SELECTING PILE CONSTRUCTION METHOD USING FUZZY APPROACH

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ABSTRACT

The selection of pile foundation construction method depends mainly upon the subjective opinion of construction practitioners. Therefore, this experience has to be documented and stored in the intelligent company database for usage in future pile construction projects. This research introduces an attempt to store the experts’ subjective experience using a fuzzy expert system (FES) or fuzzy model. The proposed model uses soil type, environmental conditions, water table position, and granular strata location as input variables. It produces the appropriate pile construction method and its associated membership value as outputs. The FES system is designated based upon construction facts and practitioners’ opinion. It is validated and a sensitivity analysis is performed to check its sensitivity to any changes in the inputs. It proves its robustness in selecting the appropriate pile construction method.

KEY WORDS

Fuzzy expert system; pile construction method; fuzzy variables; fuzzy rules; soil conditions.

INTRODUCTION

It is difficult to establish a set of rules that exactly select the right pile construction method for every site or job. Guidelines can be constructed to help the selection process in many sites. Difficulty in selecting the proper construction method for piles arises because of the large number of factors that dictate this decision. Furthermore, there are many pile types available in the market that make the selection process tough. The contractor/consultant should look at each construction site critically to decide whether the proposed pile construction method accommodates ground conditions, environment, and available budget. The factors that dictate this selection process can be summarized as follows: (1) large variation in soil conditions; (2) environmental conditions; (3) economics of the construction method; and (4) availability of large number of pile construction methods. Usually, the selection process relies on the experience of contractor/consultant or their geotechnical engineers (practitioners). This experience should be documented so that when an engineer leaves the company, his/her experience is still owned by this company.

There is a lack of models and tools that capture the experience of practitioners on how to select the appropriate pile construction method. Therefore, this research aims at and focuses on building a prototype fuzzy expert system (FES) that documents practitioners’ opinion and facilitates the selection process of pile construction method considering environmental and soil conditions. This research contributes to the state of the art of pile construction selection.

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methodology by developing the FES model that facilitates geotechnical engineer’s job (contractor/consultant).

DIFFERENT TYPES OF PILE SYSTEMS

Fuller (1983) reported that piles are generally constructed of timber, concrete, steel, or combination of these materials. Concrete piles include three categories as shown in Figure 1: pre-cast; cast-in-place; and composite piles. The basic types of cast-in-place piles are uncased and cased. Uncased cast-in-place concrete piles include drilled-hole, cast-in-situ, and auger-grout. Drilling or otherwise excavating a hole in the ground and filling it with plain or reinforced concrete constructs the drilled-hole pile. Holes can be drilled with a short-flight auger or a bucket drill. Drilled-hole piles are known by several names, such as bored piles, drilled piers, caisson piles, or drilled shafts (Fuller, 1983). Fleming, Weltman, Randolf, and Elson (1992) categorized the pile types into two basic methods of installation: driving the pile into the ground (driven piles); or excavating the ground, usually by boring, and filling the void with concrete (bored piles).

Figure 1: Types of Concrete Piles (Adapted from Fuller, 1983).

FACTORS THAT AFFECT PILE CONSTRUCTION METHOD SELECTION

Young (1981) stated that there are three chief factors determining the selection of pile construction method: site environment, soil conditions, and economics of the construction method. Thornton (1992) reported that the factors that govern the selection of pile construction method are environmental conditions and price. Therefore, the factors that dictate the decision of selecting pile construction methods can be categorized as: (1) environmental conditions, (2) soil conditions, and (3) economics.
ENVIRONMENTAL CONDITIONS

Environmental conditions for piling process can be classified into: inside city (close to buildings); outside city (far from buildings); and marine works. When piles are constructed inside a city site (close to buildings), there will be many environmental problems arise when using driven piles, such as vibration of the surrounding buildings’ foundation due to hammer usage in addition to its associated noisy (Young, 1981). In such case, drilling piles are most proper to do the job because they are neither constructed with vibration nor noisy. In open sites or outside city sites, there will not be similar concerns whereas the pile type will be dictated by the soil conditions and economics (Young, 1981). In marine works, the most preferable pile construction method is driven piles. Consequently, these environmental conditions play a very effective rule in selecting pile construction method.

SOIL CONDITIONS

Soil condition is the largest factor that dictates the choice of pile type. For example, if the soil is clay or a big stratum of soil is clay, the decision favors drilling type pile. On the other hand, if the soil is granular, such as sand, the decision favors driven type pile. There are many intermediate conditions in which the selection is not obvious and the contractor/consultant experience is the major player in this case (Young, 1981). Generally, stiff soils dictate the drilling pile type and granular soils dictate driven pile type decisions. Consequently, soil conditions are essential when deciding the pile method of construction.

ECONOMICS OF PILE FOUNDATION

As previously explained, there are many pile construction methods that vary too much in their expenses. In situations where many alternatives are suitable and available make it difficult for practitioners to select the economical method, especially when the cheapest tender will not be necessarily the economical method. Many economical problems result in the wrong usage of pile construction method based on soil type and ground water conditions. Sometimes the availability of pile machine is the major economical factor that dictates the pile construction method decision. Therefore, the economics of pile construction method is a considerable factor that has to be considered when selecting the appropriate pile type.

SOIL CLASSIFICATIONS

Because soil type is a major factor in selecting pile construction method, soil classification is essential. The textual soil classification can be determined on the bases of the amounts of sand, silt-size, and clay-size materials expressed as percentages of the total weight of these three sizes only, and not as percentages of the total weight of the soil (Ramiah and Chickanagappa, 1990). Table 1 shows the composition (%) for the textural soil classification. For example, if a soil has 10% of clay-size materials, 10% of silt-size materials, and 80% of sand, then this soil can be classified as sand. Consequently, the ranges in Table 1 can be considered as borderlines for different textural soil classifications.
FUZZY EXPERT SYSTEM (FES) [FUZZY MODELING CONCEPTS]

The FES is an expert system that uses a collection of fuzzy membership functions and rules, instead of Boolean logic, to reason about data. The process of building the FES includes (Horstkotte, 2002; Chao and Skibniewski, 1998; Meesad, 2001; and Hwang, 1999):

1. **FUZZIFICATION**: the membership functions defined on the fuzzy input variables are applied to their actual values to determine the degree of truth for each fuzzy rule premise.
2. **INFERENCE**: the true value for the premise of each fuzzy rule is computed, and applied to the conclusion part of each rule.
3. **COMPOSITION**: all of the fuzzy subsets assigned to each output variable are combined together to form a single fuzzy subset for each output variable.
4. **DEFUZZIFICATION** (optional): which is used when it is useful to convert the fuzzy output set to a crisp number.

Table 1: Textural Classification of Soil Based on Grading (Modified After Ramiah and Chickanagappa, 1990)

<table>
<thead>
<tr>
<th>Textural Class</th>
<th>Composition in Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand</td>
</tr>
<tr>
<td>Sand</td>
<td>80-100</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>50-80</td>
</tr>
<tr>
<td>Sandy Silt</td>
<td>0-50</td>
</tr>
<tr>
<td>Silt</td>
<td>0-20</td>
</tr>
<tr>
<td>Clay-sand</td>
<td>45-80</td>
</tr>
<tr>
<td>Silt</td>
<td>0-45</td>
</tr>
<tr>
<td>Sandy Clay</td>
<td>35-70</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>0-35</td>
</tr>
<tr>
<td>Clay</td>
<td>0-50</td>
</tr>
</tbody>
</table>

The FES is designated based upon several fuzzy logic concepts: fuzzy set; fuzzy number; fuzzy relations and implications; fuzzy variables and their values; fuzzy rules; and others. This paper only introduces certain definitions for some of the above concepts. Fuzzy set is a collection of objects in a set whose elements have different degrees of belonging (membership) to the set. The membership function is used to calculate the elements’ degree of belonging to the fuzzy set (Tsoukalas and Uhrig, 1997). The elements of all the sets under consideration in a given situation belong to an invariable, constant set, called the universal set or universe or more often the universe of discourse. The term universe of discourse is used in fuzzy logic (it comes from the classical logic) and describes the complete set of individual elements that can be referred to or quantified (Tsoukalas and Uhrig, 1997).

Fuzzy number is a continuous fuzzy set that is used to represent the “about,” “almost,” or “nearly” qualities of numerical data and contains two properties: convexity and normality (Lorterapong and Moselhi, 1996; Tsoukalas and Uhrig, 1997). Convexity ensures that membership function has only one distinct peak; however, normality ensures that at least one element in the fuzzy set has a membership equals to 1.0. In real-world problems, triangular and trapezoidal fuzzy numbers are frequently used (Lorterapong and Moselhi, 1996).
Linguistic variables are called fuzzy variables. It is a variable whose arguments are fuzzy numbers that are referred to as fuzzy values (Tsoukalas and Uhrig, 1997). For example, the arguments of the linguistic variable temperature may be LOW, MEDIUM, and HIGH (fuzzy values). Each fuzzy value is modeled by its own membership function based on a unified universe of discourse (Tsoukalas and Uhrig, 1997). In summary, any linguistic (fuzzy) variable consists of different fuzzy values that can be represented by a membership function on a unified scale (universe of discourse).

The FES is a procedure for performing a task formulated as a collection of fuzzy if/then rules. These rules are representation for a linguistic if/then statement that governs or limits the FES. The rules in the FES have the following form: IF precondition 1 AND precondition 2 AND precondition 3 AND …. THEN consequence 1 AND consequence 2 AND …. (Chao and Skibniewski, 1998). Each fuzzy rule has to fulfill the character of “completeness of rule base.” Completeness is the knowledge representation scheme that can represent every entity within the intended domain (universe of discourse). For more details about fuzzy concepts and expressions, the reader is referred to Tsoukalas and Uhrig (1997).

KNOWLEDGE ACQUISITION

Two steps have been used to acquire the knowledge needed for this research: (1) construction facts and literature review; and (2) practitioner interviews. Fifteen pile construction practitioners have been interviewed to collect data for this research. The practitioners provide information about many project conditions and the most suitable pile construction method. The collected data are divided into model building (70%) and validation (30%) data sets. The first data set is used to build the model; however, the other data set is used for validation.

THE FES DESIGN

Based on the limitations of the pile construction methods, the FES rules are constructed. The membership functions of fuzzy input and output variables are an essential part in building the FES as shown in Figure 2. The input variables in this study are environmental conditions, soil type, water table situation, and granular soil position. These inputs are entered into the FES to provide the selected pile construction method(s) and the percent of membership function for each method. Therefore, the FES consists of three different components as shown in Figure 2: fuzzy input variables and the membership functions of their fuzzy values; fuzzy rules based on mamdani-min implications; and fuzzy output variables. The explanation of how to build each component of the FES is shown in the following sections.

FUZZY VARIABLES

Two major input variables are considered in this study: environmental and soil conditions; however, economics will be embedded in this model in future study. As discussed earlier, soil conditions are divided into three sub-factors: soil type, water table situation, and granular strata position. Soil type variable is represented using three different scales: sand, silt-size, and clay-size percents as shown in Table 1. Therefore, soil type has been divided into three variables: soil type on sand scale, soil type on silt scale, and soil type on clay scale.
Consequently, this study considers the following input variables:
1- Environmental conditions 2- Soil type on sand scale 3- Soil type on silt scale
4- Soil type on clay scale 5- Water table situation 6- Granular strata position

One output variable is considered in this study (recommend pile construction method based on the FES inputs).

**VALUES OF FUZZY VARIABLES**

**Values of input fuzzy variables**

Six input fuzzy variables are considered in this study. Each one has its own fuzzy values in which their membership functions express their nature along the universe of discourse of the entire fuzzy variable. All figures that show these input variables are not included in this paper because of space limitation. The fuzzy values in addition to their membership functions for input variables are described as follows:

(a) *Environmental Conditions Fuzzy Variable*: Environmental conditions fuzzy variable is divided into four different fuzzy values: close to buildings; far from buildings with available headroom for the driving machine; far from buildings without headroom; and marine works. If one fuzzy value is selected, the other fuzzy values will be zeros. There is no overlap between the different fuzzy values. Each value is subjective and can be represented by a fuzzy set. For example, a zone of 0-1 mile distance can represent the fuzzy value “close to buildings”. Any distance within this zone belongs to the fuzzy value “close to buildings” with a percent. Therefore, this fuzzy value can be represented with a membership function.

(b) *Soil Type Fuzzy Variable on Sand, Silt, and Clay Scales*: Soil type fuzzy variables are divided into nine fuzzy values based on categories and ranges that are shown in Table 1. These ranges represent the borderlines for different textural soil classes. It is assumed that these borderlines are approximate separators where the soil type that is limited by this borderline can be extended beyond this border with a percent (membership) value. For example, soil can be classified as 100% clay if it has above 50% clay size material, below 50% silt size material, and below 50% sand size material. Beyond these borders (limits), the soil can be classified as clay with a percent (0-100%). To represent a soil “clay with zero
percent,” this study assumes that 10% increase beyond the borderline reaches the membership value of zero. This assumption is based on the phenomenon that 10% is the least width of any soil type on any of the three scales. For example, clay borderline can be extended inside the borders of silty clay up to 10% with a membership value less than 1. Therefore, on the clay scale, the clay borderline is 50% whereas the clay membership will not be zero because any soil that has 50% clay is considered as clay but with percent. On the 40% scale clay, one can say this soil cannot be considered clay because this is the borderline for silty clay with anther soil type, which is, of course, not clay. Consequently, it can be considered clay with zero percent membership value. The same assumption is applied for all the other textural soil categories. On the other hand, the middle point of each range, Table 1, is considered the maximum membership value (one) for this membership function.

(c) **Water Table Variable Fuzzy Variable:** Soil water table is a reasonable effective factor in the methodology of pile construction method selection. This study considers only two fuzzy values for water table fuzzy variable: low water table and high water table.

(d) **Granular Strata Position Fuzzy Variable:** Practically, granular strata affect the pile construction method decision when drilling type is used. This study considers two different fuzzy values for this fuzzy variable: middle position; and upper position.

**Values of output fuzzy variable**

The output fuzzy variable includes the selected method of construction for a specific pile project. This fuzzy variable has four different fuzzy values: driven piles (dp); bored piles using bentonite slurry (bp-sm); bored piles using casing (bp-cm); and bored piles using dry method (bp-dm). A figure that represents the output fuzzy variable is not included in this paper because of space limitation.

**Fuzzy Rules**

A typical FES must have a group of rules. The entire group of rules is collectively known as a rule base or knowledge base (Horstkotte, 2002). It has to cover the entire universe of discourse of the input and output fuzzy variables (completeness of rule base). The available fuzzy variables have the number of fuzzy values that are shown in Table 2. The variables, as mentioned in Table 2, result in large number of rules, which make the problem difficult to address using any fuzzy computer application. Therefore, to reduce the computation process, some variables have been modified. The environmental conditions fuzzy variable is modified to have three fuzzy values instead of four. The “far from building with no headroom available (ffb-nh)” fuzzy value has been eliminated because it gives the same results as the “close to buildings (ctb)” fuzzy value. The fuzzy values of soil type fuzzy variable have been reduced to one value instead of three values. The selected fuzzy value is “soil type on sand scale” because the soil textural classifications are well distributed and defined on that scale. Consequently, based on the previous discussion, 18 fuzzy values have been reduced and the modified number of fuzzy values is shown in Table 3. After this modification, the fuzzy model can be designated using 66 rules whereas this is the minimum number of rules that can be used in this problem. The opinion of construction practitioners is used to build this set of
66 rules. An example of one rule: IF a pile has to be constructed in a sand soil AND inside city zone AND high water table AND middle granular strata, THEN, the selected construction method is bored pile (slurry method (bp-sm)).

**THE FES FEATURES**

There are several features that have been set to the designated FES, such as membership functions, fuzzy relations, fuzzy implication, and the defuzzification method. Triangular shape is selected to represent the membership functions for the fuzzy values of input and output fuzzy variables for two reasons: (1) it is very simple to apply and to understand from construction personnel; and (2) it is commonly used by researchers in the fuzzy logic field, such as Lorterapong and Moselhi (1996). Fuzzy relations of the current FES use the “max-min composition.” “Mamdani-min implication operator” is used in the current FES as a fuzzy implication. The Center of Gravity (Centroid) as a method of defuzzification is used as inference in the current FES. For more details about these features, the reader is referred to Tsoukalas and Uhrig (1997). The MATLAB computer package is used to build, analyze, and conclude the results of the FES.

Table 2: The Number of Fuzzy Values Corresponding to Each Fuzzy Variable.

<table>
<thead>
<tr>
<th>Fuzzy Variable</th>
<th>Number of Fuzzy Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Conditions (Input)</td>
<td>4</td>
</tr>
<tr>
<td>Soil Type on the Sand Scale (Input)</td>
<td>9</td>
</tr>
<tr>
<td>Soil Type on the Silt Scale (Input)</td>
<td>9</td>
</tr>
<tr>
<td>Soil Type on the Clay Scale (Input)</td>
<td>9</td>
</tr>
<tr>
<td>Water Table Situation (Input)</td>
<td>2</td>
</tr>
<tr>
<td>Granular Soil Position (Input)</td>
<td>2</td>
</tr>
<tr>
<td>Pile Type (Output)</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3: The Modified Number of Fuzzy Values Corresponding to Each Fuzzy Variable.

<table>
<thead>
<tr>
<th>Fuzzy Variable</th>
<th>Number of Fuzzy Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Conditions (Input)</td>
<td>3</td>
</tr>
<tr>
<td>Soil Type on the Sand Scale (Input)</td>
<td>9</td>
</tr>
<tr>
<td>Water Table Situation (Input)</td>
<td>2</td>
</tr>
<tr>
<td>Granular Soil Position (Input)</td>
<td>2</td>
</tr>
<tr>
<td>Pile Type (Output)</td>
<td>4</td>
</tr>
</tbody>
</table>

**MODEL VALIDATION**

The designated FES must be tested to check whether its output is similar to practitioners’ opinion. Therefore, the conditions of 61 pile construction cases (validation data set) are entered into the FES to check its validity as shown in Figure 3. The designated FES results show that 51 out of 58 cases are assessed similar to practitioners’ decision, which represent 87.9%. Consequently, the model is valid with 87.9 %. This validation effort needs more data by implementing the proposed FES to real projects. A feedback has to be collected to show the degree of practicality for the FES and enhance the system.
SENSITIVITY ANALYSIS

The designated FES has extensively been used to answer more than one hundred questions about the proper pile construction method corresponding to different soil, water table, granular strata, and environmental conditions. Twelve charts have been constructed according to the FES results; one of them is shown in Figure 4, which is constructed for conditions: close to buildings, medium water table, and middle granular strata. By fixing these conditions in Figure 4 and changing the sand percent in soil type variable from 10-100% result in the proper construction method with a membership function varies from 0 to 1. For example, at 10% sand in addition to the other conditions, the appropriate method is to use bored with casing (bp-cm) at 100% membership value. On the other hand, at 70% sand in addition to the other conditions, the appropriate method is to use bored with casing (bp-cm) at 91% and bored with slurry (bp-sm) at 9% membership value.

CONCLUSIONS AND RECOMMENDATIONS

Because the problem of selecting pile construction method is subjective in nature, fuzzy logic is used to designate a FES that helps selecting the most appropriate method based on several conditions. Literature review and practitioner opinions are consulted to designate the FES, its rules, and its validation process. Fuzzy input and output variables in addition to fuzzy rules of the FES are designated to cover most of the pile selection method features. The FES is validated to prove its robustness in selecting the appropriate pile construction method. A sensitivity analysis is performed to check the sensitivity of the FES to any changes in the inputs. It also provides the appropriate pile construction method and its associated membership value. The author recommends additional future work as follows:

- Enlarge this study to comprise economics, loading conditions, and more soil types (number of input and/or output fuzzy variables; and their fuzzy values).
- Increase the sensitivity of the FES by changing the fuzzy logic features, such as the composition method, the implication operator, and the method of defuzification.
Design an automated tool that assists contractors, designers, and owners select the appropriate pile construction method.

Figure 4: Pile Construction Method and Its Associated Membership Value at Different Conditions: (Close to Buildings - Medium Water Table - Middle Granular Soil Strata)

REFERENCES


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http://physics.uwstout.edu/geo/sect7.htm


