Application of Expert System for Soil Classification from CPT

by

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Dissertation submitted in partial fulfillment of the requirements for the
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(Civil Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

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(Assoc. Prof. Dr. Indra S.H. Harahap)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
July 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgement, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD FAREEZ BIN MOHD YUSOFF

ABSTRACT

Data obtained from Cone Penetration Test has been used to develop site layering system and soil classification. Common approach for soil classification from cone data is to use graph and charts that correlate cone resistance and other non dimensional factor to obtain a soil type. This approach, or other approach based on this type of graph has been known to produce a rapid change of soil type even for a close vertical distance. This rapid change is believed beyond the possible range associated with random formation of oil, rather because of fixed artificial boundary established when developing such graph. In this context, fuzzy approach is consider to be superior to represent smooth change between soil layers compare to crisp approach. This paper describes procedure for soil classification based on Cone Penetration Test (CPT) using Fuzzy Expert System (FES). Fuzzy membership function is derived to approximate known correlation between cone penetration and friction resistance to each soil group. Simple rules are used to classify primary soil group (sand, silt, clay) and secondary soil group (silty clay, clayey sand, etc.). Preliminary work using only membership function of primary soil type indicates that soil type inferred using FES is found out to be comparable to other method in term of consistency between two adjacent cone readings. However, FES moderately performs to identify secondary soil type if compared to visual observation from boring log.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND STUDIES

Cone Penetration Test (CPT) or Cone Penetration Test with Pore Pressure (CPTU) was an in situ testing method initially developed in Dutch during 1950s for the purpose of determining the geotechnical engineering properties of soils and define soil stratigraphy. Back then, the CPT mainly determines the geotechnical properties of bearing capacity. Most modern electronic CPT cones now, employs a pressure transducer with a filter to gather pore water pressure data thus making data obtained from CPT and CPTU results useable in developing soil stratigraphy.

Common approach for soil classification from cone data are either to correlate the CPT results with the sample boring from borehole which is 10ft to the CPT hole or to use graphs that correlate cone resistance and other non dimensional factor to obtain soil type. The first comprehensive soil classification chart was developed for use by Douglas and Olsen (1981). The soil classification chart utilized the tip resistance and the friction ratio to determine the soil type. General trend of the chart indicates that high tip resistance and low friction ratio are criteria for Sand while low tip resistance and high friction ratio are criteria for Clay.

Expert system is a program that able to imitate human expertise by applying inference methods to a specific body of knowledge called domain which is knowledge that frequently represented as rules. Knowledge and experience possessed by engineers will be acquired and structured in a form suitable for manipulation by the expert system. Due to its ability to combine factual knowledge with judgment to handle incomplete and uncertain data, such system is favorable to engineers.

1.2 PROBLEM STATEMENT

The approach or other approach based on the type of graph created by researchers before has been known to produce a rapid change of soil type even for a close vertical distance. This rapid change is believed beyond the possible range associated with random formation of soil, rather because of fixed artificial boundary established when developing such graph. In this context, fuzzy approach is consider to be superior to represent smooth change between soil layers compare to crisp approach.

Although the Knowledge Based Expert System had shown positive result from the usage of The Schmertmann profiling chart, the success rate of the soil classification are still low and can be improved. This is because the Schmertmann profiling chart is based on the onshore soil sample and trial of data shows that it is impractical to tally the soil identification by CPT data and the soil identification by sample based on the Schmertmann's. As offshore soil sample known to have slightly different properties than onshore soil sample, classification of soil can be define more efficiently using the proposed chart that are specialized for offshore soil sample which are Guide for identification of soil type from piezocone data (After Robertson et al, 1986).

1.3 OBJECTIVE & SCOPE OF STUDY

The objectives to be achieved by the end of this project are:

- To describes procedure for soil classification based on Cone Penetration Test (CPT) using Fuzzy Expert System (FES).
- To compare the FES results of analysis with the visual observation of the sample for each borehole logs.
- To change the previous rules of FES and to include new rules by using new classification guide.
- To update on the Secondary Soil Type Member function for FES with new information on Soil Classification.

The scope of work for the project shall be conducted for several offshore soil CPT holes taken within Malaysia. Several more data will be used to further studies on the soil classification. The time given is considered to be sufficient to complete all the scope of work, as this is a two-semester project.

CHAPTER 2

LITERATURE REVIEW

2.1 KNOWLEDGE BASED EXPERT SYSTEM

Knowledge Based Expert System is a computational system program that solves problems which normally require human intelligence by manipulating and functioning with human knowledge provided beforehand. The expert system represents the expert's knowledge as data or rules in the computer. It is designed to carry the intelligence and information found in the intellect to other member for problem solving by calling upon the expert's knowledge data and rules for problem solving. Conventional computer programs perform tasks using the conventional decision making logic which contain algorithm for solving specific problem and boundary conditions. Knowledge Based Expert System, revolutionized the decision making logic; rather than only depending on the basis algorithm and specific boundary, the system collects small fragments of "human-reasoning" skills into a knowledge-base which used to reason through problem with appropriate knowledge. Hence, different problem in domain of the knowledge-based can be solved using the same program without reprogramming.

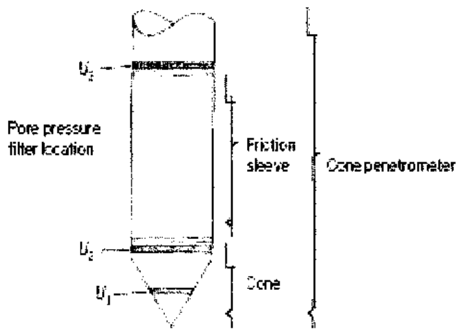
C-Languages Integrated Production System, CLIPS is an expert system tool developed by the Software Technology Branch (STB), NASA/Lyndon B. Johnson Space Center. CLIPS are designed to facilitate the development of software to model human knowledge or expertise. Key features of CLIPS; knowledge representation that able to handle variety of knowledge with support for three different programming paradigms: rule-based, object-oriented and procedural (Riley, 2006). In addition to that, portability since it comes with source codes that can be modified or tailored to meet specific needs and thirdly, integration and extensibility because it can be embedded within procedural code, called as a subroutine, and integrated with languages such as C, FORTRAN and ADA.

National Research Council of Canada (NRC) had implemented a FES shell on top of CLIPS. The extended version is called FuzzyCLIPS. The modifications made to CLIPS contain the capability of handling fuzzy concepts and reasoning. It enables domain experts to express rules using their own fuzzy terms. FuzzyCLIPS allows any mix of fuzzy and normal terms, numeric-comparison logic controls, and uncertainties in the rules and facts. Fuzzy sets and relations deal with fuzziness in approximate reasoning, while certainty factors for rules and facts manipulate the uncertainty.

2.2 CONE PENETRATION TEST

The cone penetration test (CPT) is an in situ testing method used to determine the geotechnical engineering properties of soils and delineating soil stratigraphy. It was initially developed in the 1950s at the Dutch Laboratory for Soil Mechanics in Delft to investigate soft soils. Based on this history it has also been called the "Dutch cone test". Today, the CPT is one of the most used and accepted in-situ test methods for soil investigation worldwide. The static cone penetrometer (CPT) and the piezocone (CPTU) represents the most versatile tools currently available for in-situ soil exploration as there has been significant growth and development in the use of CPT for the past 30 years and this is reflected in the impressive growth of the theoretical and experimental knowledge on the cone penetrometer and piezocone as well as in the several applications of the test to highly specialized measurements, e.g. seismic, environmental and electrical resistivity measurements. The test method consists of pushing an instrumented cone tip first into the ground at a controlled rate that is 3m per thrust. CPT for geotechnical applications was standardized in 1986 by ASTM Standard D 3441 (ASTM, 2004). Later ASTM Standards have addressed the use of CPT for various environmental site characterization and groundwater monitoring activities. Particularly for geotechnical soil investigations, CPT is gaining popularity compared to standard penetration testing as a method of geotechnical soil investigation by its increased accuracy, speed of deployment and reduced cost over other soil testing methods. The ability to advance additional in-situ testing tools using the CPT direct push drilling rig, including the seismic tools described below, is accelerating this process.

The piezocone test (CPTU) is a cone penetration test (CPT) with additional measurement of the pore water pressure at one or more locations (U_1, U_2 and U_3) on the penetrometer surface (see figure below):



Cone penetration testing, with pore water pressure measurements, gives a more reliable determination of stratification and soil type than a standard CPT. In addition; CPTU provides a better basis for interpreting the results in terms of mechanical soil properties. Mechanical properties to be evaluated are:

- Shear strength parameters
- Deformation and consolidation characteristics.

Other than that, site layering system also can be done with CPT as its capability to obtain soil continuous soil profile (Baligh et al, 1980) and obtaining the soil type through classification (Schmertsmann, 1978, Sanglerat, 1982 and Robertson, 1990). However, the cone penetration test induces complex changes in stresses and strains around the cone tip. No one has yet developed a comprehensive theoretical solution to this problem. Thus, the interpretation of cone penetration data is made with empirical correlations to obtain required geotechnical parameters.

These are several factors that affect the interpretation of CPT data:

1. **Equipment design:** It influenced the measured parameters and therefore affects the subsequent interpretation. Three major areas of cone design that influence the interpretation are unequal area effects, piezometer location, size and saturation, and accuracy of measurements. Calibration and calculation for corrected results are needed. Test results in sand are little influenced by the above factors.

2. **In situ stresses:** Studies have shown that the in situ horizontal effective stress has a dominant effect on the cone resistance, and the friction sleeve stress. Therefore, the stress (geologic) history of the deposit is of great importance

in CPT interpretation. The interpretation of CPT data should have qualitatively account for such effects that may influence the horizontal stresses like applied surface load, static and vibratory compaction or the installation of piles.

3. **Stratigraphy:** The transition from one layer to another will not necessarily be registered as a sharp change. Cavity expansion and strain path theories as well as laboratory studies (Schmertmann, 1978) shows that the cone resistance is influenced by the material ahead and behind the penetrating cone. Hence the cone will start to sense a change in material type before it reaches the new material and will continue to sense a material even when it has entered a new material. Therefore, CPT will not always measure the correct mechanical properties in thinly interbreed materials.

4. **Rate of Penetration:** Rate effects can be caused to some extent by creep and particle crushing. In general, however, the pore pressure effects predominate especially when using the piezocone in fine grained soil. A tenfold increase in rate causes 10%-20% increase in cone resistance in stiff layer and 5-10% in soft clays (Powell and Quarterman, 1988). Therefore, the recommended rate are 20mm/s with allowance of 5mm/s

2.3 SOIL CLASSIFICATION

Till recent years, the most comprehensive recent work on the soil classification using CPT data is that by Douglas and Olsen (1981). Their proposed soil-behavior type classification chart shows the correlation of CPT data and other soil type indices, such as those provided by Unified Soil Classification System (USCS). The work by Douglas and Olsen were used by others and initiated researchers to develop other classification chart. Most used classification method and accepted as standard classification chart, was developed by Robertson and Campanella (1983) as the charts is organized in a very similar manner yet it broke the chart into 12 different soil types. The chart was developed to cater the use of pore pressure parameter obtained by CPTU in 1985 by changing the use of friction ratio to the pore pressure ratio. Robertson (1990) again, modified the parameters by normalizing all of the data to the overburden and effective overburden at which the soil was tested so that it allows direct comparison between soils of different depths.

Though it is widely accepted, the one disadvantage of the charts is that the user must decide which chart to use, either the friction ratio version or the pore pressure version. This had concern the researchers Jefferies and Davis (1993) as the usage of both charts together to classify soil samples may results a different classification. Normalized CPT chart that included all three normalized measurements; Cone Bearing Q_T, Friction Ratio F_R, and Pore Pressure Ratio Bq was then formulated. The three parameters are utilized by developing the grouping of Q_T (1-Bq) with the F_R parameter. The grouping had been simultaneously proposed by Houlsby (1988) and Been et al. (1988) to aid in unification of CPT soil classification charts. Effect of pore pressure data from piezocone is to expand the interpretation range in finer soils. However, they stated that, CPT classification charts cannot be expected to provide accurate predictions of the soil type based on grain size distribution but can provide a guide to soil behavior type. Most classification charts, use the cone penetration resistance, q_c, and friction ratio, R_f. Where :

$$f_R = \frac{fs}{qc} \times 100\% \qquad \text{(Equation 1)}$$

Due to the existence of a lot of classification chart from yesteryears till now, overlap in zones of each graph should be expected and correction of parameters can be done as each graph can complete the other. Most used graph are Simplified soil behavior type classification for standard electric friction cone (Robert et al. 1986), Profiling chart per Douglas and Olsen, Charts by Jones and Rust 1982:Baligh et al-2.1980; Senneset and Janbu 1984, Profiling chart per Robertson and Campanella and The Schmertmann profiling chart. While almost all the CPT methods (basically charts) give a specific classification to each soil layer along the penetrated depth; the probabilistic region estimation method proposed by Zhang and Tumay (1999) is unique in addressing the uncertainty in miss-classifying the soil. This statistical based method provides a profile of the probability or the chance of having each soil type (clayey, silty, and sandy) with depth

Expert system can be helpful to the engineer at site to have an idea of the borehole log before the boring of sample is done as soil classification for borehole is not easy and time consuming. Moreover, engineers doing the secondary soil classification on the CPT data would have to base their judgment either on their previous CPT data interpretation experience or the borehole sample itself which would make them wait for the extraction. The complexity of data interpretation can be ease by the expert system by a formulate methodology based on algorithmic techniques and fuzzification. The approach of depending the evaluation on the rules based on the soil profiling chart and the knowledge acquired from domain experts could give accurate output. This fast and effective method would be very helpful to the site engineer and will give them a head start in doing complex spudcan analysis in offshore. For this expert system, Shcmertmann soil profiling is used to classify the soil. It should be noted that Shcmertmann is chosen as the soil profiling charts had a very good limit definition for soil classification.

Schmertmann 1978 proposed the soil profiling chart shown below. The chart is based on results from mechanical cone data in North Central Florida and incorporates Begemann's CPT data and indicates zones of common soil type. It also presents boundaries for loose and dense sand and consistency (undrained shear strength) of clays and silts, which are imposed by definition and not related to the soil profile interpreted from the CPT results.

Douglas and Olsen Classification Method is a comprehensive work correlating between CPT data and USCS soil classification in order to develop a CPT-soil behavior type classification method. The classification chart uses the cone R_f tip resistance (q_c) and friction ratio (R_f) input parameters. Douglas and Olsen (1981) method demonstrates that the CPT classification charts cannot provide an accurate prediction of soil type based on soil composition, but rather serve as a guide to soil behavior type (Lunne et al., 1997)

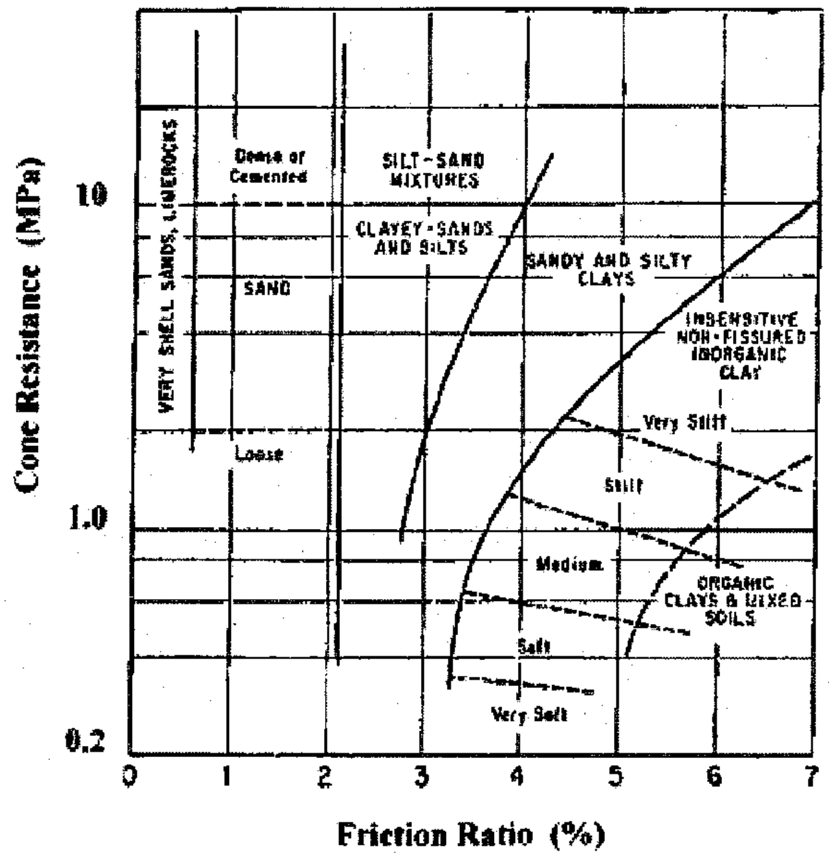


Figure 1: The Schmertmann Profiling Chart

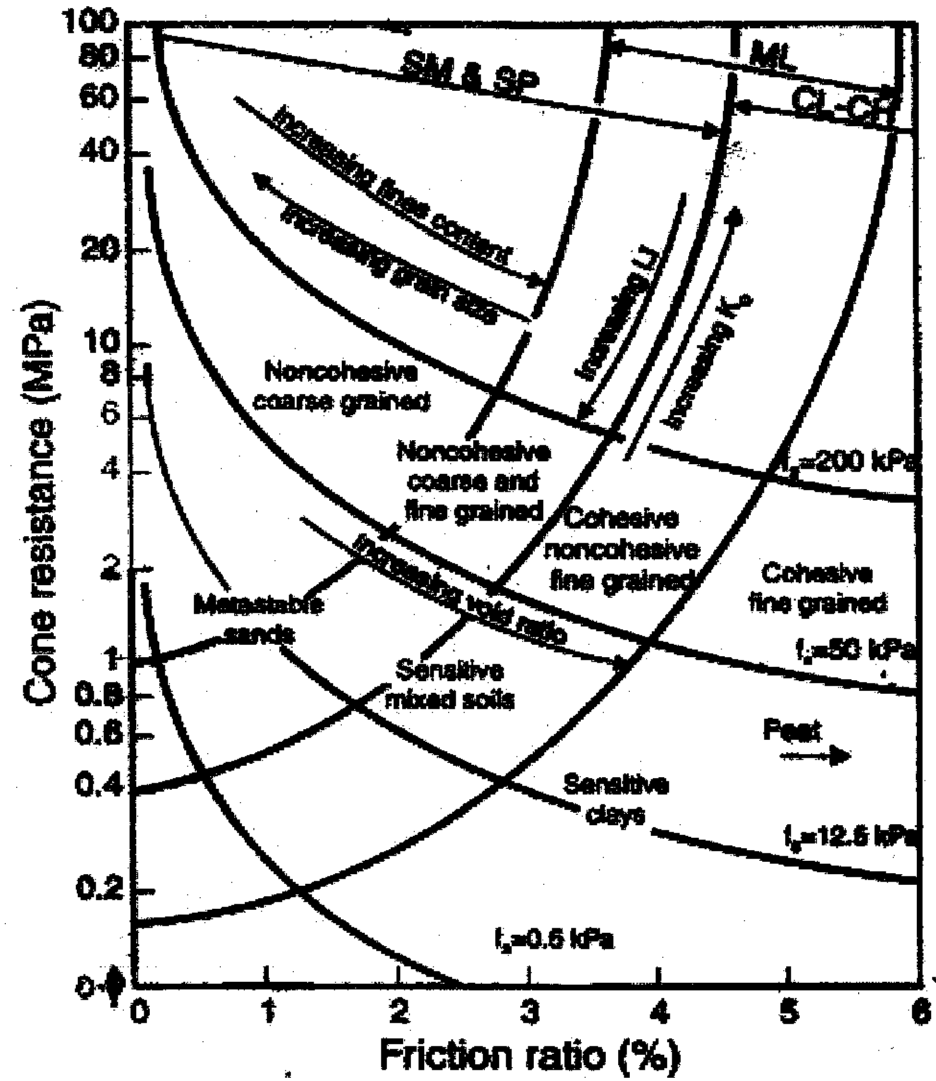


Figure 2: Dougles and Olsen Soil Chart

Robertson et al. Classification Method was developed in order to cater the use of CPTU data (q_c, f_s, u). Two charts are proposed and one chart uses the corrected tip resistance (q_t) and friction ratio (R_f) as the input data and the other uses q_t and pore pressure parameter (B_q). Engineering judgment is needed to classify the soil in case the interpretation using both charts resulting in two different groups among 12 existing group of soil behavior.

Interpretation on CPT data for soil classification was extensively described in the literature (Robertson and Campanella, 1983; Robertson 1989; Eslami1** and Fellenius, 2000). Zhang and Tumay (1999) "Statistical to Fuzzy Approach toward CPT Soil Classification" deals with the fuzzification of the CPT data in approaching the soil classification using non tradisional methods avoiding overlaps of different soil types in currently used CPT soil classification systems. Fuzzy subset approach is introduced to develop a truly independent CPT soil engineering classification, and to establish a transition between the new fuzzy approach and conventional soil classifications by utilizing local site and project specific calibrations. Nevertheless, there have been very few attempts to develop prototype artificial intelligence expert systems for expert soil classification. Kurup. and Griffin (2006) developed Prediction of Soil Composition from CPT Data Using General Regression Neural Network. Soil type is typically inferred from the information collected during a cone penetration test (CPT) using one of the many available soil classification methods. In this study, a general regression neural network (GRNN) was developed for predicting soil composition from CPT data. Measured values of cone resistance and sleeve friction obtained from CPT soundings, together with grain-size distribution results of soil samples retrieved from adjacent standard penetration test boreholes, were used to train and test the network. Alas, the program did not interpret the data well with only 86% and it only predict the primary soil type; sand, clay and silt. Toll (1996) had done paper on artificial intelligence applications on geotechnical which review on the knowledge based system and neural network on geotechnical engineering.

CHAPTER 3
METHODOLOGY

3.1 PROCEDURE IDENTIFICATION

Every phase of the research and development are identified to ensure smooth running of the project. The methodology divided into stages:

1. **Project topic selection**

   This crucial stage is to make sure that the topic chosen is feasible with the scope of studies and time frame given. Preliminary research and interview with lecturer were conducted for each scope of work.

2. **Project Planning**

   Defined scope of work is outlined along the given time frame to keep track with planned activities and to ensure that the project will be finished in the time frame and it goes smoothly without any delay.

3. **Literature Study**

   Information gathered are mostly from journal, internet, library and interview with respective supervisor who is well exposed in this area and able to clarify problems and uncertainty. Research by individuals on related topic serves a practical reference for basic understanding.

4. **Project work 1**

   Based on the schedule and planning, the project is done gradually. First stage is to prepare the data for the program as the input. Besides that, the software which is still new needed to be understand and learned quickly to continue with further study and analysis on the second stage.

5. **Soil Classification Chart/Guide Revision**

   For the efficiency of the Knowledge Based Expert System, comparison and improvement needed to be done by comparing the result with the new one analyzed from different type of Soil Classification Chart. In this step, revision and literature research are done to select the best Chart for comparison besides the Schmertmann's.

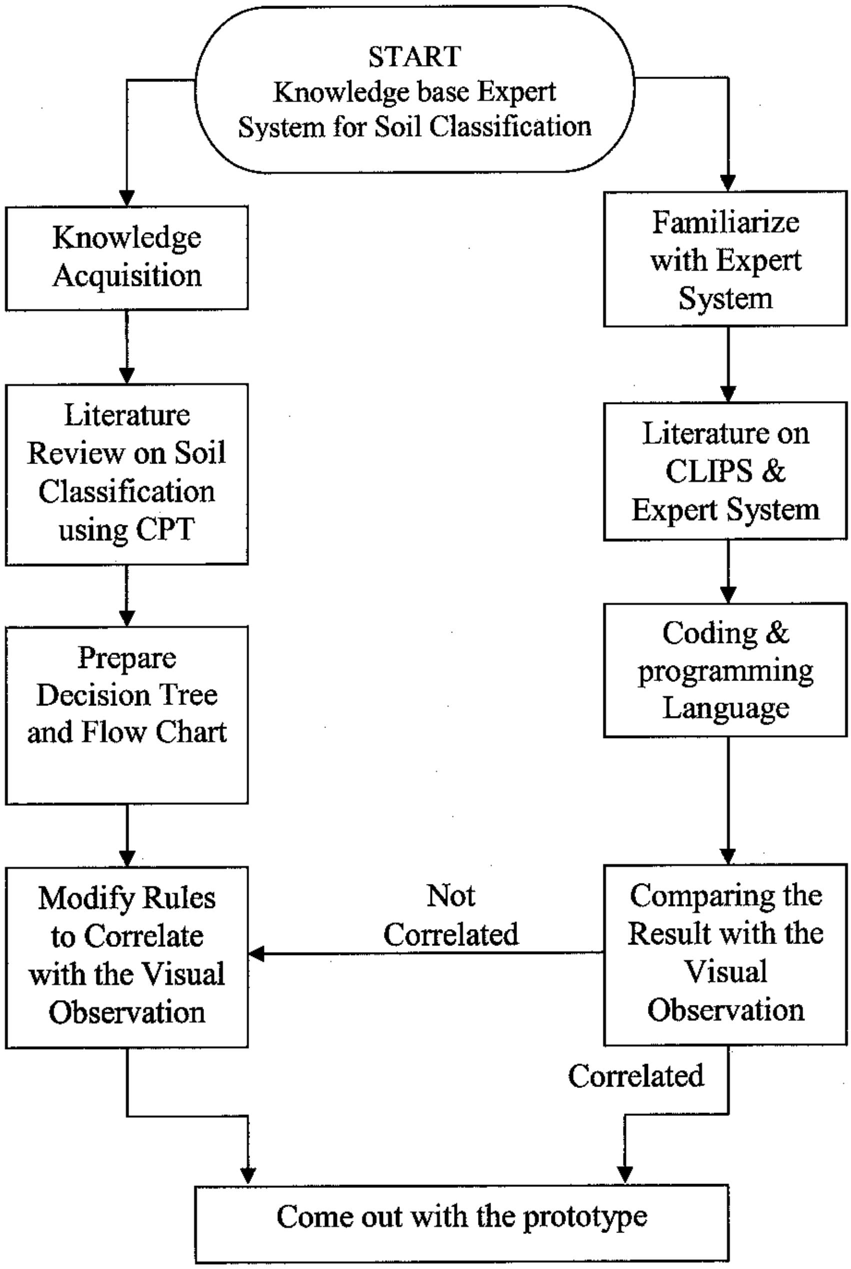
6. **Defining Rules**

As new information is gathered, limitations and boundary from the specified soil classification charts are to be extracted and designed so that, it can be read and serve as rules and limitations in the selection process in the expert system. New rules are defined for the new soil classification so that comparison can be made to measure the efficiency of the expert system.

7. **Project work 2**

Based on the schedule and planning, the project is done gradually. Several test run will be conducted on the data sample using the new rules of selection and success rate are predicted to increase.

Figure 3: Details Flow Chart of Procedures for the Project



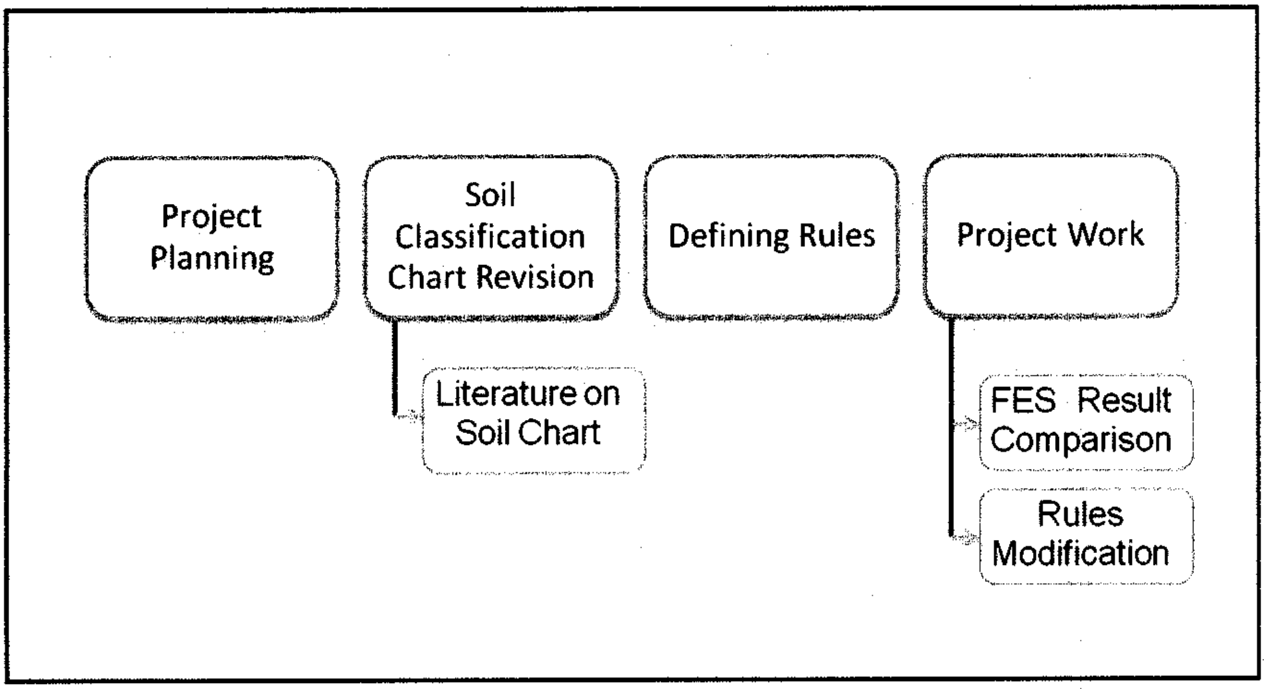


Figure 4: Rules Modification Process

The project is now on the highlighted box in figure 3. The steps which are modifying rules and limits are needed as to increase the tally correlation between the visual observation and the results itself. The modification process is based on the diagram in figure 4.

3.1.1 Procedure in Updating the Membership Function

The development of the membership function can be categorized in four parts:

1. **Correlation of Data and Sample**

   It can be denoted as the crucial step in developing the membership function for the expert system. Experience, knowledge and judgment are the main criteria that required by expert system and differentiate it with other analytical software. In order to know whether the expert system is required in the soil classification of CPT data, correlations have to be made between the data and visual sample observation. From the correlation with expert system analyzed soil classification and visual sample observation, we can identify the system's weakness or lack of 'experience'.

2. **Knowledge Acquisition and Representation**

   The knowledge acquisition phase of expert system development is the steps where author, acquire the 'experience' or knowledge which the experts uses to analyze the data and come to classify the soil into their respective primary and secondary soil and use it to update the memberships function by updating the selection criteria so that the effectiveness of this expert system increases. There are many literature and discussion used as references to update the membership, so expert system can give results that tally with the visual observation of sample and at the same time it does not contradict with most of the existed soil classification chart. In order to update the member function, consultation were done with supervisor Dr. Indrasati and engineers from TLGeosciences Sdn. Bhd. to extract the knowledge based on their experience.

3. **Evaluation and Adoption**

   More discussion will be concentrated in developing the function member to upgrade the expert systems. Selection rules and limit will be revised and adjusted to reach the desirable soil classification result by using the FES.

4. **Rules Adjustment and Implementation**

   In order to compare the previous results with the new one, new set of rules and limits are adapt from the Roberston et. al Method of Soil Classification Charts. The rules are extracted and modified in order to implement it in the expert system for the membership function to analyze and select. The rules adjustments need to be done to increase the reliability of the expert system.

For the soil classification in this project, several soil parameters are needed in doing the calculation and analysis. The basic parameters are the depth of the soil measured from the sea bed downwards in meter, the cone resistance, q_c which is basically used to find the soil strength at that depth (in-situ) with calculation of corrected value. It also provides useful information on the in-situ condition of soil. Friction ratio, f_R is expressed from skin friction, f_S by using equation 1. Where:

$$f_R = \frac{fs}{qc} \times 100\%$$

3.2 TOOLS REQUIRED

For this project, the programming is written in CLIPS format, that is an expert system choose as a platform for the project. CLIPS can be run using either Window operating system such as Windows XP or MAC. The program flow is planned in word document, such as tabulating the knowledge and maps decision tree. The program scripting itself can either be written in the notepad or CLIPSedt.exe. The scripting can be edited later on after saving the file as a *.clp format. The program then is test and run using CLIPS for identifying errors and to test run the analyzing. Programming flow will be repeatedly done to satisfy all boreholes so the correlation is correct and further errors can be avoided. Prototype is ready when all editing of rules are done.

Lists of tools used:

1. Expert System: CLIPS (C Language Integrated Production System)
2. Microsoft Office 2007
3. Windows XP Home Edition

Due the nature of the research, long hour focusing to the computer monitor may cause eye sore, migraine and anxiety. 15 minutes of rest is required for every 2 hours script writing and data analyzing to avoid detrimental symptom and promote healthy work culture.

CHAPTER 4
RESULTS AND DISCUSSION

For this project, it is started with the comparison between the computer analyzed soil classification and the visual observation done by the geotechnical engineer. Then, for each soil primary class (clay, silt and sand) and secondary soil class (clayey, silty and sandy), the author have recorded the hit and miss result of the comparison between 10 set of CPT data based classification by the expert system and the visual observation done; where hit is the number of results that correlate to the visual observation and miss is the number of results that differ from the visual observation. The author has decided to do graph of every 'hit and miss' for each soil type and the comparison the primary soil side by side.

Fuzzy Experts System proposed on using the Schmertmann Soil Classification Chart System as the based on developing the rule for selection. Based on the literature study done, Schmertmann Soil Classification chart are not conventionally used compared to Robertson Soil Classification for CPT data. Although the chart are developed based on the North America soil sample and give an empirical result, the expert system can still be used for as we can alter the membership function for different un-empirical data.

For the soil classification that is noted in this research, the primary soil types have been defined and listed below:-

1. **Clay** : Composed primarily of fine-grained minerals with particle size of 0.002 mm and smaller which show plasticity through a variable range of water content.
2. **Silt** : Soil derived from granular material and its particles ranging from 0.0625 mm to 0.002 mm in diameter.
3. **Sand** : naturally occurring granular material composed of finely divided rock and mineral particles ranging in diameter from 0.0625 (or $^{1}{}_{16}$ mm) to 2 mm.

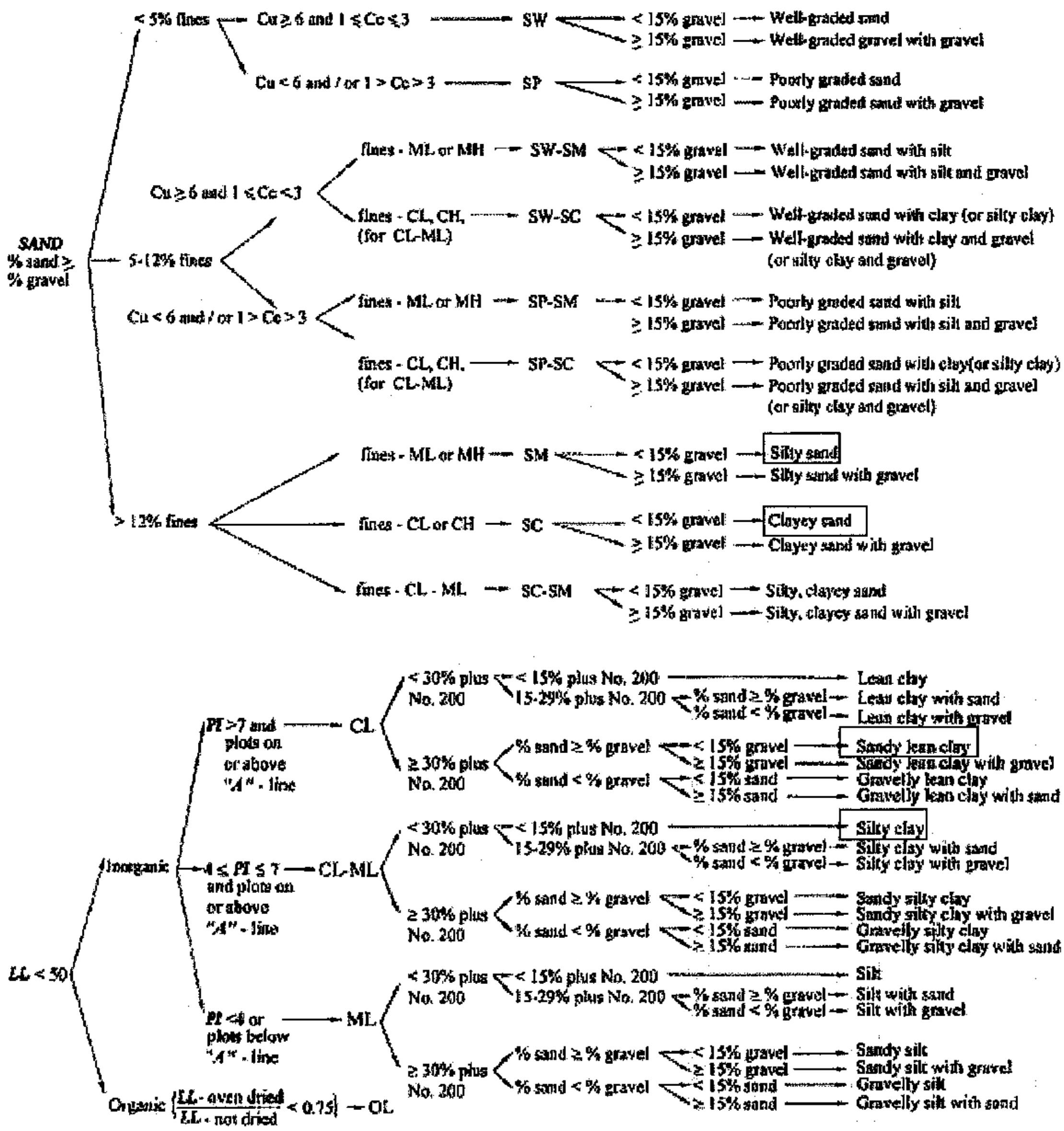


Figure 5: Flow chart for classifying soil (ASTM D 2487)

The secondary soil type can be defined as in the flow chart. For example, Silty Sand is defined as soil with the percentage of fines soil more than 12% and from ML or MH group with less than 15% gravel in the soil. Other secondary soil can be described by the flow chart that based on the laboratory test.

CPeT-IT is software for the interpretation of CPTU data design by Gregg Drilling Inc. and cone penetration testing (CPT) and Professor Peter Robertson, co-author of the comprehensive text book on the CPT. It is a program designed to process, plot and interpret CPT results in a highly efficient manner using simple, intuitive Windows-based interface units. CPeT-IT provides colorful plots of the raw CPT data, basic CPT plots, Soil Behavior Type (SBT) charts and plots, as well as plots of interpreted geotechnical parameters.

The program also provides the ability to process CPT files in batch mode and to produce overlay plots of several CPT profiles. Plots can also show additional information, such as, location of soil and/or groundwater samples, hand augering, drill-outs and the location of the groundwater level and a reference hydrostatic groundwater pressure profile.

CPeT-IT takes CPT data and performs basic interpretation in terms of Soil Behaviour Type (SBT) and various other geotechnical parameters using the current published correlations based on the comprehensive review by Lunne, Robertson and Powell (1997), as well as recent updates by Professor Robertson (T. Lunne, P.K. Robertson and J.J.M. Powell, Cone Penetration testing in Geotechnical Practice, 1997). The interpretations are presented only as a guide for geotechnical use and should be carefully reviewed.

The rapid processing of the CPT results allows the user to evaluate sensitivity of interpretation to different variables, view results in a graphical format and provide more time for users to apply appropriate engineering judgment to the results.

4.1 Previous Work

Table 1 shows the expert systems first run results consist of hit and miss for each category and soil class. The expert system efficiency is illustrated in the figure 7 where number of interpreted data and data which are not interpreted are put in to bar chart. The unknown data are put aside and does not suitable for data comparison.

For phases one, FES works and executes under the membership function plot in figure as such:

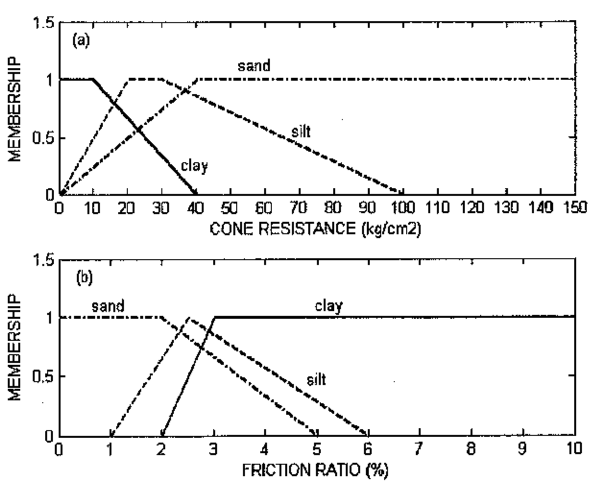


Figure 6: Plot of Membership Functions

Table 1: Results of the first run with the current soil classification rule.

total data=	**12199**
unknown sample=	8247
known sample=	3952
primary soil (clay) hit=	1244
primary soil (clay) miss=	13
secondary soil (silty clay) hit=	325
secondary soil (silty clay) miss=	919
secondary soil (sandy clay) hit=	0
secondary soil (sandy clay) miss=	0
primary soil (Sand) hit=	1983
primary soil (Sand) miss=	434
secondary soil (silty Sand) hit=	1049
secondary soil (silty Sand) miss=	934
secondary soil (clay Sand) hit=	0
secondary soil (clay Sand) miss=	0
primary soil (Silt) hit=	45
primary soil (silt) miss=	196
secondary soil (clayey silt) hit=	45
secondary soil (clayey silt) miss=	0
secondary soil (sandy silt) hit=	0
secondary soil (sandy silt) miss=	0

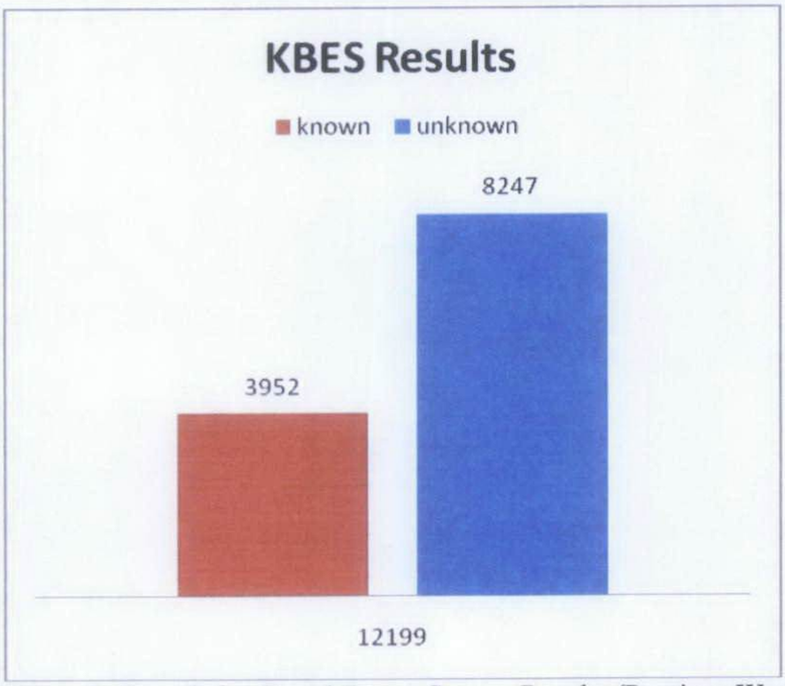


Figure 7: Knowledge Based Expert System Results (Previous Work).

From the known data, the primary soil type is chuck down from all boreholes and put together in a bar chart (Figure 7) to differentiate the expert system's performance towards identifying each major type as some soil type is harder to identify than the other. Thus, from the figure, improvement on the function member can be done as we know the section that the expert systems lack of knowledge.

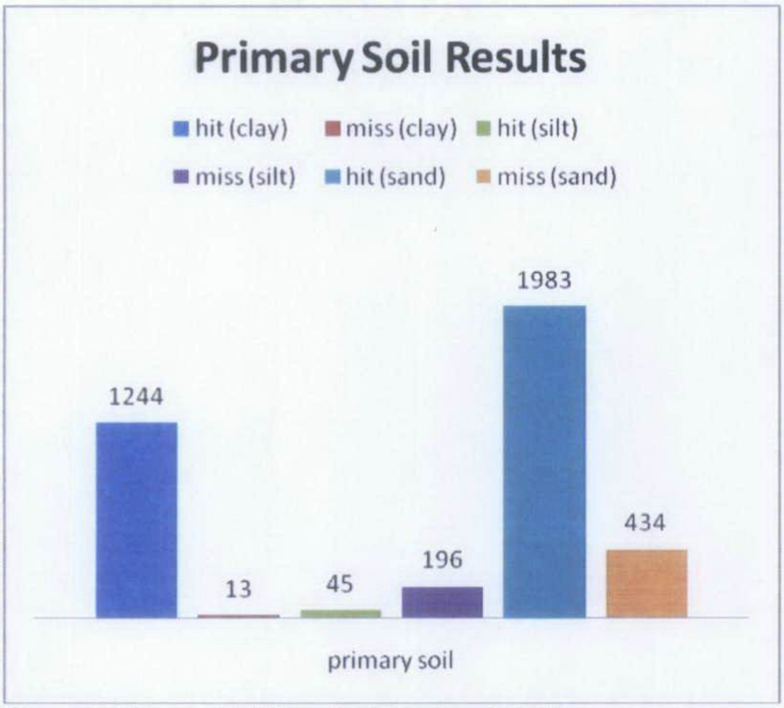


Figure 8: Primary Soil Results (Previous Work)

Silty Clay and Silty Sand results are presented in figure 9 and figure 10 respectively. Figure 9 shows the Clayey Silt results. This result is obtained assuming that Clayey Silt and Silty Clay are approximately similar. The reasons of the assumption are detailed in discussion. Graphs for Sandy Clay, Sandy Silt and Clayey Sand are not presented as each borehole tested give no visual observation of such soil type.

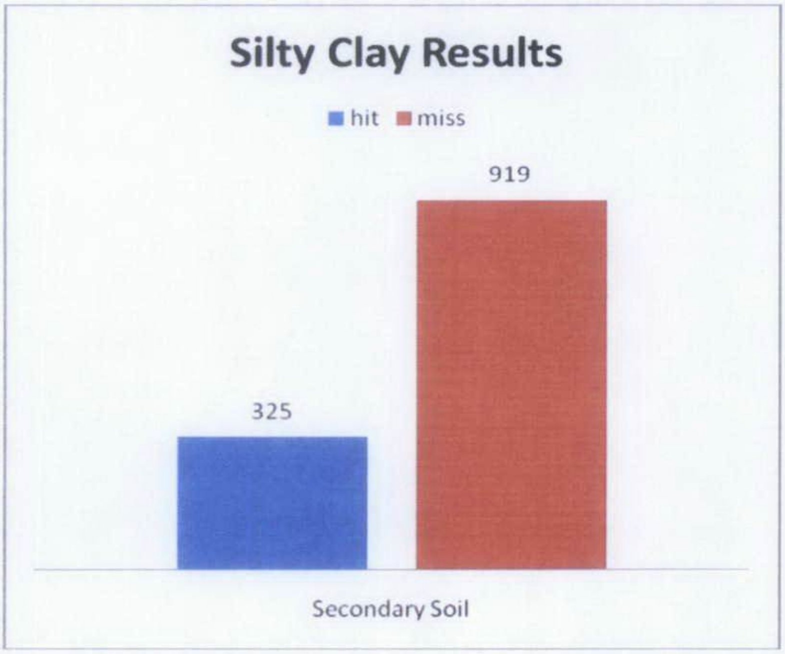


Figure 9: Silty Clay Results (Previous Work)

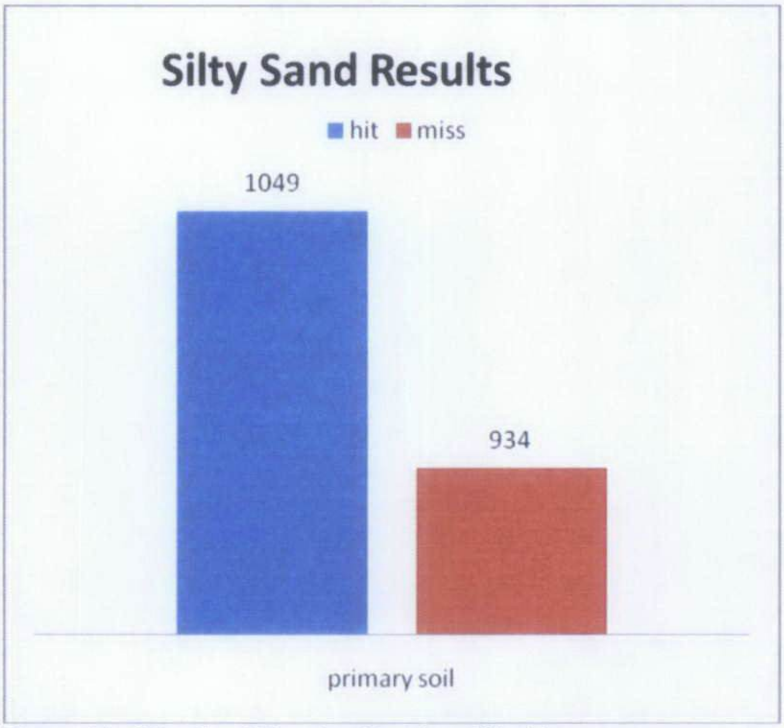


Figure 10: Silty Sand Results (Previous Work)

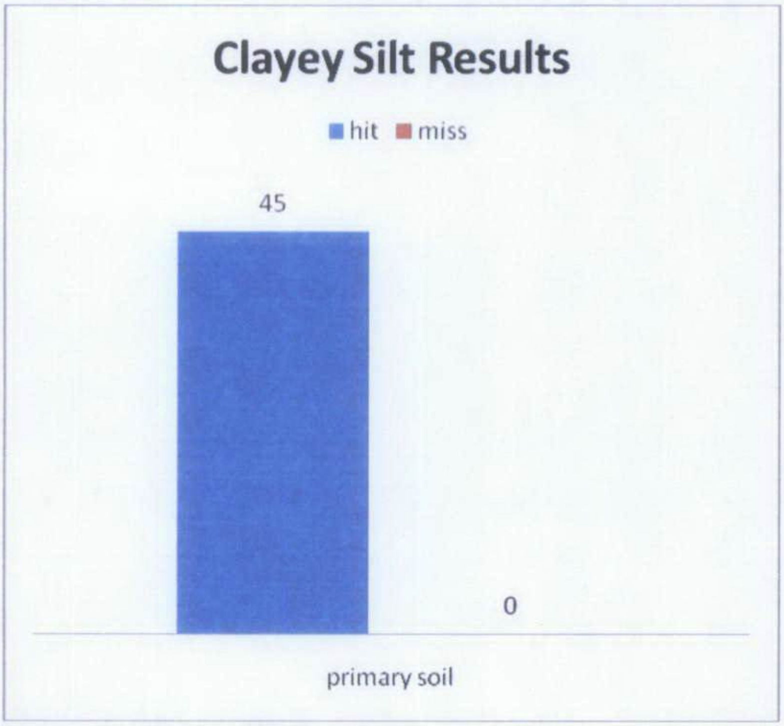


Figure 11: Clayey Silt Results (Previous Work)

Soil type obtained from the FES is compared with the visual observation done by geotechnical engineers and lab technician. By visual observation, the procedure of classification consists of considering color, particle size and shape, and soil consistency. Therefore in this case, experience and technical skills essentially needed in classifying soil type. Observation based on the FES shows that transition from one layer to another with different soil type is remotely smooth. Although the soil transition from FES is good and seems logical, a lot of contradictions occur when comparing the results with the visual observation results. It should be noted, even though, that the borehole log are used in doing comparison, the visual observation is not 100% accurate because of the lack of experience from the geotechnical engineers and lab technicians in classifying the borehole sample that may lead to the inaccurate soil stratification. They tend to be conservative and mostly defined the soil silty clay, silty sand and clayey silt. It is because the difficulties to handle the offshore soil sample as it is high in water content and much movement can cause the sample to be disturbed and a lot of lab test cannot be done.

In figure 7, the identified data are very small compared to undetermined data (unknown). This error in translation of CPT data to expected result is not yet to be recognized. Most of the unknown results are clay sample and the sample of upper part of borehole ranging from 0.0m to 20.0m. This pattern is in agreement with all boreholes as the unknown results are decrease with the increasing depth of borehole.

The compaction of the soil may contribute to this inefficiency as parameter used in identifying the soil which are the cone bearing capacity, q_c and friction ratio, f_R are highly affected by the compaction. From 3952 of known data, it can be seen that, sand soil is the most easily recognize by FES followed by clay soil and silt respectively. Sand is easily recognized as it have a define boundary of cone bearing capacity, q_c and friction ratio, f_R to differentiate it from silt and clay. Clay limit is easily defined with its water content. Since FES uses only cone bearing capacity, q_c and friction ratio, f_R for the computerized graph and soil type selection, some error in identifying occur.

For primary soil type in figure 8, it is recorded that sand soil being the one most identified, while clay soil have the less percentage of miss data sample followed by sand and silt. There are two cases of miss-identifying of primary soil type. The first and most is the miss-identifying that occur only at the transition of two different layers (i.e. from clay to sand). Even with visual observation, the layer transition in the borehole log from one layer to another are still too sudden rather than smooth transition as the geotechnical engineers may not well experienced. The data of sand and clay which miss are usually sighted at the transition layer from clay to sand or vice versa. The second case of miss-identifying is when a different layer of soil is detected in the middle of another major layer of soil. It is possible that there are less than 0.7m different layer of soil encountered between the primary soils as the engineer would not take into consideration soil layer with depth less than 0.7 m as it did not affect the primary layer stratification and soil strength.

Silt is the less identify with the lowest encountered and 'hit'. Silt is hardly defines as it is an intermediate soil between clay soil and sand soil. Inexperienced personal may wrongly defined silt as sand or clay. By depending only on visual observation, it is highly tricky to identify silt. Furthermore, the computerized graph also had only a small range of high possible of silt compared to sand and clay. Modification and alteration on silt rules of selection will be revised to cater the needs of the borehole log as long as it did not contradict the conventional soil classification chart.

For the secondary soil type, figure 9 to figure 10 present that clayey silt have the highest percentage of success identified followed by sand and clay. There are no records of sandy clay, clayey sand and sandy silt as the borehole log of the visual observation shows no such sample encountered. The clayey silt have the high percentage of successful attempt provided that primary soil classification are correct and clayey silt and silty clay encountered in a silt layer are assumed as similar. This is because in the real life practice, the difference of silty clay and clayey silt is not defined properly and the two of them have the same visual appearance.

In addition to that, from the soil classification chart for CPTU data from Jefferies and Davies (1991) and from Robertson *et al.*(1986), see in figure 12 and 13 below that silty clay and clayey silt are put into one zone which is no.4 (Jefferies and Davies ,1991) and no.5 (Robertson *et al.*1986). Thus assumption made does not contradict the conventional chart.

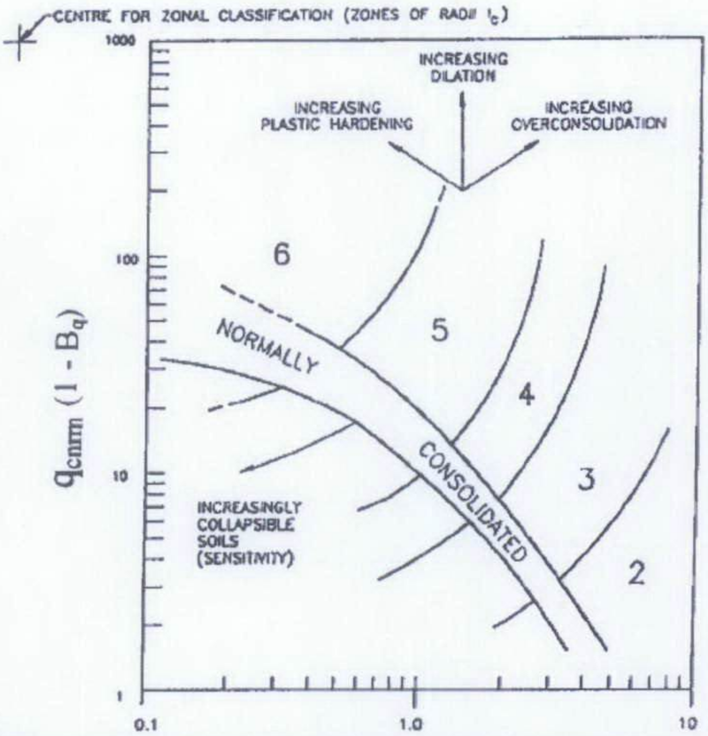
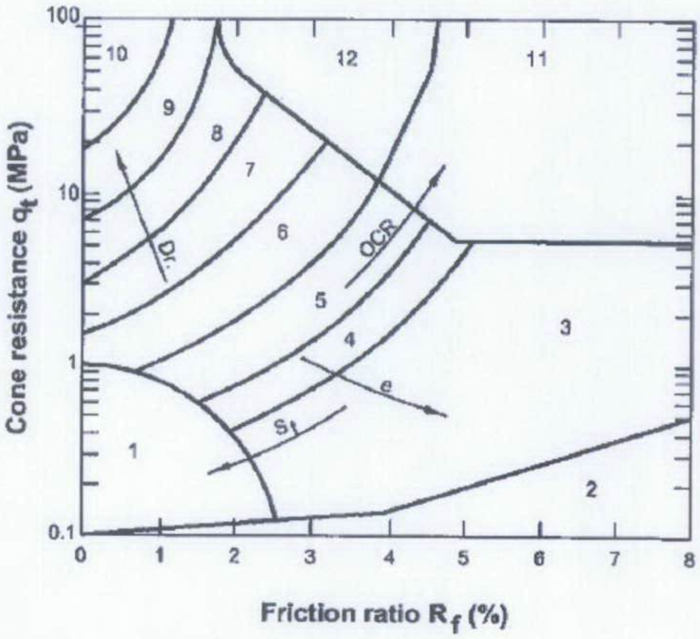


Figure 12: Soil Profiling Chart per Jefferies and Davis (1991)



Zone:	Soil Behaviour Type:				
1.	Sensitive fine grained	5.	Clayey silt to silty clay	9.	Sand
2.	Organic material	6.	Sandy silt to clayey silt	10.	Gravelly sand to sand
3.	Clay	7.	Silty sand to sandy silt	11.	Very stiff fine grained *
4.	Silty clay to clay	8.	Sand to silty sand	12.	Sand to clayey sand *
				*	Overconsolidated or cemented

Figure 13: Soil chart after Robertson et al, 1986

For the second phase of the project, the comparison are made between the visual observations did by the geotechnical engineers and the computers analyzed soil classification which is the fuzzy expert system (FES) and published software (Cpet-IT). Then, for each soil primary class (clay, silt and sand) and secondary soil class (clayey, silty and sandy), the author have recorded the hit and miss result of the comparison between eight set of CPT data based classification by the expert system and the visual observation done; where hit is the number of results that correlate to the visual observation and miss is the number of results that differ from the visual observation. The author has decided to do chart of every 'hit and miss' for each soil type and the comparison the primary soil side by side. The Cpet-IT was used to identify any error in some of the visual observation done by several of the fresh engineers as their skills in identifying may be disputable. By counter checking the result of the comparison, the success rate of the expert system increased and the results can be verified.

Fuzzy Experts System proposed on using the Robertson Soil Classification for CPT data rather than the Schmertmann Soil Classification Chart System proposed before as it cannot be implied for the offshore soil effectively. The expert system can still be used for as we can alter the membership function for different un-empirical data.

4.2 Recent Work

For this recent work, modification and alteration are made to the membership function especially the primary limit value for selection of sand, clay and silt soil. The limit for the new membership function is based on the Robertson's Guide for Identification from Piezocone Data rather than Schmertmann Profiling Chart to compare the performance of the system and determine the optimum assessment of soil classification done by using different limiting value. Even so, the method of selection for the soil regardless of primary soil or secondary soil is still the same with the previous work. Furthermore, improvement on the secondary were also done by changing its rule so that its tally with the visual sample data and also another type of computer analyzed soil classification software namely Cpet-IT by Geologismiki.

Table 2. Membership Function Statement of q_c

```
(deftemplate soil_by_qc range (0 to 100Mpa)
 (clay (0.15 0) (0.85 0.9) (2 0.75) (5.8 0.625)
       (6 0.2) (10 0))
 (silt (0.5 0) (3 0.48) (6  0.425) (7 0.425)
       (20 0.15) (38 0))
 (sand (1.5 0) (6 0.625) (20 1) (100 1))
  (not_clay_silt NOT clay AND NOT silt)
  (not_clay_sand NOT clay AND NOT sand)
  (not_silt_sand NOT silt AND NOT sand))
```

Table 3. Membership Function Statement of f_R

```
( deftemplate soil_by_fr range 0 to 10%
( (clay (0.8 0) (2 0.24) (3 0.48) (3.8 0.58)
       (8 0.33))
  (silt (0 0.15) (1 0.27) (2.4 0.52) (4.6 0))
  (sand (0 0.61) (1 0.55) (2 0.39) (3 0.27)
       (3.2 0.24) (4.6 0.39) (4.8 0.42) (8 0.42))
  (not_clay_silt NOT clay AND NOT silt)
  (not_clay_sand NOT clay AND NOT sand)
  (not_silt_sand NOT silt AND NOT sand))
```

From Table 2 and Table 3, it is shown that the limiting value for both q_c and f_R are different from the previous work as it is based on different soil classification chart. The unit for the value of q_c parameters is also changed from 0 to 100MPa instead of 300KPa from previous work. This is because of the sample data used are from the offshore thus the soil properties are different from the onshore sample data. That is also the reason for changing from Schmertmann Profiling Chart to Robertson's Guide for Identification from Piezocone Data. The process of extracting value for both methods for selecting soil type is the same. Calculation of the probability of the soil being encountered for each value in the actual Schmertmann Profiling Chart and Robertson's Guide for Identification from Piezocone Data are sort out as such in the graph as in figure 5 and figure 14 respectively. The parameters which are the friction ratio, f_R and Cone resistance, q_c are plotted against its probability called membership. Both of the graphs are used by the expert system in the soil selection process. The updated plot of the membership function for the recent updated works shows more defining lines of boundary between soils namely sand, clay and silt. This has given the expert system more 'knowledge' in executing the arguments.

The limit for clay starts at 0% of f_R with no probability encountering clay and goes to maximum of 3.8% of f_R achieving 58% of encountering clay (Figure 14). The graph hits a turn point and decrease back to 8% of f_R. at the membership probability of 33%. Silt starts at 15% of membership probability with 0% f_R and hike to the maximum point with 2.4% of f_R and the probability of 0.52%. The graph of the membership function later than decrease to 4.6% of f_R with probability of 0%. Based on the friction ratio vs. membership function, sand soil has the dominant region of probability. The probability of encountering sand does not affected much by the friction ratio as it affect other soil type namely clay and silt. This is because; the friction ratio itself cannot determine the soil types of a sample independently as there are a lot of overlapping region between sand-clay, sand-silt and clay-silt. The fact is sand soil can be found throughout 0-8% friction ratio. Correlations between other parameters are needed to classify the soil into primary and secondary soil thus correlating friction ratio and cone resistance with the membership. The plot of membership function that utilize cone resistance (MPa) shows that, there are no dominant soil in the graph because the differences of type of soil with strength. Lower strength soil usually will be clay and higher strength soil will be sand. The intermediate soil is the silt. The basic pattern of the plot eases the selection process of the soil type.

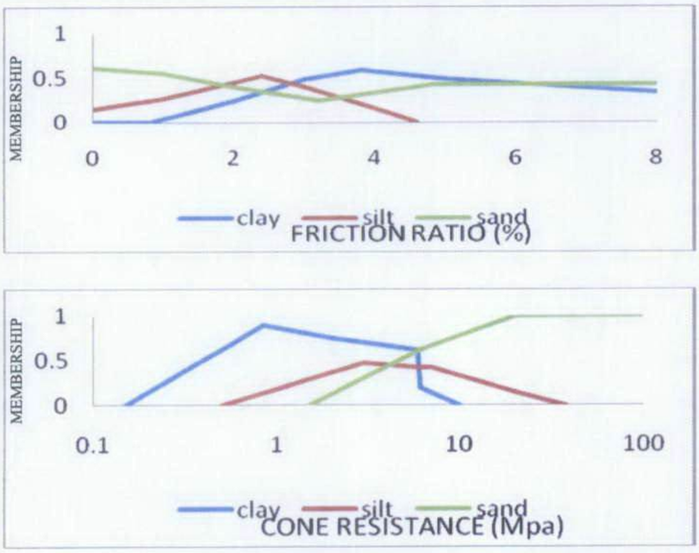


Figure 14: Plot of Membership Functions

Table 4: Results of the updated soil classification rule (latest work).

No.	Soil Type	Hit	Miss	Success Rate (%)
1.	Clay	3381	1885	64.2
2.	Sand	3520	540	86.7
3.	Silt	45	454	9.1
4.	Silty Clay	244	5310	4.4
5.	Silty Sand	139	3927	3.5
6.	Clayey Sand	1	10	9.1
7.	Clayey Silt	39	469	7.7
8.	Sandy Silt	6	0	100.0

Table 4 shows the expert systems results consist of hit and miss for each category and soil class after some rules modification and alteration. The expert system efficiency is illustrated in the figure 8 where number of interpreted data and data which are not interpreted are put in to bar chart.

Comparing the previous work and recent results, the updated soil classification rules actually give more accurate and promising results. This is because in the updated rule, the unknown data is considered 'miss' while in the previous work, unknown rule doesn't taken into consideration of the 'hit and miss' analysis. Therefore the assessment of the result is more reliable and effective in determining the efficiency of the system.

In addition to that, the results for the updated soil classification are more reliable as it is also being based on several more reference and not just merely on the visual sample data. Referring to table 4 the miss or unsuccessful attempt in determining the data into soil type is really high with the rate of 67.2%. While the KBES bar chart (Figure 15) shows that the success rate for the system to identify each data into soil class using the updated system hits up to about 87%. The difference of the system's success rate from the previous work to recent work is about 54.2%. This enormous difference satisfy the users selection of soil classification charts. Asides from that, by referring to figure 16, the **'hit'** ratio which is the success ratio of the classification compared to the borehole sample also increased for the sand group up to 86.7% differ from the last run by 4%. Unfortunately, for sample clay group, the **'hit'** ratio falls down by 34.7% from before and resulting to only 64.2% of success ratio in classifying the soil sample data.

All secondary soil type data are presented in Figure 17 for comparison and discussion. For the secondary soil, some results are obtained based on some assumption made forehand which are; Clayey Silt and Silty Clay are approximately similar and same goes to Sandy Silt and Silty Sand. The reasons of the assumption are detailed in discussion. Chart for Sandy Clay, is not presented as each borehole tested give no visual observation of such soil type.

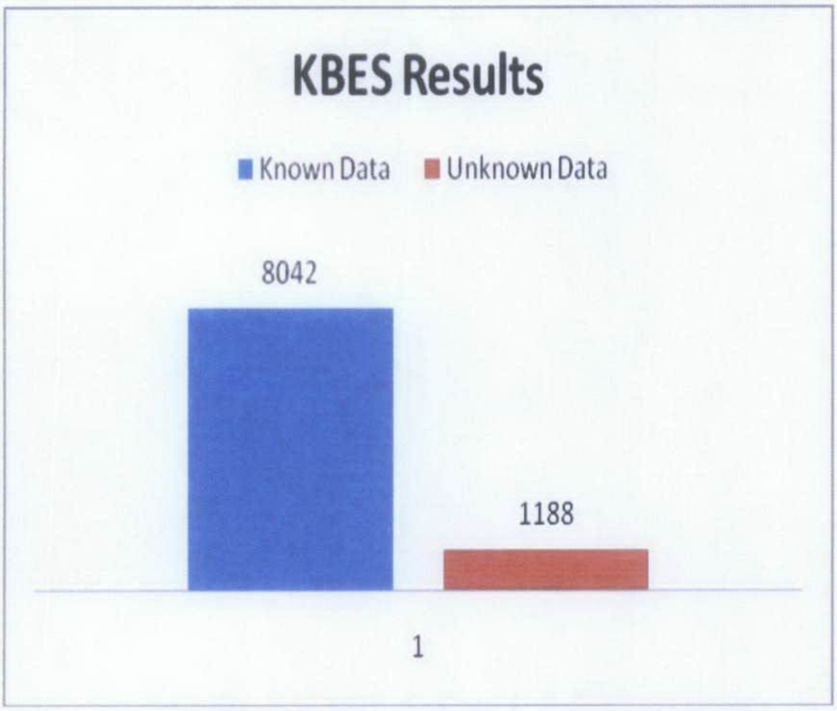


Figure 15: KBES Effeciency Bar Chart (Latest Work)

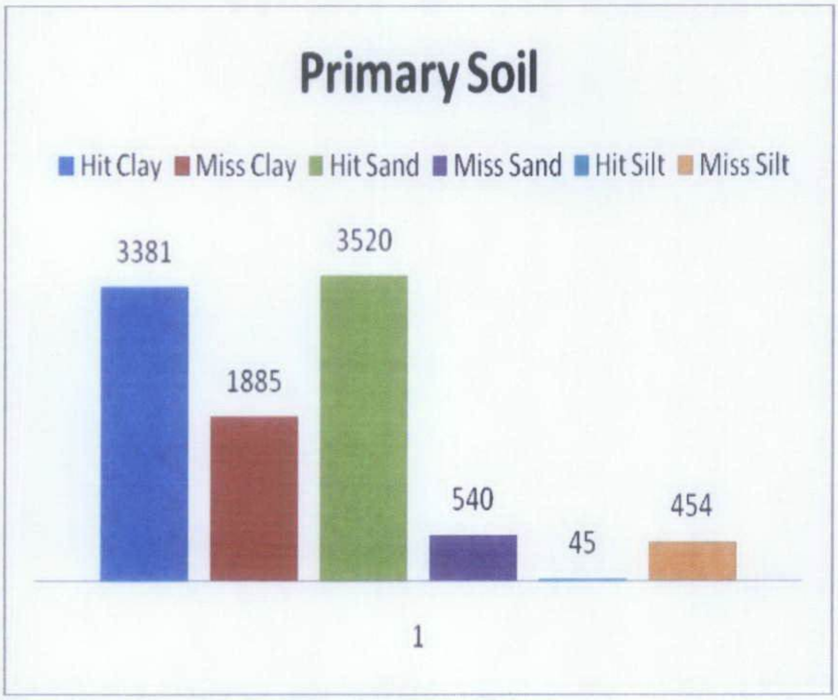
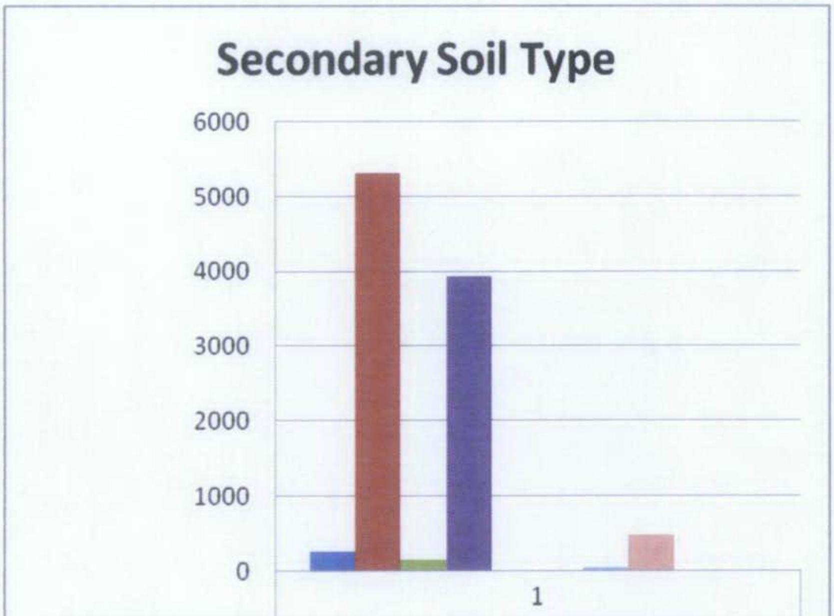


Figure 16: Primary Soil Results (Latest Work)



	1
Hit Silty Clay	244
Miss Silty Clay	5310
Hit Silty Sand	139
Miss Silty Sand	3927
Hit Clayey Sand	1
Miss Clayey Sand	10
Hit Clayey Silt	39
Miss Clayey Silt	469
Hit Sandy Silt	6
Miss Clayey Silt	0

Figure 17: Secondary Soil Type Results (Latest Work)

For the secondary soil type, Figure 17 present that sandy silt have the highest percentage of success identified with 100% and the other soil type classification are not suitable for comparison. Insufficient reliable sample data had disrupted the progress of the project as most of the comparisons from FES results for secondary soil contradict with the visual observation. Therefore, to avoid reckless rule changing of the functions and to make sure that the visual observation data given were reliable, author had turn to base the efficiency test of the FES with the Cpet-IT results and consult the TLGeotechnics Engineers for their experience and view. There are no records of sandy clay as the borehole log of the visual observation shows no such sample encountered. Thus, the comparison cannot be done.

However, there are some layer of sandy clay exist and it is verified with the Cpet-IT. Comparison between the Cpet-IT and the FES shows that the secondary membership functions work well and success rate are high. Even so, data comparison for layer by layer cannot be done as it is only the demo version of the Cpet-IT.

Newer rules actually had been in development and trial version. The comparison of FES results, visual observation data and Cpet-IT is currently ongoing for the second assessment of the secondary soil with the new trial rules. Acceptable and tolerable results are shown so far. Up to this point of progress, only part of the whole amount of data had been analyzed by FES with the new rules and only a few had been sort out and compared to Cpet-IT and visual observation data. There will be newer results for the FES that will evaluate the success using the comparison of soil classification.

Table 5: Results of the updated secondary soil classification rule.

No.	Soil Type	Hit	Miss	Success Rate (%)
1.	Silty Clay	240	191	55.6
2.	Silty Sand	901	305	74.7
3.	Sandy Silt	67	0	100
4.	Clayey Silt	31	78	28.4

Results on Table 5 are the results for the secondary soil analyzed with FES's new rules and compared to the visual observation sample data with the verification of Cpet-IT, although the results did not consist of all borehole log data, the success rate is increased for all secondary type. It can be well said that the new rules will enhance the performance of the expert system. Nonetheless, modification and adjustment are still needed in order for the secondary membership function to be defined properly and thus resulting in a higher reliability of soil classification.

Table 6 presents the changes that have been made in the rules for selection of secondary soil type. Example shown is for the Silty Sand and Silty Clay cases (refer table 7). The system reads the soil type as silty sand although the ranking selection chooses clay and sand that supposedly define the secondary soil type as Sandy Clay or Clayey Sand. This occurrence cannot be explained by referring just to the syntax because there are no errors detected in the FES script. On the other hand, it seems that the errors in the syntax have resulting good outcome from the FES as the secondary soil type success rate is increasing. Further studies will be done towards this matter and consultation with IT expertise will be needed so that the system can be understood for better efficiency and performance.

Table 6. Rules for Selection of Secondary Soil Type (Silty Sand)

```
(defrule clayey_sand_1  "Soil is Silty Sand"
     (declare (salience 99))
     (phase class)
     (soil_by_qt clay)
     (soil_by_fr sand)
     (soil_type sand ?)
=>
     (assert (soil_type silty_sand (gensym*)))
```

Table 7. Rules for Selection of Secondary Soil Type (Silty Clay)

```
(defrule sandy_clay_1  "Soil is Silty Clay"
     (declare (salience 99))
     (phase class)
     (soil_by_qt clay)
     (soil_by_fr sand)
     (soil_type clay ?)
=>
     (assert (soil_type silty_clay (gensym*)))
```

CHAPTER 5

CONCLUSION AND RECOMMENDATION

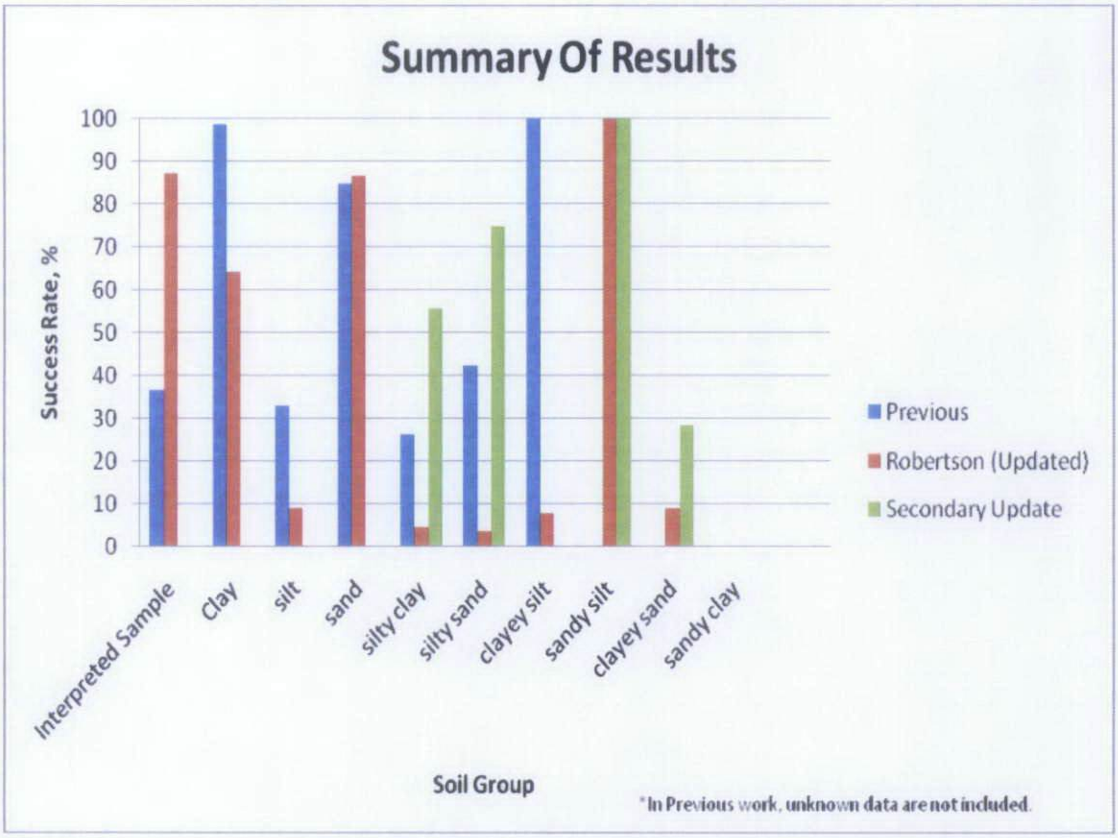


Figure 18: Summary of Results

From figure 18, it can be drawn into conclussion that the expert system update has achieved its objective. Eventhough some of the soil sample detection performance is reduced based on the success rate, but the system as an overall increas its performance. The interpreted sample has increase from as low as 32.8% to 87% due to the change of chart used in the selection process. The new rules and limit derived from the robertson and campanela soil classification chart shows more promising results than the previous work wherby it used shmertmann's soil classification chart. Although the success rate in detecting soil sample is increased, the success rate for clay soil and silt soil is reduced. Thus making the system still in need of improvement and update from various kind of empirical value and data. For the secondary membership function update, the bar chart for the secondary soil type shows clearly that with the secondary update done, the percentage of the success rate is increased for all secondary soil sample detected. However, more reliable sample are needed to confirm, verified and improve the rules and selection limits for the secondary soil.

This assimilation project between the expert system with the CLIPS software and information about the soil classification from CPT data has come out with a prototype which able to guide in education and training session in soil profiling from CPT data. It should be noted that the knowledge based expert system is the platform to developed FES with the association of CLIPS and the knowledge itself. Thus, FES for now is only as a guide for soil classification and profiling. Expertise still needed in determining the soil type both primary and secondary as they are more versatile and had the knowledge.

Information gathering and learning expert system especially CLIPS is done with synchronize so that the efficiencies can be put into practice in gaining reliable and implementable information for the FES function member development. Apart from that, in this part of research also, the author had gathered data sample of borehole logs from TLGeotechnics Sdn. Bhd. to be used in the comparison of the predicted data gained from the first run of FES analysis. This is to determine the system's performance and to know the ability of FES.

The new rules and limits have shown such an increased in the capability of the expert system to recognize in both known data and also Sand group data. But, with that also, the recognizing of the Clay group have been reduced. Sorting the FES results by comparing it to visual observation data and Cpet-IT have enhance the reliability of the results as it is not dependent on single reference which may be slightly inaccurate. Nevertheless, alteration and modification of the rules and limits are still needed to be done so positive effects are affecting all the soil group recognition.

Comprehension and understanding on the chart needed to be enhance so alteration and modification of the rules are not contradicting with the chart's classification and not violating the 12 soil behavior of the chart. For improved results of the classification, author proposed on including the second chart of the Robertson's and utilized the pore pressure parameter data. This can result in more reliable classification and alteration and modification on a single chart can be lessened.

REFERENCES

1. Eslami, A. & Fellenius, B.H. 2000 & 2004. Soil Profile Interpreted from CPTu Data & CPT and CPTu Data for Soil Profile Interpretation: Review of Methods and a Proposed New Approach, *Iranian Journal of Science & Technology,* Transaction B, Vol. 28, No. B1.

2. M. T. Tumay, M. Y. AbuFarsakh & Z. Zhang 2004. From Theory to Implementation of a CPT-Based Probabilistic and Fuzzy Soil Classification, *The Internet Journal of Geotehcnical Engineering, Vol. 13 B*

3. Gui, M.W., Bolton, M.D., Garnier, J., Oorte, J.F.C., Bagge, G., Laue, J. & Renzi, R. 1998. Guidelines for Cone Penetration Tests in Sand, *Centrifuge 98, Kimura, Kusakabe & Takemura (eds) 1998 Balkerna, Rotterdam, ISBN 9054109866*

4. Robertson, P.K & Campanella, R.G. 1983. Interpretation of Cone Penetration Tests, *Canadian Geotechnical Journal, Vol. 20, No.4, Nov. 1983.*

5. Robertson, P.K. 1989. Soil Classification Using the Cone Penetration Test, *Department of Civil Engineering, The University of Alberta, Edmonton, Alta., Canada T6G 2G7*

6. Robertson, P.K. & Campanella, R.G. & Wightman, A. 1982. SPT-CPT Correlations, *Journal of Geotechnical Engineering,* Vol. 109, No. 11, November, 1983: 18348

7. GREGG Drilling CPT software. URL: http://www.greggdrilling.com/What's%20New%20Pages/cptsoftware.htm

8. Baligh, M., Vivatrat, V. & Ladd, C.C. 1980. Cone Penetration in Soil Profilin, *Journal of the Geotechnical Engineering Division,* ACSE, 104(4): 447-461.

9. Giarrantano J.C Giarrantano & Riley G. 1994. *Expert Systems: Principle and Programming,* 3rd edition, PWS.

10. Schmertmann, J. H. 1978, *Guidelines for Cone Penetrometer Tests: Performance and Design,* Report No. FHWA-TS-78-209, U.S. Dept. Transportation, Federal Highway Administration, Washington.

11. Sanglerat, G. 1982. *The Penetrometer and Soil Exploration,* 2nd ed. Amsterdam: Elseiver

APPENDIX

```
(defglobal
        ?*depth* = 0.0
        ?*cone* = 0.0
        ?*friction* = 0.0
        ?*fricRatio* = 0.0
        ?*soil-type* = nil
        ?*ins* = 0
        ?*qt* = 0
        ?*fr* = 0
        ?*data_in* = OK
        ?*phase* = 0
        ?*cf_clay* = 0.0
        ?*cf_silt* = 0.0
        ?*cf_sand* = 0.0
        ?*cf_max*  = -9999999.9
        ?*CFThres* = 0.0
        ?*cfactor* = 0.0
        ?*FileNameDataIn* = "Ambun1.dat"
        ?*FileNameDataOut* = "Ambun1.out"
 )
;;
;;      *** CLASSES ***
;;
  (defclass DUTCHCONE (is-a USER)
      (role concrete)
      (pattern-match reactive)
      (slot depth
                  (create-accessor read-write))
      (slot cone_resistance
                  (create-accessor read-write))
      (slot friction_resistance
                  (create-accessor read-write))
      (slot friction_ratio
                  (create-accessor read-write))
      (slot soil_type
                  (create-accessor read-write))
      (slot cfactor
                  (create-accessor read-write))
  )

  (defmessage-handler DUTCHCONE print-result ()

    (format oFile "%5.2f %7.2f %5.2f %5.2f %13s %5.2f %n"
                 ?self:depth
                 ?self:cone_resistance
                 ?self:friction_resistance
                 ?self:friction_ratio
                 ?self:soil_type
                 ?self:cfactor
    )
  )
  (defmessage-handler DUTCHCONE put-initial-data primary
                          (?depth ?cone ?friction ?fricRatio)
;;     (printout t "message-handler put-initial-data " crlf)
    (dynamic-put depth ?depth)
    (dynamic-put cone_resistance ?cone)
```

```
    (dynamic-put friction_resistance ?friction)
    (dynamic-put friction_ratio ?fricRatio)
;;     (dynamic-put soil_type unknown)
    (dynamic-put cfactor 0.0)
  )

  (defmessage-handler DUTCHCONE put-data primary (?soil_type)
;       (printout t "message-handler put-data " ?soil_type " cfactor "
?*cfactor* crlf)
    (dynamic-put soil_type ?soil_type)
    (dynamic-put cfactor ?*cfactor*)
  )

 (deftemplate soil_by_qt
      0  100 MPa
;;       ( (clay (z    10   40))
;;         (silt (pi   30   30))
;;         (sand (s    10   50))
      ( (clay (0.15 0) (0.85 0.9) (2 0.75) (5.8 0.625) (6 0.2) (10 0))
        (silt (0.5 0) (3 0.48) (6  0.425) (7 0.425) (20 0.15) (38 0))
        (sand (1.5 0) (6 0.625) (20 1) (100 1))

        (not_clay_silt NOT clay AND NOT silt)
        (not_clay_sand NOT clay AND NOT sand)
        (not_silt_sand NOT silt AND NOT sand)
      )
 )
 (deftemplate soil_by_fr
      0  10  %

      ( (clay (0.8 0) (2 0.24) (3 0.48) (3.8 0.58) (8 0.33))
        (silt (0 0.15) (1 0.27) (2.4 0.52) (4.6 0))
        (sand (0 0.61) (1 0.55) (2 0.39) (3 0.27) (3.2 0.24) (4.6 0.39)
(4.8 0.42) (8 0.42))
;;       ( (clay (s    1.0  3.0))
;;         (silt (pi   4.0  4.0))
;;         (sand (z    2.0  5.0))
        (not_clay_silt NOT clay AND NOT silt)
        (not_clay_sand NOT clay AND NOT sand)
        (not_silt_sand NOT silt AND NOT sand)
      )
 )

 (deffacts input_file_status
     (data_in ok)
     (phase read)
     (phase select)
 )
;;
;;  **** FUNCTIONS ***
;;


;;
;;
;;
;; Deffunction fuzzify
```

```
;;
;; Inputs:   ?fztemplate  - name of a fuzzy deftemplate
;;           ?value       - float value to be fuzzified
;;           ?delta       - precision of the value
;;
;; Asserts a fuzzy fact for the fuzzy deftemplate. The fuzzy set is
;; a triangular shape centered on the value provided with zero
;; possibility at value+delta and value-delta. Note that the function
;; checks the bounds of the universe of discourse to generate a fuzzy
;; set that does not have values outside of the universe range.
;;

 (deffunction fuzzify (?fztemplate ?value ?delta)

        (bind ?low (get-u-from ?fztemplate))
        (bind ?hi  (get-u-to   ?fztemplate))
;           (printout t "Station 0")
;           (printout t  " " ?value " " ?delta crlf)

        (if (<= ?value ?low)
          then
           ( printout t "Station 1")
            (assert-string
              (format nil "(%s (%g 1.0) (%g 0.0))" ?fztemplate ?low
?delta))
          else
            (if (>= ?value ?hi)
              then
           ( printout t "Station 2")
                (assert-string
                   (format nil "(%s (%g 0.0) (%g 1.0))"
                               ?fztemplate (- ?hi ?delta) ?hi))
              else
            ( printout t "Station 3")
                (assert-string
                   (format nil "(%s (%g 0.0) (%g 1.0) (%g 0.0))"
                               ?fztemplate (max ?low (- ?value ?delta))
                               ?value (min ?hi (+ ?value ?delta)) ))
            )
        )
;       (printout t " " ?hi crlf)
  )


;;
;;  "Fuzzify Cone Resistance and Friction Ratio"
;;
;;
;; Input     ?cone  - cone resistance
;;           ?fr    - friction ratio
;;
;;
;;fuzzify
 (deffunction fuzzify_cpt (?cone ?fr)
       (fuzzify soil_by_qt ?cone 0.1)
       (fuzzify soil_by_fr ?fr   0.1)
;;       (printout t " " ?cone)
```

```
 )
;;*********************************************************************
******************
;;print
 (deffunction print (?depth ?cone ?friction ?soil_type)
       (printout oFile "Qc= " ?cone " FR= " ?friction  " Soil: "
?soil_type crlf)
       (printout t " " ?cone " " ?friction  " " ?soil_type crlf)
 )
;;*********************************************************************
*******************
;;print_cv
 (deffunction print_cv (?depth ?cone ?friction ?soil_type ?cf)
;;       (printout oFile "Qc= " ?cone " FR= " ?friction  " Soil: "
?soil_type crlf)
       (printout oFile "  " ?depth " " ?cone " " ?friction  " "
?soil_type " CF= " ?cf crlf)
;;       (printout t "  " ?depth " " ?cone " " ?friction  " "
?soil_type " CF= " ?cf crlf)
 )
;;*********************************************************************
*******************
;;            print-result
 (deffunction print-result ()
      (do-for-all-instances ((?test DUTCHCONE)) TRUE
        (send ?test print-result)
      )
 )
;; *******************************************************************
;;             init-data
  (deffunction init-data (?depth ?cone ?friction ?fricRatio)
      (bind ?test (make-instance (gensym*) of DUTCHCONE))
      (send ?test put-initial-data ?depth ?cone ?friction ?fricRatio)
  )
;

(deffunction read-cpt-data()
    (while (neq (bind ?depth (read FileData)) EOF)
     do    (bind ?cone   (read FileData))
           (bind ?friction (read FileData))
           (if   (neq ?cone 0.)
            then (bind ?fricRatio (* (/ ?friction ?cone) 100.0))
            else (bind ?fricRatio 0.0))
           (init-data ?depth ?cone ?friction ?fricRatio)
           (printout t ?depth "  " ?cone "  " ?fricRatio crlf)
    )
 )

;; *******************************************************************
;;             assert-class
  (deffunction assert-class (?soil_type)
;;      (bind ?test (make-instance (gensym*) of DUTCHCONE))
      (send ?*ins* put-data ?soil_type)
  )
;
;;*********************************************************************
**
```

```
;;              assert-soil-type
 (deffunction assert-soil-type (?soil_type)
;        (bind ?*soil-type* ?soil_type)
;        (assert-class ?soil_type)
;;       (bind ?*cf_max* 0.0)
;;       (bind ?*cfactor* (get-cf ?print))
      (if (< ?*cfactor* ?*CFThres*) then (return))
      (if (< ?*cfactor* ?*cf_max*) then (return))
      (if (or (or (eq ?soil_type clay)
                  (eq ?soil_type silt))
                  (eq ?soil_type sand))
       then
            (bind ?*soil-type* ?soil_type)
            (assert-class ?soil_type)
            (return))
;
       (if    (and (eq ?soil_type sandy_clay)   (< ?*cf_clay* ?*cf_sand*))
        then (return))
       (if    (and (eq ?soil_type silty_clay)   (< ?*cf_clay* ?*cf_silt*))
        then (return))
;
       (if    (and (eq ?soil_type clayey_sand) (< ?*cf_sand* ?*cf_clay*))
        then (return))
       (if    (and (eq ?soil_type silty_sand)   (< ?*cf_sand* ?*cf_silt*))
        then (return))
;
       (if    (and (eq ?soil_type clayey_silt) (< ?*cf_silt* ?*cf_clay*))
        then (return))
       (if    (and (eq ?soil_type sandy_silt) (< ?*cf_silt* ?*cf_sand*))
        then (return))


       (bind ?*soil-type* ?soil_type)
       (assert-class ?soil_type)
;
 )
;
;
;
; ********************************* RULES
************************************
;
;
;
 (defrule init
        (declare (salience 10000))

=>
        (close)
        (open ?*FileNameDataIn* FileData "r")
        (open ?*FileNameDataOut* oFile "w")
        (read-cpt-data)
        (assert (phase class))
;;        (printout t "Data File Opened" crlf)

 )
 (defrule select-object
```

```
      (declare (salience 9999))
      ?phase <- (phase select)
      ?ins <- (object (is-a DUTCHCONE)
                      (depth ?depth)
                      (cone_resistance ?cone)
                      (friction_ratio ?fricRatio)
                      (soil_type nil)
              )

=>
;       (printout  t "select object" crlf)
       (bind ?*depth* ?depth)
       (bind ?*cone* ?cone)
       (bind ?*fricRatio* ?fricRatio)
       (bind ?*ins* ?ins)
       (bind ?*qt* (fuzzify soil_by_qt ?*cone* 0.1))
       (bind ?*fr* (fuzzify soil_by_fr ?*fricRatio* 0.1))
       (send ?*ins* put-data (bind ?soil_type unknown))
       (retract ?phase)
       (assert (phase class))
;;       (printout t "****depth " ?*depth* "****ins " (instance-name
?*ins*) crlf)
;;       (printout t "****depth ****ins " ?ins crlf)
;;       (printout t ?*qt* "   " ?*fr*)
 )
;;
;;
;;   SOIL CLASSIFICATION FROM DUTCH CONE PENETRATION TEST
;;
;;
;;
;;   Soil Classification by Dutch Cone Test
;;
;;
;;
;;  (defmodule CPT)

;; Main Soil Type
;;
  (defrule clay  "Soil is Clay"
     (declare (salience 999))
     (phase class)
     (soil_by_qt clay)
     (soil_by_fr clay)
     (soil_by_qt not_silt_sand)
     (soil_by_fr not_silt_sand)
=>
;     (printout  t "soil is clay" crlf)
     (assert (soil_type clay (gensym*)))
;     (print ?*depth* ?*cone* ?*fricRatio* clay)
  )

  (defrule silt  "Soil is Silt"
     (declare (salience 100))
     (phase class)
     (soil_by_qt silt)
     (soil_by_fr silt)
```

```
      (soil_by_qt not_clay_sand)
      (soil_by_fr not_clay_sand)
=>
      (assert (soil_type silt (gensym*)))
;;      (print ?*cone* ?*fricRatio* silt)
  )

  (defrule sand  "Soil is Sand"
      (declare (salience 100))
      (phase class)
      (soil_by_qt sand)
      (soil_by_fr sand)
      (soil_by_qt not_clay_silt)
      (soil_by_fr not_clay_silt)
=>
      (assert (soil_type sand (gensym*)))
;;      (print ?*cone* ?*fricRatio* sand)
  )

;;
;; Secondary Soil Type
;;
;; Silty Clay or Clayey Silt
;;
;;
  (defrule silty_clay_1  "Soil is Silty Clay 1"
      (declare (salience 99))
      (print  "sandy clay 1" crlf)
      (phase class)
      (soil_by_qt clay)
      (soil_by_fr silt)
      (soil_type clay ?)

=>
      (assert (soil_type sandy_clay (gensym*)))
;;      (print ?*cone* ?*fricRatio* "silty clay 1")
  )

  (defrule silty_clay_2  "Soil is Silty Clay 2"
      (declare (salience 99))
      (phase class)
      (soil_by_qt silt)
      (soil_by_fr clay)
      (soil_type clay ?)
=>


      (assert (soil_type sandy_clay (gensym*)))
;;      (print ?*cone* ?*fricRatio* "silty clay 2")
  )


  (defrule clayey_silt_1  "Soil is Clayey Silt 1"
      (declare (salience 99))
      (phase class)
      (soil_by_qt clay)
      (soil_by_fr silt)
```

```
      (soil_type silt ?)
=>
      (assert (soil_type sandy_silt (gensym*)))
;;      (print ?*cone* ?*fricRatio* "clayey silt 1")
  )

  (defrule clayey_silt_2  "Soil is Clayey Silt 2"
      (declare (salience 99))
      (phase class)
      (soil_by_qt silt)
      (soil_by_fr clay)
      (soil_type silt ?)
=>
      (assert (soil_type sandy_silt (gensym*)))
;;      (print ?*cone* ?*fricRatio* "clayey silt 2")
  )


;;
;; Sandy Clay or Clayey Sand
;;
  (defrule clayey_sand_1  "Soil is Clayey Sand or Sandy Clay 1"
      (declare (salience 99))
      (phase class)
      (soil_by_qt clay)
      (soil_by_fr sand)
      (soil_type sand ?)
=>
      (assert (soil_type silty_sand (gensym*)))
;;      (print ?*cone* ?*fricRatio* "clayey sand 1")
  )

  (defrule clayey_sand_2  "Soil is Clayey Sand 2"
      (declare (salience 99))
      (phase class)
      (soil_by_qt sand)
      (soil_by_fr clay)
      (soil_type sand ?)
=>
      (assert (soil_type silty_sand (gensym*)))
;;      (print ?*cone* ?*fricRatio* "clayey sand 2")
  )

  (defrule sandy_clay_1  "Soil is Clayey Sand or Sandy Clay 1"
      (declare (salience 99))
      (phase class)
      (soil_by_qt clay)
      (soil_by_fr sand)
      (soil_type clay ?)
=>
      (assert (soil_type silty_clay (gensym*)))
;;      (print ?*cone* ?*fricRatio* "sandy clay 1")
  )

  (defrule sandy_clay_2  "Soil is Sandy Clay or Clayey Sand 2"
      (declare (salience 99))
      (phase class)
```

```
;;      (set-alpha-value 0.2)
;;      (set-threshold 0.0125)
     (soil_by_qt sand)
     (soil_by_fr clay)
     (soil_type clay ?)
=>
     (assert (soil_type silty_clay (gensym*)))
;;      (print ?*cone* ?*fricRatio* "sandy clay 2")
  )



;;
;; Silty Sand or Sandy Silt
;;
  (defrule silty_sand_1  "Soil is Silty Sand or Sandy Silt 1"
     (declare (salience 99))
     (phase class)
     (soil_by_qt silt)
     (soil_by_fr sand)
     (soil_type sand ?)
=>
     (assert (soil_type clayey_sand (gensym*)))
;;      (print ?*cone* ?*fricRatio* "silty sand 1")
  )


  (defrule silty_sand_2  "Soil is Sandy Silt or Silty Sand 2"
     (declare (salience 99))
     (phase class)
     (soil_by_qt sand)
     (soil_by_fr silt)
     (soil_type sand ?)
=>
     (assert (soil_type clayey_sand (gensym*)))
;;      (print ?*cone* ?*fricRatio* "silty sand 2")
  )


  (defrule sandy_silt_1  "Soil is Silty Sand or Sandy Silt 1"
     (declare (salience 99))
     (phase class)
     (soil_by_qt silt)
     (soil_by_fr sand)
     (soil_type silt ?)
=>
     (assert (soil_type clayey_silt (gensym*)))
;;      (print ?*cone* ?*fricRatio* "sandy silt 1")
  )

  (defrule sandy_silt_2  "Soil is Sandy Silt or Silty Sand 2"
     (declare (salience 99))
     (phase class)
     (soil_by_qt sand)
     (soil_by_fr silt)
     (soil_type silt ?)
=>
```

```
      (assert (soil_type clayey_silt (gensym*)))
;;       (print ?*cone* ?*fricRatio* "sandy silt 2")
  )


  (defrule get-certainty-factor
      (declare (salience 98))
      ?select <- (soil_type ?soil_type ?)
=>
      (if   (eq ?soil_type clay)
       then (bind ?*cf_clay* (get-cf ?select))
;            (printout t "clay " ?*cf_clay* crlf)
      )
      (if   (eq ?soil_type silt)
       then (bind ?*cf_silt* (get-cf ?select))
;            (printout t "silt " ?*cf_silt* crlf)
      )
      (if   (eq ?soil_type sand)
       then (bind ?*cf_sand* (get-cf ?select))
;              (printout t "sand " ?*cf_sand* crlf)
      )
      (bind ?*cfactor* (get-cf ?select))
      (if   (<= ?*cf_max* ?*cfactor*)
       then (bind ?*cf_max* ?*cfactor*)
;;           (printout t "depth ", ?*depth* " soil type " ?select "
cf_max " ?*cf_max* crlf)
;;           (printout t "clay " ?*cf_clay* "silt " ?*cf_silt* "sand "
?*cf_sand*)
;;     else (retract ?select)
      )
;;      (printout t "depth= " ?*depth* " cf_max " ?*cf_max* crlf)
;;      (printout t "clay " ?*cf_clay* "silt " ?*cf_silt* "sand "
?*cf_sand*)
  )

  (defrule select-soil-type-and-throw-the-rest
      (declare (salience 97))
      (phase class)
      ?selected <- (soil_type ?soil_type ?)
=>
      (bind ?*cfactor* (get-cf ?selected))
      (assert-soil-type ?soil_type)
      (retract ?selected)
  )



  (defrule restart
      (declare (salience 95))
      ?class <- (phase class)
=>
      (assert (data_in ok))
      (retract ?*qt*)
      (retract ?*fr*)
      (bind ?*cf_max* -999999.999)
      (bind ?*cf_clay* 0.0)
      (bind ?*cf_silt* 0.0)
```

```
      (bind ?*cf_sand* 0.0)
      (bind ?*cfactor* 0.0)
      (assert (phase select))
      (retract ?class)
   )

   (defrule print_result
      (declare (salience 9))
;;      (phase print)
=>
      (print-result)
   )
;;
;;  End of MODULE CPT
;;
;;
```