors. Consequently, the final productivity model outcome in the deterministic and simulation techniques tends to be optimistic. The QFW effect can assist in adjusting the optimistic or ideal values through the application of a productivity index (PI).

The QFW is an evaluation model composed of a one-level hierarchical structure. This one-level consists of ten major qualitative factors that have been selected based on Table 1. Figure 1 shows these ten factors: operator efficiency, weather conditions, site conditions, job management, soil removal system, pouring system, mechanical problems, owner and/or consultant problem(s), site investigation, and productivity estimate accuracy. The QFW model evaluates these productivity factors to provide a quantitative measurement for each factor's effect on productivity. In fact, these ten factors have different attributes or categories that constitute each factor. This study concentrates only on the main factors without investigating sub-factors or attributes level consideration.

The final outcome of the QFW is an index that assesses the worth of the qualitative factors. This index can be calculated by adding the factors value functions that have the following general form in equation (1):

$$QFW = \sum_{i=1}^{n} W_i * V_i(x_i) \qquad (1)$$

This functional form was chosen on the basis of the formulation used by Dias & Ioannou (1995) and (1996) for evaluating build operate transfer (BOT) projects. As shown in Figure 1, the Q*FW* index uses n = ten productivity factors x_i. The overall contribution of each factor is given by its worth score $V_i(x_i)$ multiplied by its composite weight W_i. The term x_i is added to the model to allow inclusion in the function for any extended future work using the sub-factors or sub-categories of productivity qualitative factors.

The worth score of a factor $V_i(x_i)$ reflects the one-dimensional value of the performance level of the factor as it exists for a specific project. The composite relative weight of a factor W_i reflects its relative importance to the other factors, irrespective of any particular project.

Table 1: Piling Process Productivity Factors

Factor	Description
Soil type (i.e. sand, clay, stiff clay, etc).	The production rate differs from soil type to another according its cohesion property.
Drill type, size, and construction method.	It covers the type and size of drill rig (i.e. bucket or auger) and the construction method: dry, casing, or wet methods.
Angle of swing.	The angle that piling equipment rotates to unload the spoil soil.
Method of spoil soils removal.	It affects the piling equipment waste time waiting for spoil soil removal from the site.
Pile axis adjustment.	If the pile axis is not properly adjusted, it will severely affect the construction procedure because of rework process.
Depth and size of holes.	This is a default factor where the diameter and the depth of hole influence the equipment production rate.
Equipment power.	It covers the equipment type and power or capability.
Operator efficiency.	It covers operator experience, characteristics, and personality.
Weather conditions.	Hot weather affects the efficiency of both operator and equipment while cold weather influences soil conditions. Rainy weather affects the concrete placing and the excavation procedure.
Spoil soil removal and space availability in the construction site.	The place of spoil soil and its removing methodology affects greatly the production rates. This is because small space available for spoil soils will delay the excavation waiting for removal.
Rebar cage installation procedure.	If rebar cage is not available at the time it is needed, it will delay the installation process. This depends upon the reinforcement crew efficiency and management.
Concrete pouring method.	Concrete pouring process time differs from method to another according to the placing tools (i.e. tremie and funnel).
Availability factor. (Mechanical Problems).	The mechanical problems are expected with stiff types of soil. Therefore, the availability and efficiency of the mechanical repair crew is vital in this process.
Job and management conditions.	It covers site nature, equipment moving availability inside the site, and planning and management of other resources.
Drilling Time Activities.	It includes loading, swing to and from the unloading area, unloading, haul from the hole opening to the loading area, and return back to the hole opining from the loading area.
Other Times Activities.	It includes adjust pile axis, moving machine to another pile opining, rebar cage erection, pouring tool erection, and pouring concrete.

4.1 One - Dimensional Factors' Worth Score

To determine the one-dimensional factors' worth score $V_i(x_i)$, it is necessary to evaluate the performance (quality) level x_i of the *ith* factor for a given project and then to use a value function $V_i(x_i)$ to transform it into an equivalent worth score. The transformation from the performance (quality) level x_i of the i^{th} factor into an equivalent worth score requires two steps. Since the ten factors in the QFW are qualitative in nature, the first step is to assess how well a given project performs with respect to a given factor *i* using a meaningful qualitative scale. This is essentially a "factor measurement" step in which the outcome is project-specific. The second step is to transform this qualitative performance into a one-dimensional worth (or value) score in the range 0 to 1.0. This is a "preference measurement" procedure where the outcome depends on the preference and judgment of the person doing the analysis (Dias & Ioannou, 1995).

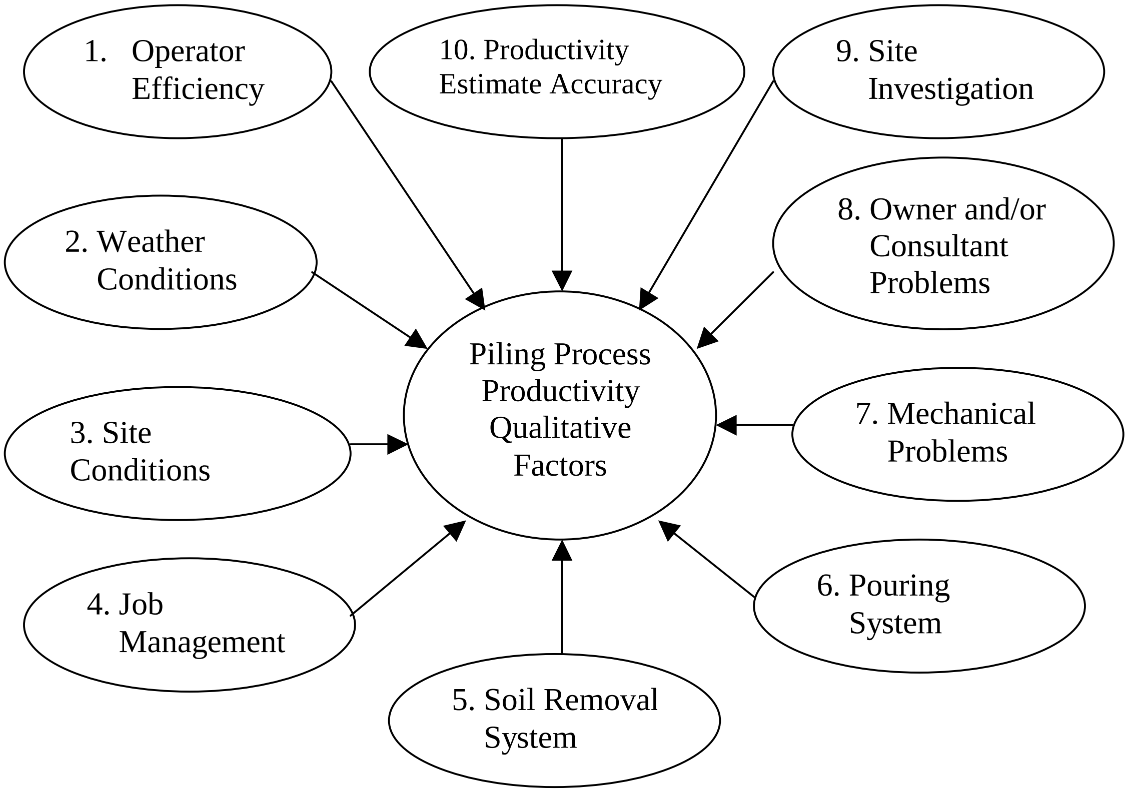

Figure 1: Piling Process Productivity Qualitative Factors

This two-step procedure allows the disassociation between the task of measuring the location of a factor on the performance scale and the task of determining the worth of the factor on the worth scale. It separates qualitative judgments that are specific to a project from the qualitative transformation to value (worth) that can be reused from one project to another. The qualitative factor measurement scale used to quantify the qualitative assessment for any factor *i* is shown in Figure 2. This scale incorporates nine performance levels that has been adapted from Dias & Ioannou (1995) and (1996). Each qualitative descriptor at the bottom of the scale has been matched to a numerical index value x_i (1-9) to allow a simple shorthand way to refer to any particular factor level using a single number (Dias & Ioannou, 1996).

The one-dimensional value (worth) functions for all the factors have the same generic form shown in Figure 3. This functional form consists of a linear function defined by two points: 0 and 10 in the performance scale. Point 0 represents the qualitative expression “Definitely Ineffective” while point 10 represents the expression “Definitely Effective”. The worth of each point in the performance scale has been defined using nine fuzzy membership functions that are shown in Figure 3. For example, value “3” in the performance scale is a member of three fuzzy numbers with different membership values. It is a member in the fuzzy number “Moderately Ineffective” with a membership of 100% (membership value = 1.0). It is at the same time a member in the two fuzzy numbers “Substantially Ineffective” and “Slightly Ineffective” with a membership of 0.0% (membership value = 0.0). It is assumed that a factor may not have a value of definitely ineffective (worth value of zero) because it has to have some effect to productivity even if it has too small effect on the process. It has an effect but might be extremely marginal for the management to consider. Therefore, zero worth is excluded from the evaluation.

Similarly, a zero value is excluded because nothing is so efficient that it will stop the process completely yielding a productivity of zero in a day. For example, site conditions might be extremely bad, but the work is still going on. In fact, productivity will be very low but there is still some kind of production going on. Therefore, it is assumed that value of 0.0 and 1.0are excluded. Accordingly, the worth values of the numbers on the performance scale are ranged from 0.1 for point 1 to 0.9 for point 9 with an increment of 0.1 for each number. For example, the worth value of the fuzzy number “Neither Effective nor Ineffective”, which is point 4, is 0.4. Consequently, if there is a qualitative value of “Neither Effective nor Ineffective” to a factor, it means that this factor has a 100 % membership value in this fuzzy number. Hence, the worth value of this qualitative factor for this specific project is 0.4 regardless of its weight within the other factors. Based on the previous discussion, the worth score of each factor can be determined using the performance scale as shown in Figures 2 and 3. At this moment, the worth of each factor has been decided in the context of the project but the relative weight of each factor to the others is not considered. It is very important to consider the relative weights of each factor to the others because this gives the true effect of this factor. Hence, the first step of the QFW model has been completed and the second step will be discussed in the following sub-section.

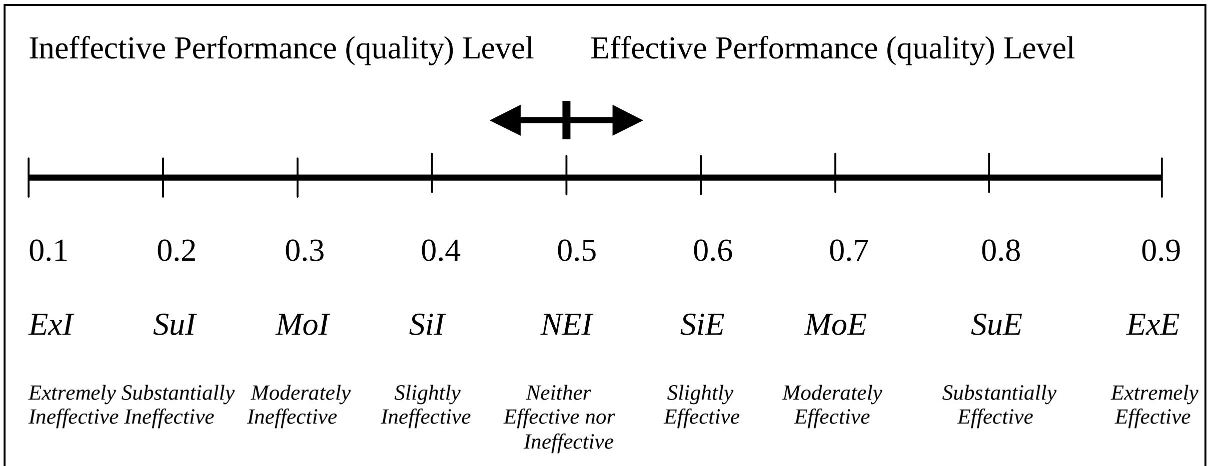

Figure 2: Productivity Factors Subjective Performance Scale

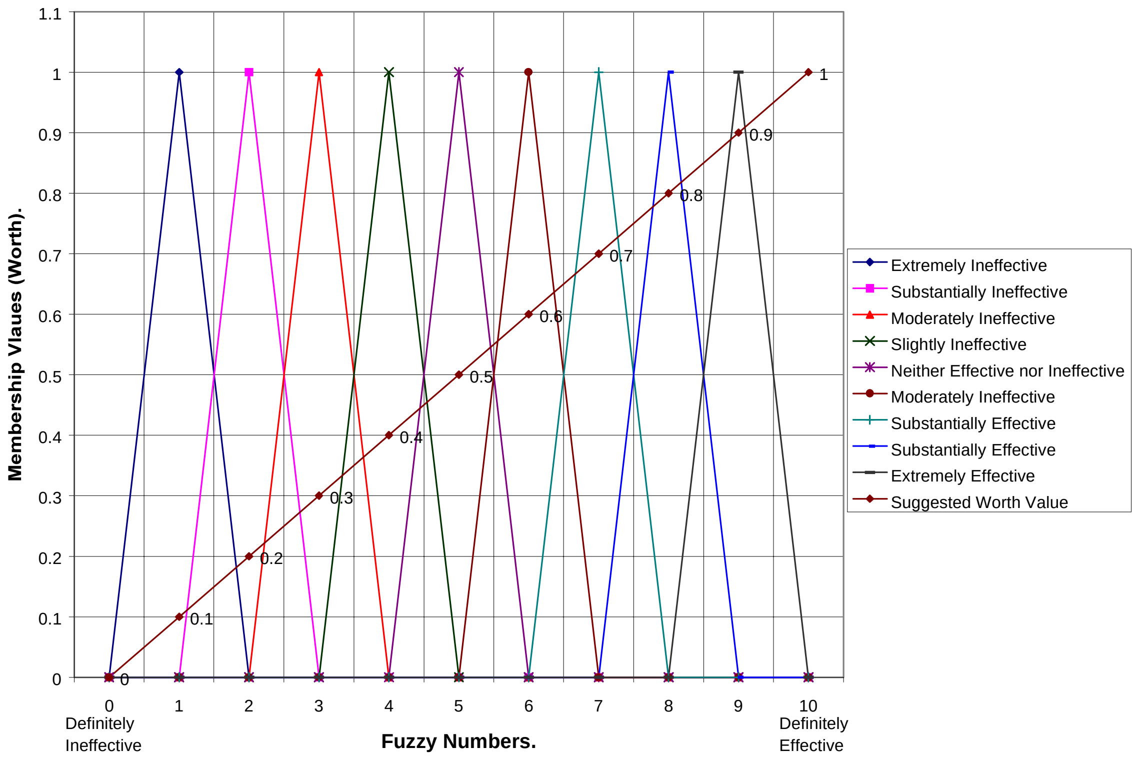

Figure 3: Fuzzy Representation for the Qualitative Performance Scale (Performance Worth).

4.2 Relative Weights for Qualitative Productivity Factors

The factors' relative weights were obtained by performing the following procedure:

1. A pair-wise comparison was made between the qualitative productivity factors of piling process. Experts evaluate qualitative factors and estimate a relative importance weight for each factor against the other. This methodology provides a pair-wise comparison matrix for each individual expert.
2. The eigenvalue method of Saaty (1980) is used for calculating the eigen vector or weighting vector for each pair-wise matrix. This method was developed by Saaty as part of the Analytic Hierarchy Process (AHP). It is an analytical method of calculating the factors weights using the pair-wise comparison matrix.
3. Finally, the relative weight W_i for each factor is calculated and used in the QFW model.

This is the fixed part of the QFW that does not change according to project type. The W_i does not change from one project to the next because it represents the relative importance of each productivity factor to the other. Consequently, the project type does not affect this relative importance because it is general and is not project specific. The eigenvalue method was used to quantify the evaluation of the productivity qualitative factors. The result of this method provides relative weights for each factor on a scale out of 1.0 or 100 points. Each factor weight represents the relative importance of this factor among the other factors that affect the piling process.

4.3 Aggregating the QFW Model

After determining both $V_i(x_i)$ (factor's worth) and its composite relative weight W_i , the QFW value can be calculated by multiplying both terms and then, summing the result for all the ten factors based on equation (1). The outcome would be a QFW value that represents the effect of all the qualitative factors to productivity. This will only provide the effect of these factors on productivity. For example, it shows the effect of qualitative factors on productivity as percentage. But this does not answer the fundamental question of how this value can be included in the assessed productivity models using the deterministic and simulation techniques. Hence, there will be an important need to determine a productivity index (PI) based on QFW. The PI will be used in adjusting the productivity using both techniques.

5. PRODUCTIVITY INDEX (PI)

Because the results of deterministic and simulation techniques are optimistic, they have to be scaled or adjusted using some kind of indices to make it close to reality. These techniques depend mainly on the quantitative variables to build the productivity models. Therefore, the required index will represent the qualitative variables in both techniques. The productivity will be calculated by multiplying the productivity index (PI) by the calculated productivity from each technique. Hence, the final outcome can be calculated using equation (2) as follows:

$$P_f = P_r * PI \qquad (2)$$

The first term on the right hand side of equation (2) represents the optimistic outcome (P_r) that resulted from either deterministic or simulation techniques. But the second term in the right hand side (PI) is calculated using equation (3) as follows:

$$PI = 1 - QFW \qquad (3)$$

Hence, the productivity index (PI) is the complement of the QFW because the latter represents the bad effect (deficiency) of the qualitative factors on productivity while the former represents the work efficiency. Consequently, productivity is equivalent to the optimistic productivity estimate multiplied by the PI. For example, if QFW results in 20% deficiency; then, the work is done with 80% efficiency. Hence, productivity is equivalent to $0.8*P_r$.

6. 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 had different parts. It collected the piling process productivity qualitative factors in one of these parts. The questionnaire participants 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 out data forms, and telephone calls. The second technique used the questionnaire.

7. THE PI MODEL IMPLEMENTATION TO PILING PROCESS DATA SET

Piling process data were analyzed using the concepts introduced above. The QFW factor was calculated as shown in equation (1). These two terms are the worth score of a factor $V_i(x_i)$ that reflects the one-dimensional value of the performance level of the factor as it exists for a specific project and the composite relative weight of a factor W_i that reflects its relative importance to the other factors, irrespective of any particular project. The following two subsections introduce how to determine each term in the context of piling process productivity problem.

7.1 Qualitative Factor Worth (QFW) Model Application to Piling Process Productivity

QFW and PI determination

Both terms of equation (1) should be determined to calculate the QFW, which is equivalent to the summation of $W_i * V_i(x_i)$. The final outcome of the QFW is 0.3 as shown in Table 2 that shows the qualitative factors, their relative weight and worth, the QFW, and the PI. Since the PI is the complement of the QFW, then, the PI is equivalent to 0.70. The PI is the index that is multiplied by the deterministic and simulation optimistic productivity results to cope with the real world practice. In other words, the PI represents the effect of qualitative factors in both techniques. Upon determining productivity using either deterministic or simulation techniques, the final productivity value can be estimated considering the qualitative effect using model (2).

Table 2: QFW and PI Determination

i	Qualitative Factors	W_i	$V_i(x_i)$	$W_i * V_i(x_i)$
1	*Operator Efficiency*	0.1390	0.2147	0.0299
2	*Weather Conditions*	0.0734	0.3441	0.0253
3	*Site Conditions*	0.1060	0.3701	0.0392
4	*Job Management*	0.1188	0.2588	0.0307
5	*Soil Removal System*	0.0754	0.3294	0.0248
6	*Rate of Pouring System*	0.0971	0.2647	0.0257
7	*Mechanical Problems*	0.0974	0.2588	0.0252
8	*Owner/Consul. Problems*	0.0839	0.3118	0.0262
9	*Site Investigation*	0.1102	0.3706	0.0408
10	*Productivity Estimate Accuracy*	0.0988	0.3059	0.0302
$QFW = \sum (W_i * V_i(x_i))$				*0.30*
$PI = 1 - QFW$				*0.70*

8. CONCLUSIONS

This study has provided three insights into the piling process. It highlights the factors that influence the process productivity, assesses their relative importance, and finally develops the productivity index (PI) that represents the process efficiency. It uses the AHP method to develop the PI model, which is essential to adjust the optimistic assessment of deterministic and simulation techniques.

Ten qualitative productivity factors have been collected as the most important factors that affect piling productivity. These factors are piling machine operator efficiency, weather conditions, site conditions, job management, soil removal system, pouring system, mechanical problems, owner consultant problems, site investigation, and productivity estimate accuracy.

The operator efficiency has the maximum relative weight of 0.139 out of 1.0 with a standard deviation of 0.0478. Job management, site investigation, and site conditions compete for the following three ranks with relative weights of 0.1188, 0.1102, and 0.1060 with a standard deviation of 0.0417, 0.0458, and 0.0296, respectively. The lowest relative weight is 0.0734 for weather conditions with standard deviation of 0.0297.

Since the PI is the complement of the QFW, it has the value of 0.7 because the QFW equals 0.3 for the piling process. The PI is the index that is multiplied by the deterministic and simulation optimistic productivity results to cope with the real world practice.

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10. APPENDIX I: NOTATION

QFW = Qualitative Factors Worth
W_i = Relative weight for each factor i using Eigen Value method.
$V_i(x_i)$ = Worth value for each qualitative factor (x_i).
x_i = Different qualitative factors i.
n = Number of qualitative factors (10 factors).
P_f = the final productivity value using deterministic or simulation technique.
P_r = the resulted optimistic productivity value using both techniques.
PI = the productivity index represents the qualitative factors.
QFW = the productivity qualitative factors worth.
VF = Validation Factor
PMR = Productivity Model Result from Simulation
CP = Collected Productivity
i =1,2,3,…………,n.