COMPUTER-AIDED DECISION SUPPORT SYSTEM FOR SAFETY MONITORING OF GEOTECHNICAL CONSTRUCTION

Min-Yuan Cheng[1], Amos Chien-Ho Ko[2], Chih-Hung Chang[2]

[1]*Department of Construction Engineering, National Taiwan University of Science and Technology, Associate Professor*

[2]*Department of Construction Engineering, National Taiwan University of Science and Technology, Research Assistant*

Abstract: This study endeavor focuses on developing a decision support system for safety monitoring of foundation constructions. According to statistical investigations, foundation excavation is the most construction activity apt to causing construction accidents. In all geotechnical engineering work, it is clear that there will be discrepancy between prediction and performance. Consequently designs tend to be conservative, although on occasions they may well be unsafe. Very conservative design means extra cost whereas failure means both loss of resource and even life. Safety is an essential consideration in all construction projects. Instrumentation programs can not only fill the gap of the insufficient of the design, but also provide the needed safeguards, by indicating behavior with respect to threshold limits and by providing a forewarning of any adverse effects of construction. This paper develops a GIS based decision support system to assist construction engineers to monitor and control the excavation conditions. In the system, the layout of the construction site and various instruments are represented in several data layers (coverages). Each instrument layer is integrated with a relational database receiving the data collected from the site. Applying fuzzy sets theory, the system analyzes the collected data and identifies the possible causes of the adverse conditions. Through database queries and spatial displays, the positions of the extraordinary instruments exceeding the threshold limits are identified. The primary features of the system are as follows: (1) develop a knowledge base for planning layout of instruments according to the design requirement, site characteristics, or instrument capabilities, (2) provide a checking list of quality control for instrument installations., (3) collect and transmit the measured data to the job site office using the automated transmission technology, and (4) analyze the collected data and diagnose the possible causes of the crisis situations. This system improves the instrumentation program by providing a logic and systematic manner to analyze the measured data in a real time base. Predictions of any adverse conditions and appropriate actions can be taken to prevent the occurrences of construction accidents. Furthermore, compared with manual methods, the system significantly improves the computational effort and increases the data accuracy and consistency.

Keywords: geotechnical construction, foundation excavation, safety monitoring, decision support system, instrumentation program, fuzzy sets theory.

1. INTRODUCTION

According to the statistical investigations of previous researches, foundation excavation is one of the most construction activities apt to causing construction accidents. Geotechnical constructions are normally executed in an environment characterized by varying degrees of uncertainties. The designer of geotechnical construction works with a wide variety of naturally occurring heterogeneous material, which may be altered to make them more suitable, but exact numerical values of their engineering properties cannot be assigned [1]. Laboratory or field tests may be performed on selected samples to obtain values for engineering properties, but these tests will only provide a range of possible values. Thus, The design of geotechnical construction will be based on judgment on selecting the most probable values within the ranges of possible values for engineering properties. Because of uncertainties inherent in the design, it is clear that there will be discrepancy between prediction and performance. Consequently designs tend to be conservative, although on occasions they may well be unsafe. Very conservative design means extra cost whereas failure means both loss of resource and even life [2]. Safety is an essential consideration in all construction projects. Instrumentation programs can not only fill the gap of the insufficient of the design, but also provide the needed safeguards, by indicating behavior with respect to threshold limits and by providing a forewarning of any adverse effects of construction.

In practice, the engineers monitor the geotechnical conditions based on site observations and analysis of instrument measurements. Inherent in the use of instrumentation for construction reasons is the absolute necessity for deciding, in advance, a positive means for solving any problem that may be disclosed by the results of the observations. When the magnitudes of data change exceed the predetermined critical magnitudes, immediate responses have to be taken by the engineers to identify the location of the instrument and analyze the possible causes of the abnormal condition. The assessment process involves the analysis of the results of site observations and interpretation of the collected data including the instrument itself and the other instruments surrounding it. Based on the analysis results, appropriate actions should be taken to prevent the occurrence of accidents. The process of analysis and judgment involving large amount of fuzzy and uncertain factors requires engineers who have comprehensive knowledge of project conditions and abundant experience in geotechnical engineering to judge and make the right decision. However, most of the judgments are based on individual's knowledge, experience, and adaptation of past experience to present projects. With the presence of uncertainties, it is sometimes difficult for experts to give a definitive judgement of the causes of the adverse conditions…

2. RESEARCH OBJECTIVES

The primary purpose of this study is to develop a computer-aided decision support system for safety monitoring of geotechnical construction. The sub-objectives required to achieve the primary objective are the following:

- Gain the knowledge and experience of the experts in reasoning the causes of excavation accident based on the collected instrument measurements;
- Develop a similarity evaluation method to analyze the instrument readings and determine the possible causes of the adverse condition;
- Develop a computer-aided decision support system using Geographic Information System (GIS) to implement the objectives mentioned above.

3. ARCHITECTURE OF MONITORING PROGRAMS

The architecture of monitoring programs is developed according the needs of the management of the monitoring process. In Figure 1, the operational structure for instrumentation monitoring has five parts including: (1) instrumentation installation layout planning, (2) installation quality control, (3) automated data acquisition, (4) measurement data management, and (5) disaster reasoning model.

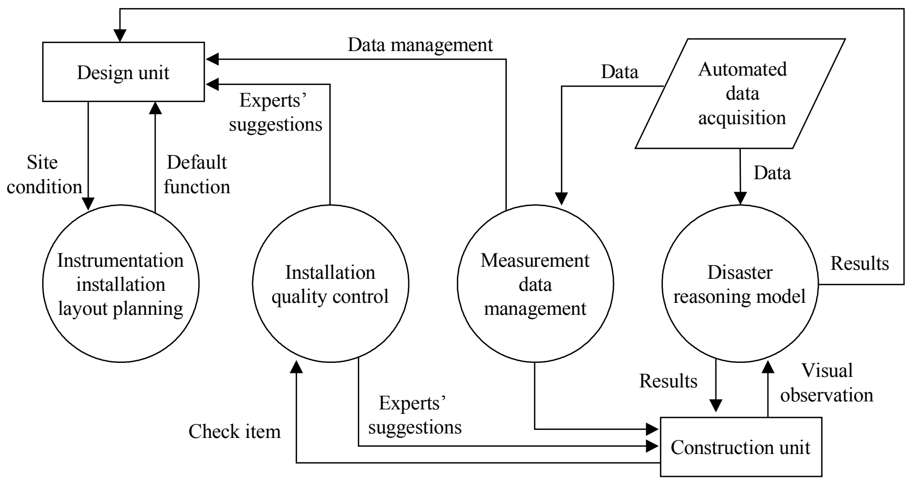

Figure 1. Operational Structure for Instrumentation Monitoring

3.1 Instrumentation Installation Layout Planning

The selection of instrument locations should reflect predicted behavior and should be compatible with the method of analysis that will later be used when interpreting the data.

3.2 Installation Quality Control

An installation quality checklist is provided for the engineers to check whether the instruments are installed correctly and properly. Installation quality of instruments impacts the correctness of measurements significantly. Thus, in the system, a quality control checklist for instrument installation is developed to assist engineers to ensure that the instruments are installed as planned.

3.3 Automated Data Acquisition

Automated data acquisition of instrument is shown in Figure 2. Through cable connection, which allows 32 channels maximum, the remote instrument measurements can be sent to the host database.

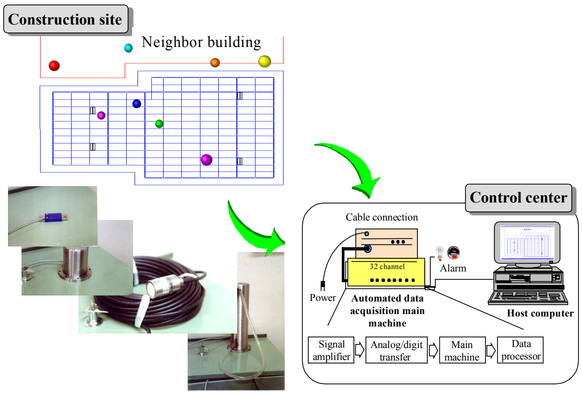

Figure 2. Automated Data Acquisition Schema

3.4 Measurement Data Management

This system allows users to query any data and parameter in databases for management. It also allows users to create their own instrument abnormal level database based on the system default database.

3.5 Disaster Reasoning Model

This section achieves the task of modeling the expert's knowledge and experience in reasoning the causes of excavation accident and expressing it in a systematic form. Due to the complexity of the problem, the judgment of safety monitoring varies from one project to another, and even from case to case within the same project. Most of the judgments are based on individuals' experience, knowledge, and adaptation of past experience to present projects. However, there still exist some rule-of-thumb practices in analyzing the instrument measurements and judging the causes of the adverse conditions. Thus, this study developed a disaster reasoning model for construction excavation to systematically acquire and represent experts' knowledge and experience.

Figure 3 shows the process of developing the disaster-reasoning model for excavation safety monitoring and describes as follows.

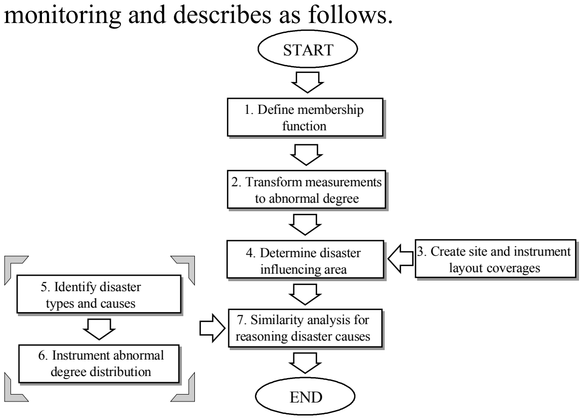

Figure 3. Disaster-Reasoning Model Development Process

3.5.1 Constructing Membership Functions for Each Instrument

Classical logic is the conventional method used to assess if an instrument measurement is normal or not. The statement can be zero or one – and nothing in between [3]. However, geology is a field characterized by varying degrees of vagueness and uncertainties. Classical logic judgment of excavation instability origins is apt to invoke confusions as the instrument measurement lies between normal and extraordinary conditions. Thus, this study applies fuzzy sets theory to develop instrument extraordinary membership functions to represent the extraordinary class of measurements within ambiguous area.

The extraordinary classes of measurement are categorized into five intervals, namely normal, slightly normal, abnormal, very abnormal, and extremely abnormal. The rating of each interval is defined as shown in Table 1. According to the interval ratings, the Fuzzy Statistics Method is used to design a questionnaire to obtain the membership functions of extraordinary classes for each instrument. Using interior wall inclinometer as an example, the membership function is shown in Figure 4.

Table 1. The Abnormal Class of Measurement

Abnormal class	Abnormal level
Normal	1
Slightly abnormal	2
Abnormal	3
Very abnormal	4
Extremely abnormal	5

3.5.2 Transforming Measurements to Abnormal Sets

This section uses the same example and the membership functions developed in Figure 4 to introduce the procedure and equations of converting instrument measurements into abnormal sets. In this case, it is assumed the initial value (V_i) of the interior wall inclinometer is 0 cm, the warning value (V_w) is 3 cm, the action value (V_a) is 5cm, and the measurement (V_m) is 2.7cm. The conversion process is described as follows:

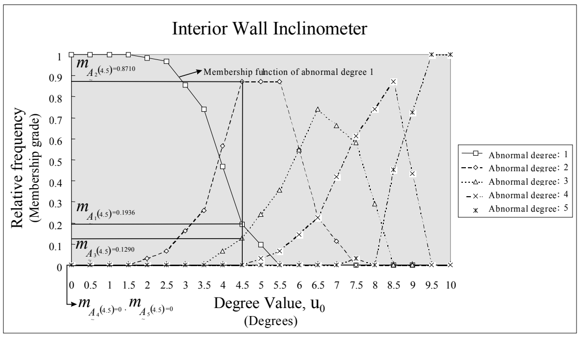

Figure 4. The Membership Function of interior wall inclinometer

1. Converting the measurement to the degree value:

According to equations (1) and (2), the measurement of 2.7cm is calculated and transformed to the degree value (u_0).

a. as $V_i \leqq V_m \leqq V_w$

$$u_0 = 0 + [V_m / (V_w - V_i)]*5 \text{---------------------}(1)$$

(1)

b. as $V_w \leqq V_m \leqq V_a$

$$u_0 = 5 + [(V_m - V_w) / (V_a - V_w)]*5 \text{----------}(2)$$

i.e. $u_0 = 0 + (2.7/3)*5 = 4.5$

2. Identifying the corresponding membership grades

The membership function is represented as follow [4]:

$\mu_{\underset{\sim}{A}_n}(u_0)$: membership function of abnormal level n when the degree value equals u_0.

$\underset{\sim}{A}_n$: the fuzzy subset of abnormal level n (n=1~5) ;

u_0 : measurement degree value

Using the degree value 4.5 calculated in step 1, the intersections of the degree value with the membership functions shown in Figure 4 can be identified. The corresponding relative frequencies are the membership grades.

$\mu_{\underset{\sim}{A}_1}(4.5) = 0.1936$, $\mu_{\underset{\sim}{A}_2}(4.5) = 0.8710$

$\mu_{\underset{\sim}{A}_3}(4.5) = 0.1290$, $\mu_{\underset{\sim}{A}_4}(4.5) = 0$

$\mu_{\underset{\sim}{A}_5}(4.5) = 0$

3. Determining the maximum membership grade

The fuzzy subset with the maximum membership grade identified in step 2 is defined as the instrument abnormal level. This research uses composite maximum to derive maximum membership grade, which is defined as follows [5,6]:

Universe U with n fuzzy subsets, $\underset{\sim}{A}_1, \underset{\sim}{A}_2, \underset{\sim}{A}_3, \ldots, \underset{\sim}{A}_n$, and $u_0 \in U$.

If

$$\mu_{\underset{\sim}{A}_i}(u_0) = Max\left\{\mu_{\underset{\sim}{A}_1}(u_0), \mu_{\underset{\sim}{A}_2}(u_0), \mu_{\underset{\sim}{A}_3}(u_0), \cdots, \mu_{\underset{\sim}{A}_n}(u_0)\right\}$$

Then

u_0 is subject to $\underset{\sim}{A}_i$

Continuing with the example mentioned above:

$$\mu_{\underset{\sim}{A}_i}(u_0) =$$

$$Max\left\{\mu_{\underset{\sim}{A}_1}(u_0), \mu_{\underset{\sim}{A}_2}(u_0), \mu_{\underset{\sim}{A}_3}(u_0), \mu_{\underset{\sim}{A}_4}(u_0), \mu_{\underset{\sim}{A}_5}(u_0)\right\} =$$

$$Max\left\{\mu_{\underset{\sim}{A}_1}(4.5), \mu_{\underset{\sim}{A}_2}(4.5), \mu_{\underset{\sim}{A}_3}(4.5), \mu_{\underset{\sim}{A}_4}(4.5), \mu_{\underset{\sim}{A}_5}(4.5)\right\}$$

$$= Max\{0.1936, 0.8710, 0.1290, 0, 0\} = \mu_{\underset{\sim}{A}_2}(4.5)$$

$$\therefore\ u_0 = 4.5 \in \underset{\sim}{A}_2$$

Hence, the degree value of the interior wall inclinometer is subject to $\underset{\sim}{A}_2$. That is, when the measurement is 2.7 cm, the instrument abnormal level is subject to the fuzzy subset $\underset{\sim}{A}_2$ with the maximum membership grade. Thus, the instrument abnormal level is equal to 2.

3.5.3 Developing Site and Instrument Layout Coverages

The site and instrument layout coverages are developed using GIS. In addition to the site coverage representing the site geometry, ten data layers are created to display the instrument layouts. The safety condition of each instrument is represented graphically with different colors. For example, white color represents stable excavation condition, yellow color signifies that the measurement shows warning conditions, and red color signals that the measurement exceeds the action threshold. According to the different safety conditions, managers should take appropriate actions to prevent accidents.

3.5.4 Determining the Unstable Influencing Area

When the instrument exceeds the threshold of warning or action values, the managers have to judge the instability origins based on site reconnaissance, instrument measurements with adverse conditions, and the comparative distribution of nearby instrument measurements. Thus, this system allows users to encircle the unstable influencing area where measurements will be automatically selected. The data can be used for determining the instability origins using the comparison evaluation method.

3.5.5 Failures Types and Causes

Through literature review and interviews with experts, excavation failures are compiled and classified into two levels: failure types and causes.

1. Identification of failure types

Figure 5 shows the failure types of construction excavation. In the figure, seven types of excavation failures, including retaining wall deflection, neighborhood building settlement and incline, support system damage, retaining wall leaking, foundation heaving, foundation boiling, and foundation lift are identified.

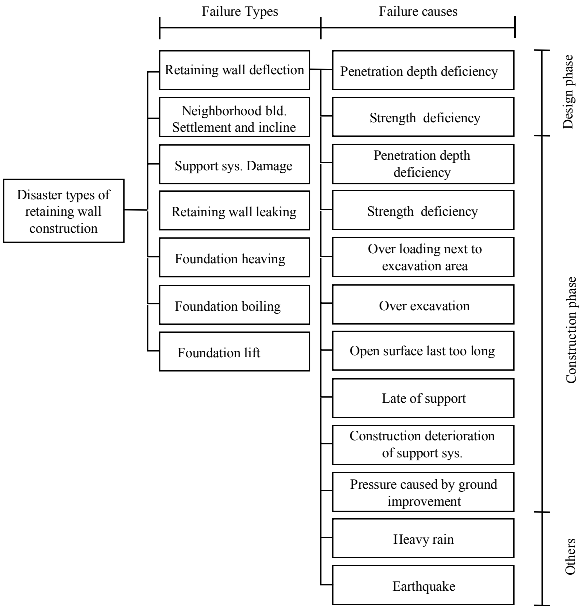

Figure 5. HOT Diagram for Retaining Wall Deflection

2. Determining failure causes

According to the failure types identified, the Hierarchy of Objective Technique (HOT) is used to determine the relationship between the failure causes and types. Sixty-one failure origins are identified along with each category. Figure 5 is an example of the HOT diagram for retaining wall deflection. In the figure, the twelve items were classified into three parts, namely design, construction, and others.

3.5.6 Identifying Possible Distribution of Instrument Abnormal Levels for each Failure Cause

This section describes the creation of the Failure Origin Reasoning Matrix (FORM) to represent the possible distribution of instrument abnormal level for each failure origin. During the failure reasoning process, experts usually infer failure origins based on the distribution of the instrument measurements collected. Hence, this study developed a questionnaire to survey the possible distribution of instrument abnormal level for each failure origin and expressed it within a knowledge base (KB). The KB contains sixty-one matrices representing the possible distributions of the instrument abnormal level of the failure origins.

3.5.7 Comparison Analysis for Reasoning Failure Causes

Two kinds of matrices, Failure Origin Reasoning Matrix (FORM) and Measurement Abnormal Level Matrix (MALM), are created in this study. The comparison analysis of failure origins is conducted by comparing these two matrices. Euclid distance between these two sets of data is calculated and compared to identify the most similar failure origin [7]. Figure 6 shows the evaluation process. In the figure, the instrument measurements are first collected and converted into the abnormal levels. Aggregating the measurements within the circled area forms the MALM. For reasoning the failure origins, the similarity index between the MALM and each FORM is calculated using equation (3).

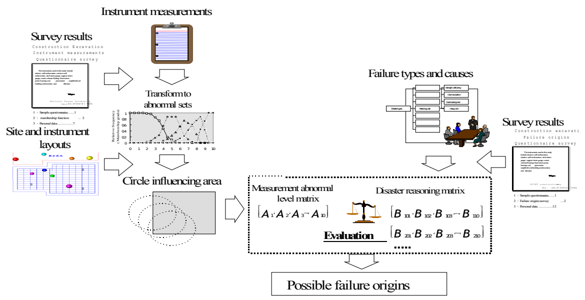

Figure 6. Similarity Evaluation of Disaster Causes

Let $A = \left[a_1, a_2, a_3, \ldots, a_{10}\right]^T$

$B_j = \left[b_1, b_2, b_3, \ldots, b_{10}\right]^T$

where

A: Measurement Abnormal Level Matrix (MALM)

B: Failure Origin Reasoning Matrix (FORM)

j: number of failure origins (j = 1~ 61)

$$S\left(A, B_j\right) = 1 - \left[\frac{1}{10}\sum_{i=1}^{10}\left[a_i - b_i\right]^2\right]^{1/2} \text{----(3)}$$

where

$S\left(A, B_j\right)$: similarity index

Using equation (4), the most similar failure origin is obtained.

The most similar failure origin = $Max\left\{S\left(A, B_1\right), S\left(A, B_2\right), \ldots, S\left(A, B_j\right)\right\}$ --------(4)

Tables 2 and 3 are used for example to illustrate the process of calculating the similarity index. Table 2 is the FORM representing the retaining wall deflection caused by the deficiency of retaining wall penetration depth. Table 3 is the MALM.

1. Transforming the abnormal level to “linguistic value”

Before calculation of the similarity index, the values in Table 2 and 3 are first converted into “linguistic value”. In fuzzy sets theory, “linguistic value” is used to describe the truth or false degree of a natural language. False for 0 and truth for 1. The fuzzy range lies between [0,1]. Linguistic value is used in this study to convert the instrument abnormal level ranging from 1~5 to 0~1. The conversion equation is shown in equation (5).

$$LV = (AL - 1) * 0.25 \text{------------------------} (5)$$

where

LV: linguistic value, AL: abnormal level

Using equation (5), the abnormal levels are converted to the linguistic values shown in Table 2 and 3.

Table 2. Survey Results of Retaining Wall Deflection in Design Phase

Disaster type: retaining wall deflection										
Design phase										
Instruments / Disaster causes	inometerInterior wall	nometerExterior wall	Rebar strain gauge	Strut strain gauge	Floating point	Heave gauge	Groundwater well	Piezometer	Tiltmeter	Settlement point
Deficiency of retaining wall penetration-depth	**4.0**	**3.9**	**3.0**	**3.1**	**2.1**	**1.3**	**1.1**	**1.1**	**2.9**	**2.6**
	0.447	0.619	0.180	0.301	0.301	0.461	0.301	0.301	0.539	0.807
	0.112	0.160	0.059	0.097	0.143	0.358	0.274	0.274	0.186	0.313
Linguistic value	0.75	0.725	0.5	0.525	0.275	0.075	0.025	0.025	0.475	0.4

Table 3. Measurement Abnormal Level after Transformation

Instruments	inometerInterior wall	nometerExterior wall	Rebar strain gauge	Strut strain gauge	Floating point	Heave gauge	Groundwater well	Piezometer	Tiltmeter	Settlement point
Measurement abnormal level	2	1	1	3	2	1	5	5	2	2
Linguistic value	0.25	0	0	0.5	0.25	0	1	1	0.25	0.25

2. Similarity calculation

The matrices obtained in step 1 are used to calculate the similarity index using equation (3).

$$S(A,B_j) = 1 - \left\{\frac{1}{10}\left[(0.75-0.25)^2 + (0.725-0)^2 + (0.5-0)^2 + (0.525-0.5)^2 + (0.275-0.25)^2 + (0.075-0)^2 + (0.025-1)^2 + (0.025-1)^2 + (0.475-0.25)^2 + (0.4-0.25)^2\right]\right\}^{0.5} = 0.452$$

Likewise, the similarity indices between the MALM and the rest of the FORMs are calculated.

3. Maximum similarity

According to equation (4), the FORM with the maximum similarity index is the most similar failure origin deduced in the model.

6. CONCLUSION

This study pioneers the application of Fuzzy Statistics Method in the instrumentation program for determining excavation failure origins. Using this method, the knowledge and experience of experts for failure determination is systematically acquired and stored as a knowledge base. Also, the fuzzy process for evaluating failure causes conducted by experts can be defuzzifized and applied in a systematic manner. The system’s ‘disaster-reasoning’ engine successfully represents and integrates experts’ knowledge and experience required for failure evaluation into a computer environment. Moreover, satisfactory solutions for failure origins can be identified.

Development of the computer integrated monitoring system successfully improves the efficiency of instrumentation programs for construction excavation. Due to GIS’s ability to integrate locational and thematic information, the graphical display and database queries, including graphic file management, drawing-to-data query, and graphical display of monitoring conditions, are successfully used. Furthermore, integration of GIS graphical display with a ‘disaster-reasoning’ engine makes it easy for the project manager to monitor and control the excavation progress. In comparison with current methods, this paper creates a new way of thinking to represent excavation monitoring conditions graphically using GIS. This system improves instrumentation programs by integrating spatial and thematic information into a single environment. The application of the real time monitoring system can not only improve construction safety, but also positively improve construction completion time.

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