FUZZY-SETS DECISION-SUPPORT SYSTEM FOR GEOTECHNICAL SITE SOUNDINGS

DJAMALDDINE BOUMEZERANE, SMAÏN BELKACEMI and BOJAN ŽLENDER

about the authors

Djamalddine Boumezerane
University of Bejaïa,
Civil Engineering Department
Route Targa Ouzemmour 06000 Bejaïa, Algeria
E-mail: dboumezerane@gmail.com

Smaïn Belkacemi
Ecole Nationale Polytechnique,
Civil Engineering Department
10 Avenue Pasteur, Hassan Badi – El-Harrach, Algeria
E-mail: smainbelkacemi@yahoo.com

Bojan Žlender
University of Maribor,
Faculty of Civil Engineering
Smetanova 17, 2000 Maribor, Slovenia
E-mail: bojan.zlender@uni-mb.si

Abstract

A geotechnical site investigation is an important and complex task that is generally carried out in two steps. The first step, consisting of preliminary soundings, guides the subsequent site characterization. The number of soundings required to adequately characterize a site is set on the basis of an engineering judgement following the preliminary investigation, this is affected by the geological context, the area topography, the project type, and the knowledge of the neighbouring areas.

A fuzzy-sets decision-support system, considering parameters that affect the number of soundings required to adequately characterize a site, is proposed. Parameter uncertainties and a lack of information are also considered. On the basis of the available qualitative and quantitative information, the proposed fuzzy system makes it possible to estimate, for a common project, the number of site soundings required to adequately characterize the site. The cases presented show that a Fuzzy Inference System can be used as a systematic decision-support tool for engineers dealing with site characterizations.

keywords

geotechnical investigation, soundings number, fuzzy sets, fuzzy inference, uncertainties

1 INTRODUCTION

The complexity of a geotechnical site characterization is a result of the various uncertainties that need to be considered. Tang (1993) used statistical methods and probabilities to detect anomalies in the soil volume. Huang and Siller (1997) used fuzzy logic to characterize the different layers of a soil profile with a limited number of site soundings. Baecher and Christian (2003) considered two steps in the geotechnical site characterization – a site inspection that allows the setting of appropriate hypotheses and a geotechnical investigation consisting of detailed measures to be used in predictive models.

Important construction projects require detailed information about the geometry and the properties of a soil profile. A geotechnical site characterization generally starts with a review of the local and regional geology; after which the soil and rock identifications are obtained through localized site soundings. Obviously, a complete geotechnical site characterization can only be achieved with a large number of site soundings. Testing procedures commonly used to characterize sites are of the destructive type. For economic reasons we cannot identify all the points of the soil mass, and if one is able to circumvent the economic constraints, the integrity of the site could be seriously altered. In many situations, the budget constraints restrict the geotechnical knowledge of the site. A good geotechnical investigation should take into consideration all the available site information and should minimize the sources of uncertainties, while following an in-situ and laboratory-exploration program.

The number, the depth, and the layout of the sampling at a site depend on the geometry of the project, on a preliminary knowledge of the soil profile and on the type of project. Parsons and Frost (2002), in their study on the quality of a geotechnical investigation, indicate that the data collected from a site investigation represent less than 1/100 000 of the total soil volume. The determination of the number of soundings to undertake is still uncertain and fuzzy.

The sources of uncertainties associated with geotechnical analyses can be classified as: geometrical or model parameter uncertainty, model uncertainty, and human uncertainty. The type of uncertainty can be either quantifiable, random, related to the scatter of data or unquantifiable, epistemic, related to the lack of knowledge (Baecher and Christian, 2003; Christian, 2004; Tang, 1993).

Probabilities were widely used to deal with uncertainties in various geotechnical problems. Zadeh (1965) introduced the concept of the fuzzy set that has led to a new way to treat uncertainty and vagueness in all domains of engineering. In geotechnical engineering, fuzzy sets were used in various problems, like in soil and rock classifications (Huang and Siller, 1997), landslide analysis (Dodagoudar and Venkatachalam, 2000; Giasi et al., 2003), settlement calculations, and in the search for the characteristic values of a ground (Boissier, 2000; Chuang, 1995; Fetz et al., 1999; Hu et al., 2003; Nawari and Liang, 2000; Romo and Garcia, 2003; Santamarina and Chameau, 1989).

The objective of the present work is to outline, by using fuzzy sets, a systematic procedure to determine the appropriate number of site soundings required to achieve satisfactory geotechnical knowledge about the project site.

2 PROBLEM DESCRIPTION

A geotechnical site characterization is undertaken by either regular or random soundings, and the number of soundings is often based on the project engineer's evaluation. The objective of this study is to provide a systematic procedure that allows setting the required number of soundings to adequately identify the project site. Obviously, the greater the number of soundings, the better the knowledge of the site characterization; however, it is ineffective to go beyond a certain number of soundings that will not bring any more knowledge about the site.

The distribution of soundings to be made in a project area does not follow particular rules (Magnan, 2000); it depends on preliminary information, including:

- the geologic context of the project area,
- the topography of the project area,
- the project type,
- the knowledge of the neighbouring areas.

A geotechnical investigation is, generally, carried out in two stages. The first stage is a preliminary study leading to a rough site characterization that may guide a subsequent detailed site characterization. The second stage is a detailed site characterization based on the results of the preliminary study and on the project engineer's evaluation. Cambefort (1980) indicates that there is no precise rule about the number of soundings to be made on a site. He notes that the number of soundings to be made at a site depends on the results of the preliminary study. If an arbitrary loose mesh of soundings, used in the preliminary study, shows that the project area is relatively homogeneous then this number of soundings is satisfactory. However, if the results of the preliminary study show erratic information, the site characterization requires more soundings. The U.S. Corps of Engineers (1994) indicates that, for retaining-structures projects, the number of soundings to be made in the second stage varies from two to five times the number of soundings used in the preliminary stage.

The proposed approach, to determine the number of soundings to handle a geotechnical site characterization, consists of constructing an inference system based on fuzzy sets. Parameters, like the site's geologic nature, the site's topography and the project type, which may affect the number of soundings, are described. The theory of fuzzy sets makes it possible to treat parameters having vague or doubtful information as well as treating problems presented in linguistic or qualitative form. Each parameter entry (Input) of the system indicates if more or less soundings are required. The construction of the Fuzzy Inference System (FIS) allows us to implement the rules considered, by taking into account their weights, and to evaluate the final decision. The Fuzzy Inference System has the advantage of considering non-statistical uncertainties, such as inaccurate or vague variables.

3 FUZZY SETS AND INFERENCE SYSTEM

The concept of fuzzy sets consists of replacing standard sets (Crisp Sets) whose elements are discrete and carry only punctual values with sets whose elements are taken as belonging to a set with a degree of membership varying from zero to one [0,1]. Zadeh (1965) defines a fuzzy set as a class of objects with continuous degrees of membership. This set is characterized by a membership function that assigns to every object a degree of membership varying between zero and one.

3.1 FUZZY INFERENCE

A fuzzy inference model is generally based on the following three fundamental steps (Saboya et al., 2006):

- Selection of the Input and Output variables
- Description of the Input-Output fuzzy relation rules,
- Defuzzification, consisting of transforming the linguistic Output variables to values.

In the considered problem, various entry sets (Input) of the system are taken into account. These entry sets can be the geologic nature of the ground, the on-site slope, the project type, etc. The Output sets express themselves in terms of the density of the soundings on site (Important, Average, and Weak).

The fuzzy rules of the system are expressed as follows:

IF *X IS A* THEN *Y* IS *B*.

where *A* is the entry set and *B* the output set. These rules will be executed in parallel during the inference. An example of a fuzzy rule in our case can be as:

IF *"Relatively Known Geology"* THEN *"Moderate the number of soundings on the site"*.

The suitable selection of the elements for the entry sets is fundamental. Elements of the entry sets are of linguistic or qualitative form, such as the geology of the project area. For a "Known" geology, what will be the degree of knowledge that can be attributed to it? Collecting the knowledge is the difficult part in the development of the inference system. Santamarina and Chameau (1989) have noted that the information knowledge to be incorporated into a decision system is of most importance.

3.2 INFERENCE SYSTEM PARAMETERS

The proposed decision system is based on incomplete available information related to entry parameters, among which are:

- Site topography,
- Site geology,
- Site geotechnical conditions,
- Information on surrounding sites,
- Project type to be built.

The site topography is expressed in terms of the slopes in the project area; depending on the slope's intensity, the site is classified as "Strongly tilted ", "Averagely tilted" and "Weakly tilted ". The slope of the site will affect our decision about the required number of soundings to be made. The more important the slope is the more soundings will be required to characterize the site. The fuzzy sets used are of triangular and trapezoidal shape, as indicated in Fig. 1.

The site geology is expressed in terms of "Known", "Relatively Known" or "Unknown Geology". The use of geologic maps is necessary to have an initial idea about the geologic formations constituting the site, their properties, as well as the possibilities of inadequate or adverse geologic details. Clayton et al (2005) recommend, for geotechnical studies, to use geologic maps with a scale of 1/2500. The fuzzy set "Geology" is classified as "Known Geology", "Relatively Known Geology" and "Unknown Geology".

The more we know the geology; the less will be the required number of soundings. If the maps indicate variability and erratic subsurface conditions, then more soundings will be required to better characterize the site (F.H.W.A, 2002). The degree of knowledge is scaled between 0 and 100%; it indicates the knowledge level of the site's geological aspect. A map at a scale of 1/2500 provides a "Known Geology" at 80%, when a map scaled at 1/30000 does not furnish enough information. The set was constructed using the results of a questionnaire distributed to engineers and experts (Boumezerane, 2010). Fig. 2 illustrates the fuzzy set "Geology".

If the geological maps show, for the site being considered, various soil horizons, it will be necessary to make more

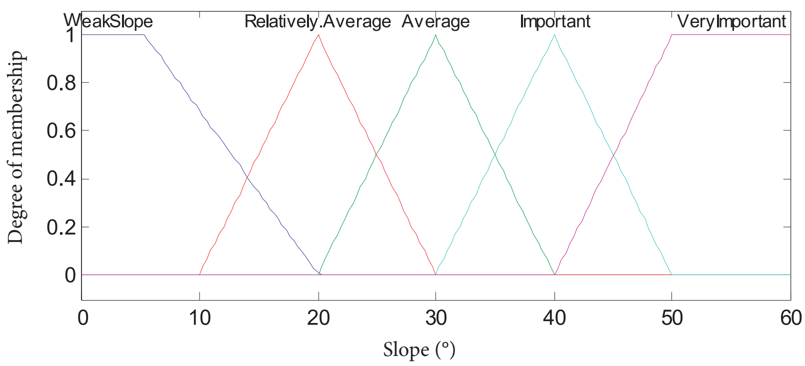

Figure 1. The fuzzy set "Topography-Slope of the site".

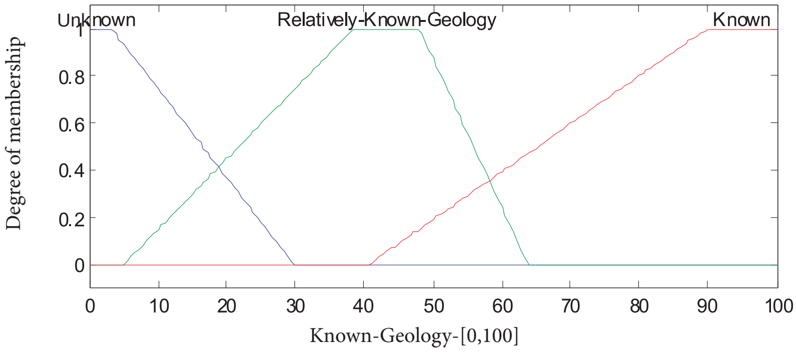

Figure 2. Fuzzy set "Known Geology" depending on the degree of information.

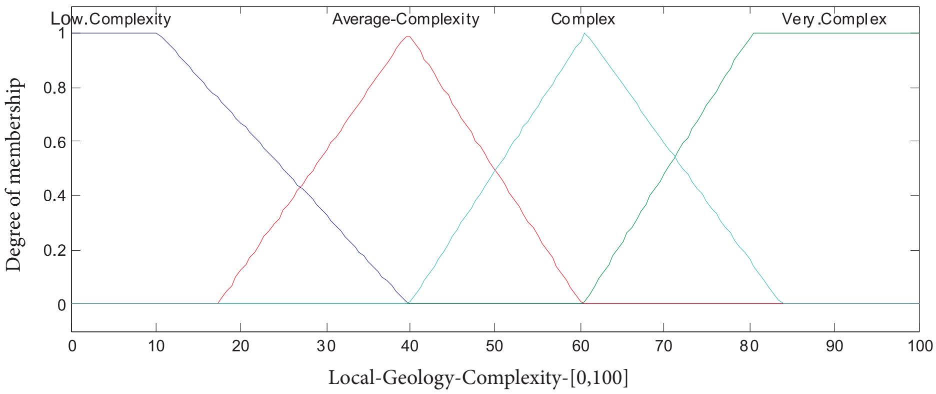

Figure 3. Fuzzy representation of "Local-Geology Complexity".

soundings than if there was only a single soil horizon. The spacing of the borings depends on the geology of the area and may vary from one site to another. The fuzzy set "Local Geology Complexity" reflects the complexity of the site's local geology. Expressed as a "Degree of complexity" of the local geology, it ranges between [0,100] with the linguistic attributes "Low-Complexity", "Average Complexity", "Complex" and "Very Complex". The membership functions and limits of the set are given in the following Fig. 3.

Ground geotechnical conditions can be incorporated using "Good strength, Medium strength or Weak strength" according to the average soil profile; universally accepted literature results can be used for this purpose. The quality of the ground geotechnical conditions is an important factor in defining the soundings' layout. When available, this information is generally given by the average trend of the soil (or rock) resistance. The weaker the quality of the geotechnical conditions, the more soundings are required. Fuzzy sets with elements based on the static modulus are used to set the geotechnical conditions of the soil. We used results given by Bowles (1977) to construct these sets (Fig. 4).

A geotechnical survey is generally made in two steps. In the first, preliminary soundings are used to guide the subsequent site characterization. The number of borings in the second step should be greater than in the preliminary phase. No exact spacing is recommended, as the boring layout should be controlled by the geologic conditions, the geotechnical aspect and the project type.

Preliminary soundings indicate a trend about the ground variability. The horizontal variability of the soil parameters influences the number of boreholes to execute. The higher the variability, the more important is the number of boreholes to execute. Significant dispersions of the soil parameters necessitate planning more soundings; otherwise a moderate number of soundings will be sufficient. Available data on the neighbouring sites can be used as the parameters of entry. If the surrounding sites' results are close to those obtained in the site's preliminary investigation, then the number of soundings to be performed

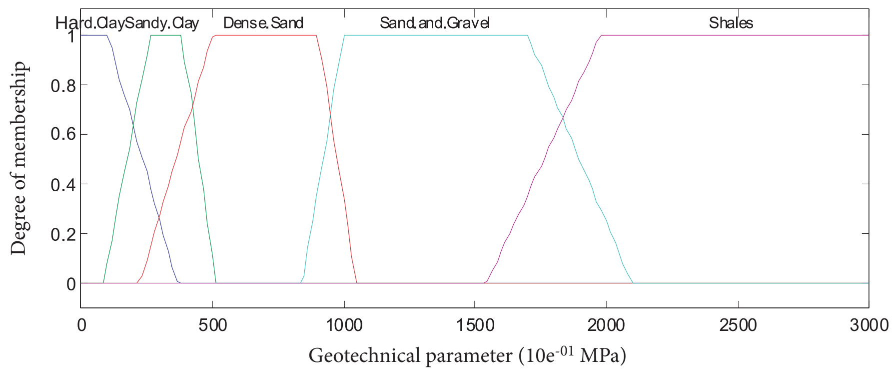

Figure 4. The fuzzy set "Geotechnical conditions" based on the Static Modulus of Soil.

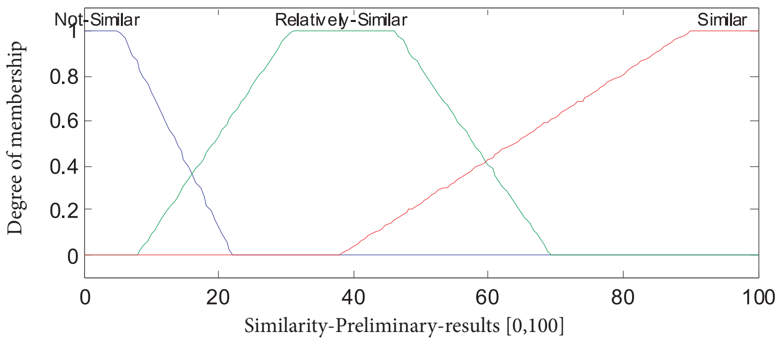

Figure 5. The fuzzy set "Similarity of preliminary results".

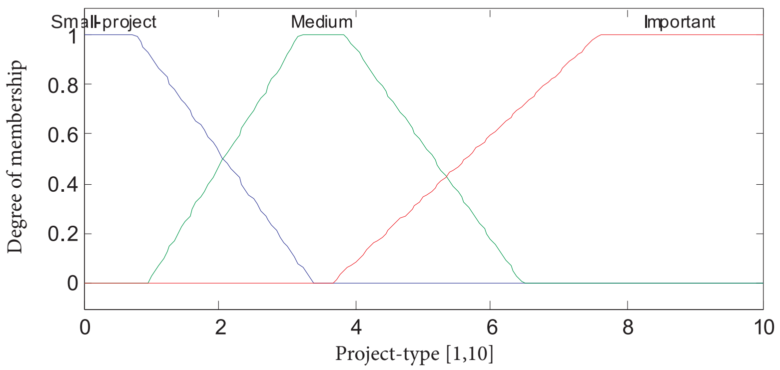

Figure 6. The fuzzy set "Type of project".

can be moderate, and if they are highly dispersed, it will be necessary to increase this number of soundings. The fuzzy set expressing the engineer's judgement on the results' similarity is given in Fig. 5.

The project type indicates whether a dense layout of the soundings is required. For the same area, when different projects are expected, each one will necessitate a different number of soundings, depending on their loading importance; a multi-storey building needs more soundings on site than a simple hall with the same area. The geometry of the project guides the spatial distribution of the soundings, which will be located according to the global shape of the building's area and by considering specific areas of the project.

The elements of the fuzzy set are expressed as "Important", "Medium" and "Small", depending on the loading induced by the project size, as indicated by Fig. 6.

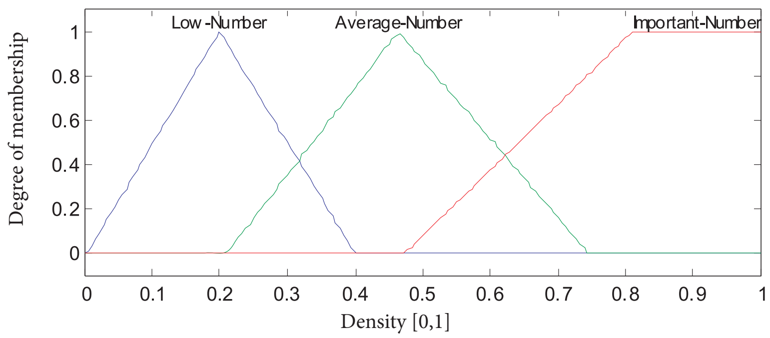

Figure 7. Output fuzzy set "Density of soundings".

The quoted parameters have important effects on the site-characterization procedure. They are expressed under linguistic and qualitative forms. They are assumed to be the input parameters of the inference system.

The Output set of the fuzzy system to construct is represented by a density, from 0 to 1, which will be transformed into the number of soundings, depending on the site conditions, and the minimum number of soundings required by the codes of practice. The linguistic labels of the fuzzy set Output are "Low", "Average" and "Important". Their membership functions are illustrated in Fig. 7.

4 INFERENCE SYSTEM DESIGN

The parameters of entry (Input) are expressed as fuzzy sets (Geology, Topography, Type of project, and Information about neighbouring sites, etc). The Output parameter is represented by a fuzzy set of the soundings' density on site. Each of these Input parameters influences, in a certain way, the number of soundings to perform on the site. Fuzzy Rules are constructed based upon the parameters available; they relate the Input to the Output (Fig. 8).

These fuzzy rules are expressed, generally, in a linguistic form and consider various possibilities; their number depends on the parameters taken into account and on the form of those rules. We used rules in the form IF A THEN B; for example, IF "Geology" is "Unknown" THEN "Important" number of soundings, etc. The Mamdani scheme of inference is used (Saboya et al., 2006). After the aggregation and defuzzification a weight *G* of decision is calculated. The defuzzification result *G* is given in a weight form and considered as a density of soundings to perform on site and varying between zero (0) and one (1). For values of *G* close to 1, it will be necessary to carry out an important number of soundings on the site. On the other hand, if *G* is near 0, then the number of soundings will be low.

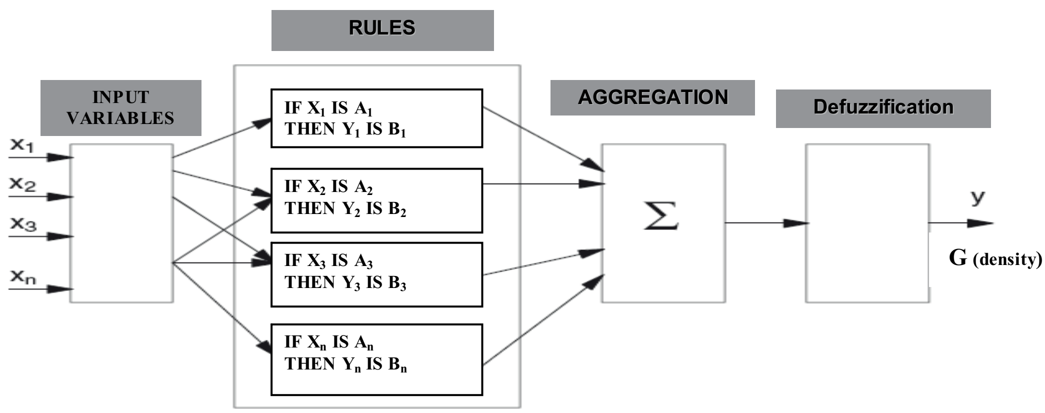

Figure 8. Scheme of the Fuzzy Inference System.

To translate this result into the number of soundings, it is necessary to calibrate the fuzzy model used to the guidelines that set the minimum soundings (Eurocode 7 1996, F.H.W.A 2002).

For this purpose, the Fuzzy Inference System is run with the following Input Parameters: Slope (°), Geotechnical conditions (MPa, m/s), Project type, Known-Geology (%), Local Geology Complexity (%), Similarity of Preliminary Results (%) and Specifically Loaded Zones. The extreme defuzzification results in weight form were G=0.201 and G=0.810. The first result is obtained in the case of extremely favourable conditions (Topography (0°), Known-Geology (100%), etc.), and few soundings are necessary to characterise the site. The second result expresses the case of extremely unfavourable conditions (Unknown Geology, Important Variability, etc) and the necessity of making a large number of soundings.

4.1 Transformation of the Fuzzy Inference System (FIS) result G into a number of soundings

The result G of the Fuzzy Inference System expresses the density of soundings on the site. To transform this density G into an optimum number of soundings N_{opt} we introduced N_{ref}, the reference number of soundings required by codes (Eurocode 7 1996, F.H.W.A 2002), and a weight G_{ref} corresponding to N_{ref} . G_{ref} is comprised in the interval of the possible results of the FIS.

For G corresponding to the "Optimum number of soundings N_{opt}*"*

and

For G_{ref} *corresponding to the "Reference number of soundings* N_{ref}*"*

we obtain

$$N_{opt} = (N_{ref} \cdot G)/G_{ref} \qquad (1)$$

G_{ref} is set to correspond to the reference number N_{ref} of soundings given by the codes. N_{ref} depends only on the area of the project.

4.2 Recommendations from codes on the number of soundings N_{ref}

Some technical documents recommend "guidelines" to set the required "minimum" sub-surface data to achieve a cost-effective, geotechnical design. The guidelines point out the dependency of the number of borings upon the type of project and its requirements. However, there are no "rigid" rules that are established for this objective (F.H.W.A, 2002). The required "minimum" number of soundings (N_{ref}) can be set through these guidelines, and it is obvious that beyond a certain number of soundings there will be an information redundancy that will not lead to a better knowledge of the site. One of the objectives of this study is to provide a systematic procedure to check whether more than a minimum number of soundings are required to characterize the site.

The guideline ("minimum" boring, sampling and testing criteria) edited by F.H.W.A (2002) indicates, for the case of the Structure Foundation, a minimum number of borings of "one (1)" per substructure unit under 30m in width and "Two (2)" per substructure unit over 30m width. Additional borings are recommended in the case of erratic subsurface conditions. Eurocode 7 (1996) recommends, for large projects, one borehole for distances between 20m and 40m. According to Simons et al. (2002) the spacing for boreholes, for structures' foundations, often lies in the range 20m to 40m. The borehole layout and frequency are partly controlled by the complexity of the geological conditions. If the ground conditions are relatively uniform, a wide spacing of boreholes may be satisfactory, but if the ground conditions are complex a closer spacing of boreholes will be required (Simons et al., 2002).

The number of soundings as set by F.H.W.A (2002) or by Simons et al. (2002) and Eurocode 7 (1996) depends only on the area of the project; other parameters that can influence the number of borings are not considered, such as soil variability, geotechnical and geological site conditions, the type of project, etc. The approach we propose permits taking into account those parameters whose information is generally qualitative and fuzzy sets are a suitable tool to use in this case.

4.3 Calibration of a reference G_{ref}

In order to apply the FIS to real sites, we calibrate a certain G_{ref} with codes (Eurocode 7 1996, F.H.W.A 2002) giving indications on the "minimum" number of soundings, noted here N_{ref} , depending only on the area of the project site.

The previously defined G_{ref} is set to correspond to the reference number N_{ref} of soundings given by the codes. The extreme defuzzification results of the Fuzzy Inference System are G=0.201 and G=0.810. As all the values of G are included in the interval [0.201, 0.81] we can consider G_{ref} as the mean value of the results range, then:

$$G_{ref} = (0.201 + 0.81)/2 = 0.505$$

This G_{ref} is taken as corresponding to the reference number N_{ref} of soundings equal to the mean of the Eurocode 7 recommendations, one sounding between 20 to 40 m. In this case N_{ref} will be one boring every 30 m of the project area.

Using expression (1) we can then predict the optimum number of soundings N_{opt} for a site's geotechnical investigation using the fuzzy inference system.

The calibration of G_{ref}=0.505 makes it possible to predict the extreme values of N_{opt} for G=0.201 and G=0.810.

We obtain for the reference mean value from Eurocode 7, N_{ref} =1/(30x30m²);

$$N_{opt} = (N_{ref} \cdot G)/G_{ref} = \\ = N_{min} = 1/30x30 \cdot 0.201/0.505 = 1/(48x48)m^2,$$

one sounding for an area of 48x48m² as a minimum number. This number is smaller than the minimum proposed by Eurocode 7, N_{min}=1/40x40m².

And

$$N_{max} = (1/(30x30) \cdot 0.810 /0.505 = 1/(24x24)m^2 ,$$

one sounding for an area of 24x24m², which is the maximum number, and in this case less important than the proposed one by Eurocode 7, one sounding for an area of 20x20m².

In a second stage we standardize G_{ref} by using the minimum value of the interval [0.201, 0.810], G_{ref}=0.201 and calibrate it with the minimum number of soundings N_{ref} recommended by Eurocode 7 (one boring every 40x40m²).

We obtain, in this case, the extreme values of N_{opt} for G=0.201 and G=0.810;

$$N_{opt} = (N_{ref} \cdot G)/G_{ref} = \\ = N_{min} = 1/(40x40) \cdot 0.201/0.201 = 1/(40x40)m^2 ,$$

one sounding every 40x40m², as the minimum and

$$N_{max} = 1/40x40 \cdot 0.810/0.201 = 1/(20x20)m^2,$$

one sounding for an area of 20x20m², representing the maximum number of borings.

The obtained numbers agree with those recommended by Eurocode 7, one boring every 40x40m² as a minimum and one boring for 20x20m² representing the maximum number.

Then, for a given site, for which an investigation is planned, we can use G_{ref} as a calibration from Eurocode 7; this allows us to have a range of values for N_{opt}.

The recommendations from F.H.W.A (2002) set a minimum number N_{ref} of soundings every 30m. We may use G_{ref}=0.201 as corresponding to this minimum number, and we can expect the maximum number of borings Nmax by using G=0.810 as the upper limit of the FIS results range. Expression (1) gives in this case:

$$N_{opt} = (N_{ref} \cdot G)/G_{ref} = \\ = N_{max}= 1/(30x30) \cdot 0.810/0.201 = 1/(15x15)m^2 ,$$

one sounding for an area of 15x15m².

The obtained N_{max} is greater than the maximum recommended by Eurocode 7 (1/20x20m²).

5 APPLICATIONS

5.1 EXAMPLE 1

In this example the data is available and the number of performed soundings on site is known. The Fuzzy Inference System is run using the available parameters and the result is used as a comparison.

The site is described in "Adaptive Ground Modelling in geotechnical engineering" (Schönhardt and Witt, 2003). The main characteristics of the project are, as shown in Fig. 9.

- Surface area of study: (100 x 250)m², Area of the project (83 x 205)m², Type of the project: Industrial; Topography: Plane; Geology (Degree of information): Relatively unknown; Preliminary results show three geological formations (Silty Clay with soft consistency, Stiff Clay between 8-14m, Sandy clay until 70m depth); Specifically loaded zones (Machines):(20x60 + 2x(20x25))m² approximately (1200+1000) =2200m², the specifically loaded area ratio is: 2200/(83 · 205)=13% of the total project area; No information available about neighbouring sites; The preliminary results show similarity (similarity around 60%); Number of preliminary soundings 8, performed at site corners, and at middle distance, and the total number of driven borings is 28 (considered here as optimum N_{opt}).

For this example, the Fuzzy Inference System parameters were set to: Slope is "Low" with a mean value around 3°, the Geologic knowledge of the site is taken as "fair"

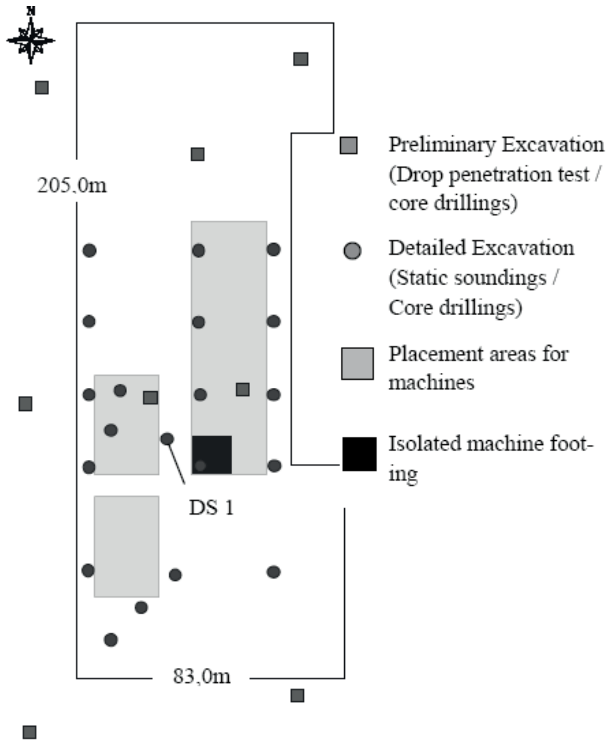

Figure 9. General view of the site of the study – performed soundings are mentioned (After Schönhardt and Witt, 2003).

around 15% (no geological maps are available) and the Geological complexity is "Average complexity". The preliminary soundings indicate that three formations are quoted and they show a certain similarity between the results (around 60%). In this industrial project, the number of zones to be subjected to a specific loading (machines) is relatively important, as indicated in Fig. 9.

The number of soundings (28) given by Schönhardt and Witt (2003) was considered to be sufficient to obtain a good knowledge of the site.

The reference number of soundings N_{ref} deduced from the mean of the Eurocode 7 recommendations is 18 for the area of the project (one sounding every 30m).

We applied the Fuzzy Inference System given the site's conditions and the result was G=0.565, which reflects in a certain way the real site conditions, including the constraints associated with the complexity of the geology and the nature of the project.

Using (1) we calculate the optimum number of soundings N_{opt}

$$N_{opt} = N_{ref} \cdot G/G_{ref} = 18x0.565/0.505 = 21 \text{ soundings}$$

The obtained number of borings is fewer than the 28 soundings used in the site.

In the second stage we use G_{ref} =0.201, the lower value of the interval of results [0.201; 0.81], as corresponding to the minimum number of boreholes N_{ref} given by Eurocode 7, one borehole every 40m. For the surface of this project we obtain N_{ref} =10 soundings. Then using expression (1) again we can predict the optimum number of soundings N_{opt} for this site:

$$N_{opt} = 10 \cdot 0.565/0.201 = 29 \text{ soundings.}$$

The predicted number of soundings in the second stage is almost the same as the one given by Schönhardt and Witt (2003). Based on the results of the FIS, the proposed optimum number N_{opt} of soundings is between 21 and 29.

5.2 EXAMPLE 2

The site of the proposed building addition is located on the side of an existing High School. It consists of a two- and three-storey building with a footprint of approximately 6500m^2. It is assumed that the loads will be typical for a building of this size and type (Strater and McKown, 2002).

A preliminary investigation was carried out and this consisted of two test borings BHB-1 and BHB-2(OW). They were drilled, within the footprint of the proposed project, to depths of approximately 12.3m and 12m. Test pits were previously excavated in the vicinity of the existing buildings to determine the subsurface soil and groundwater conditions adjacent to the existing foundations.

The subsurface conditions observed indicate:

Topsoil: very thin layer of silt.

Fill: encountered in the vicinity of most of the proposed project location is around 1m thick and consists of medium-dense brown Silty Sand. In TP1 and TP2 it consists of brown Sandy Silt with Gravel and Sandy lean Clay.

Marine Deposits: encountered in borings BHB1 and BHB2 (OW) consisted of medium dense to dense poorly graded Sand with Silt and Silty Sand. The thickness ranges from 11.3m to 13.7m in the southern portion of the site. In the northern part the thickness varies from about 0m, up to 4.5m to 6m.

Glacial Till: Consisting of very dense Sand with Silt and Gravel. These soils were encountered below the marine deposits in BHB2 (OW) at a depth of about 11.30m.

Glacial Till was not encountered in the boring BHB1. It was anticipated by the engineers that a discontinuous layer of Glacial Till, ranging in thickness from about 0 to 1.5m, is present throughout most of the site.

Bedrock: Was encountered in Test Pits TP-3 and TP-6 at depths of around 1m. But it was not encountered with the conducted borings.

Engineers in charge of the preliminary investigation recommended a subsurface exploration program of three to five additional test borings and three to five test probes within the footprint of the proposed building.

5.2.1 THE USE OF THE FUZZY INFERENCE SYSTEM

To use the Fuzzy Inference System, some of the entry parameters from the site are defined as below:

- The slope is relatively average (25%), corresponding to a mean of 15°; The information about adjoining sites exists and could be exploited; The type of project to implant is a High School of three storeys; The geology is "Relatively Unknown" and it is suspected to have a great degree of soil variability, according to the soil layers encountered in the preliminary investigation; The results of preliminary tests (two boreholes) indicate important differences. The degree of similarity between them was taken as very low; According to the engineers the loads are typical for a building of this size and type; the modulus of the layer of Sand with Silt and Silty Sand ranges from 10 to 25MPa.

The defuzzification weight result obtained with the inference system is G=0.546.

In order to calculate the optimum number of soundings for this site, we first use G_{ref}=0.505, corresponding to the mean "reference" number of soundings from Eurocode 7 (1996). The required number of soundings for this surface (6500m²) is N_{ref}=6.

Using the result G of the Fuzzy Inference System on this site and expression (1) it is possible to expect an optimum number of boreholes;

$$N_{opt} = N_{ref} \cdot G/G_{ref} = 6 \cdot 0.546/0.505 = 7 \text{ soundings}$$

When using G_{ref} =0.201 corresponding to the "minimum" number of soundings N_{ref} recommended by Eurocode 7 (1996), and for an area of 6500m² (N_{ref}=4 soundings), we obtain:

$$N_{opt} = N_{ref} \cdot G/G_{ref} = 4 \cdot 0.546/0.201 = 12 \text{ soundings}$$

The result of the Fuzzy Inference System is in the same range as proposed by the engineers in charge of this geotechnical study. They have proposed a total number of soundings that ranges from 8 to 12.

If the engineer's judgement, relative to the recommended number of borings, is considered to be reliable, then the Fuzzy Inference System used independently to evaluate the optimum number of soundings shows consistent results (from seven to twelve soundings).

6 EVOLUTION OF DENSITY G WITH REGARD TO THE INPUT PARAMETERS

The available input parameters are various and influence the density of soundings, each one in a certain way. Fig. 10 shows the variation of the Geological-complexity and Geotechnical parameters and their influence on the results when other parameters are taken constant. The surface presents a plateau of important values of G when the Geology is Complex and the geotechnical formations are relatively weak.

Another example illustrating the variation of G as a function of input parameters is given in Fig. 11 where the Known-Geology and Geological-Complexity vary and present a surface of an important density of boreholes when Geology is less known and more Complex. Those figures show the possibilities given to describe the variations of G depending on the different parameters. The fuzzy inference system is able to simulate different situations, and helps engineers to take decisions when dealing with a geotechnical investigation.

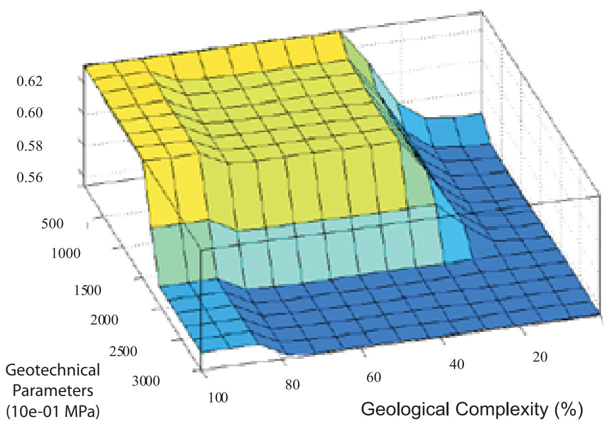

Figure 10. Influence of Geotechnical parameters and Geological Complexity on the density of the soundings (Known Geology 5%, Project Type 5, Similarity 50%).

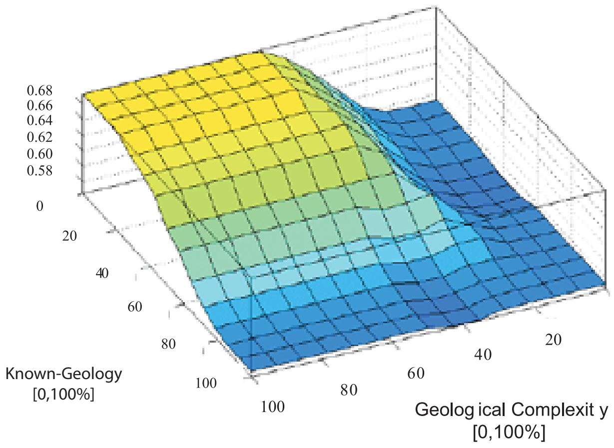

Figure 11. Influence of Known Geology and Geological Complexity on the density of the soundings (Geotechnical parameters 20MPa, Project Type 5, Similarity 5%).

6.1 COMPARISON OF FIS RESULTS WITH REGARD TO CODES (EUROCODE 7, F.H.W.A)

The following figures show the minimum number of soundings recommended by Eurocode 7 and the optimum number obtained using our approach with some parameters of entry (Known-Geology, Geology-Complexity). The project's area is varying from small to important surfaces.

Figures 12 and 13 illustrate the ability of the FIS to work with available parameters of entry that can influence a geotechnical investigation. Two parameters (Known-Geology, Geology-Complexity) are used here for an illustration. The results show the differences between the recommendations of Eurocode 7 and the expected optimum number of soundings. The differences are increasing proportionally when the area of the project is becoming important. The FIS allows us to handle the available information and we note from Fig.12 and 13 the influence of local geology complexity when it decreases. We set those recommendations as the starting points for the Engineer when dealing with Geotechnical Investigations. The more information we have the easier and more precise will be the investigation.

7 CONCLUSION

A Fuzzy Inference System is developed to handle uncertainties occurring in a geotechnical site-characterization campaign. The main idea is to reproduce the site engineer's reasoning to set the number of soundings to perform the site characterization. Various interfering parameters have to be considered in this case. Knowledge of Geology is an important part. The nature of the project to be built and the topography of the site affect the density of the soundings. Fuzzy sets are used to

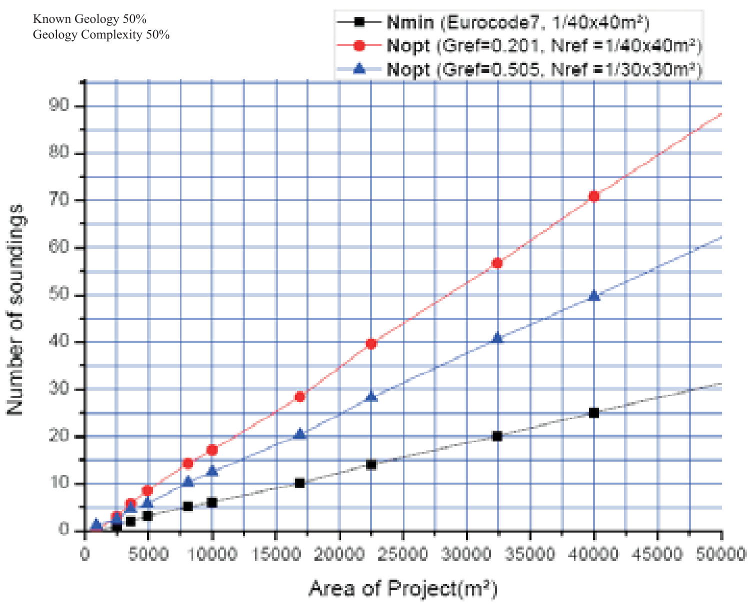

Figure 12. Optimum number N_{opt} of soundings using FIS compared to Nref (Eurocode 7) ("Known-Geology" 50% and "Geology Complexity" 50%).

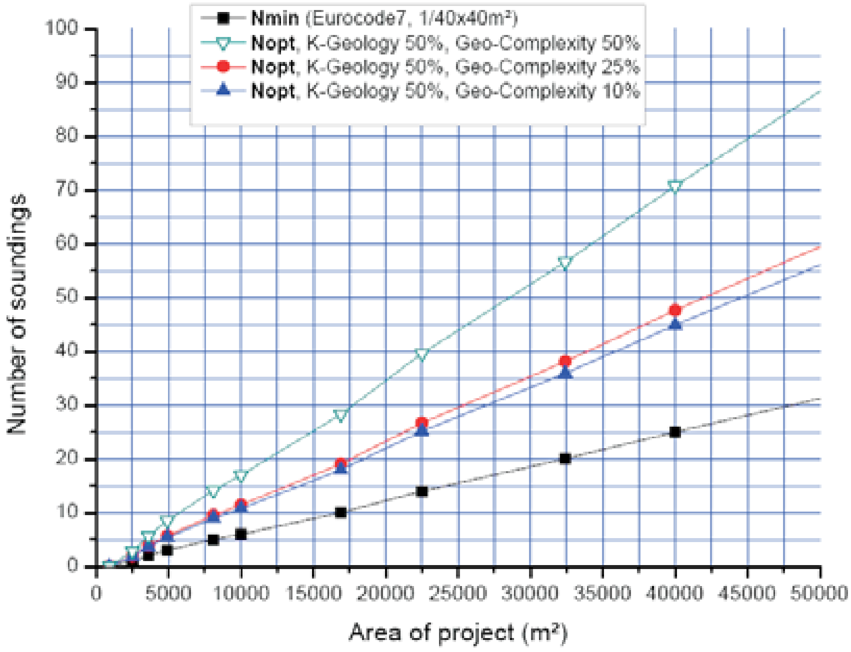

Figure 13. Optimum number of soundings compared to Nmin (Eurocode 7)
(Different cases of "Known-Geology" 50% and "Geology Complexity" 10%, 25%, 50%).

represent site-characterization parameters with possibilities to consider linguistic and qualitative information. They also make it possible to handle the uncertainties contained in the parameters. The fuzzy system consists of the Input Parameters (Geology, Topography, etc) and the Output parameters (Density of Soundings on the Site). Each entry parameter contributes to the weight of the decision. The fuzzy system assembles all the influences and aggregates them to obtain a fixed number, between 0 and 1, representing the optimum number of soundings to be performed on the site. The cases presented show the effect of the various parameters, and reveal the efficiency of the fuzzy sets used to represent the site-characterization parameters. The fuzzy inference system considers the influence of each individual entry parameter and computes the global, optimum density of the soundings relative to recommendation guidelines. The result is given in the form of a weight indicating the decision to be taken by the engineer. The available guidelines (F.H.W.A, 2002; Simons et al., 2002) give indications, depending on the project dimensions, on the number of borings required to characterize the site soil.

Confidence degree in the Fuzzy Inference System allow us to relate, for known cases, the weight G to the "optiuml" number of soundings N_{opt}. The weight G_{ref}, corresponding to the "reference" number of soundings N_{ref} recommended by technical guidelines (Eurocode 7, FHWA), is then deduced and was set as a standard value, allowing us to calculate the "optimum" number of soundings for common sites.

The cases presented show that the Fuzzy Inference System can be used as a systematic decision-support tool for engineers dealing with the site's characterization. The system is a step beyond the technical guidelines that set the required minimum number of soundings to characterize the site soil. The fuzzy inference system tells the engineer if more than the minimum number of soundings are needed to characterize the site.

REFERENCES

Baecher, G.B. and Christian J.T. (2003). Reliability and Statistics in Geotechnical Engineering. Wiley Ed.

Boumezerane D. (2010). Questionnaire about Geology and Soil Variability for Geotechnical Investigations. Department of Geotechnics, University of Maribor, Slovenia.

Cambefort, H. (1980). Géotechnique de l'Ingénieur, reconnaissance des sols. Eyrolles Editeur – Paris.

Christian, J.T. (2004). Geotechnical Engineering Reliability, How Well Do We Know What We Are Doing? Journal of Geotechnical and Geoenvironmental Engineering 130(10), 985-1003.

Clayton, C.R.I., Matthews, M.C. and Simons, N.E. (2005). Site Investigation. Department of Civil Engineering, University of Surrey.

Dodagoudar, G.R. and Venkatachalam, G. (2000). Reliability analysis of slopes using fuzzy sets theory. Computers and Geotechnics 27, 101-115.

EUROCODE 7, (1996). Section 3. Données géotechniques, AFNOR.

Fetz, J., Jäger, J., Köll, D., Krenn, G., Lessmann, H., Oberguggenberger M. And Stark, R.F. (1999). Fuzzy models in geotechnical engineering and construction management. Computer-Aided Civil and Infrastructure Engineering 14 (2), 93–106.

F.H.W.A (2002). Sabatini, P.J, Bachus, R.C., Mayne, P.W., Schneider J.A. and Zettler T.E. Geotechnical Engineering Circular 5 (GEC5) - Evaluation of Soil and Rock Properties, Report No FHWA-IF-02-034. Federal Highway Administration, U.S. Department of Transportation.

Giasi, C.I., Masi, P. and Cherubini, C. (2003). Probabilistic and fuzzy reliability analysis of a sample slope near Aliano. Engineering Geology 67, 391-402.

Hu, Z., Chan. C.W. and Huang, G.H. (2003). A fuzzy expert system for site characterization. Expert Systems with Applications 24, 123-131.

Huang, Y.T. and Siller, T.J. (1997). Fuzzy Representation and Reasoning in Geotechnical Site Characterization. Computers and Geotechnics 21(1), 65-86.

Magnan, J.P. (2000). Quelques spécificités du problème des incertitudes en géotechnique. Revue Française de Géotechnique 93, 3-9.

Nawari, N.O. and Liang, R. (2000). Fuzzy-based approach for determination of characteristic values of measured geotechnical parameters. Canadian Geotechnical Journal 37, 1131-1140.

Parsons, R.L. and Frost, J.D. (2002). Evaluating Site Investigation Quality using GIS and Geostatistics. Journal of Geotechnical and Geoenvironmental Engineering 6, 451-461.

Romo, M.P. and Garcia, S.R. (2003). Neurofuzzy mapping of CPT values into soil dynamic properties. Soil Dynamics and Earthquake Engineering 23, 473-482.

Saboya, F.Jr., Alves, M.G. and Pinto, W.D. (2006). Assessment of failure susceptibility of soil slopes using fuzzy logic. Engineering Geology 86, 211-224.

Santamarina, J.C. and Chameau, J.L.(1989). Limitations in decision making and system performance. Journal of performance of Constructed Facilities 3(2), 78-86.

Schönhardt, M. and Witt, K.J. (2003). Adaptive Ground Modelling in geotechnical engineering. Proceedings of the International Symposium on Geotechnical measurements and Modelling, 23-25 September 2003, Balkema Publishers Karlsruhe (Germany), 297-305.

Simons, N., Menzies, B. and Mattews, M. (2002). A Short course in Geotechnical Site Investigation. Thomas Telford Ed.

Strater, N.H. and McKown, A.F. (2002). Draft Report on preliminary geotechnical studies, Proposed Beverly High School Building Addition, Beverly, Massachusetts. Haley & Aldrich Inc., Boston Massachusetts, June 2002, file N° 28022-001.

Tang, W.H.(1993). Recent developments in geotechnical reliability, Probabilistic Methods in Geotechnical Engineering, pp.03-27. Li & Lo (Eds) Balkema.

U.S. Corps of Engineers, 1994. Geotechnical Investigation, Report N° EM 1110-2-2504, March 1994.

Zadeh, L.A. (1965). Fuzzy Sets. Information and Control 8, pp. 338-353.