EVALUATING TRENCH SAFETY USING FUZZY LOGIC CONCEPT AND FUZZY SET MODELS

A Thesis

Presented in the Partial Fulfillment of the Requirement for

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By

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*****

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Master’s Examination

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ABSTRACT

Trench collapse results from enabling causes, triggering causes, procedural causes or the combination of any of these three. Trench collapse provides major contribution in the accidental deaths occurring in the construction industry [1]. Hence, safety evaluation of trenches on a regular basis is essential. This evaluation is commonly expressed in linguistic terms especially when dealing with the uncertainties of trench safety. These terms are usually imprecise, not easily defined, but extremely useful. It is hard to perform the mathematical calculation and evaluate the precise safety condition of the trench; therefore the best option is to find the solution by using the fuzzy set concept and the fuzzy models. These fuzzy set models specially deal with the imprecise and linguistic terms associated with the trench condition. The thesis capitalized on the use of fuzzy set concept to manipulate these terms. This concept interprets in mathematical terms the linguistic variables of subjective appraisals of the trench enabling and triggering events and their consequences. Enabling and triggering conditions that often occur on site are analyzed to generate graphical displays, which will help to provide a guideline to determine overall trench performance. The thesis discusses three different fuzzy set models namely: (1) THE TRANSLATIONAL MODEL (2) THE ROTATIONAL MODEL and (3) THE ANGULAR MODEL
All the 3 models are discussed and the program is developed in the Visual Basic software for the convenience of the user. The trench conditions and the linguistic safety terms used in the software are created by identifying the safety concerns of the trench excavation sites and evaluating various enabling and triggering causes associated with the trench safety. Each model has its own uniqueness and advantages attached with it. The reason of using three models is, because of the preferences and choices of the different users. Each model are discussed and compared so that the user can make his own decision in using the model of his choice. These models can be used as a tool for preventing accidents and reducing enabling and triggering events in order to achieve the desired safety level of overall trench performance.
Dedicated to my family
ACKNOWLEDGMENT

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<tr>
<td>$\Sigma$</td>
<td>Summation</td>
</tr>
<tr>
<td>$\vee$</td>
<td>Disjunction (similar to union operation in set theory)</td>
</tr>
<tr>
<td>$\wedge$</td>
<td>Conjunction (similar to intersection operation in set theory)</td>
</tr>
<tr>
<td>$\subset$</td>
<td>Subset</td>
</tr>
<tr>
<td>$</td>
<td>$</td>
</tr>
<tr>
<td>$\supset$</td>
<td>Implication relation</td>
</tr>
<tr>
<td>$\infty$</td>
<td>Infinity</td>
</tr>
<tr>
<td>$\int$</td>
<td>Integration</td>
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LIST OF ABBREVIATION

OSHA  Occupational Health and Safety Administration
NIOSH  National Institute of Occupational Safety and Health
BLS  Bureau of Labor Statistics
EMR  Experience Modification Rate
SIC  Standard Industrial Classification
IMIS  Integrated Management Information System
CHAPTER 1

INTRODUCTION

1.1 Introduction

Construction is known to be one of the most hazardous industries to work in. Thousands of deaths and injuries are noted every year. The construction field has various operations that require a variety of skills and techniques and a great deal of experience and care. The construction work includes scaffolding, concreting, reinforcing, operating equipment and excavating trenches. As per the Occupational Health and Safety Administration (OSHA), every year thousand of fatalities are occurring in the construction industry, and trench collapse makes a significant contribution to the fatalities.

Trench collapse is a major source of accidental death in the U.S construction industry [1]. The actual number of fatalities occurring in trenching incidents is not known, but an estimate of 100 fatalities per year is perhaps a reasonable approximation of the magnitude of the problem [10]. An analysis of the data related to the trench was carried out by the National Institute of Occupational Safety and Health (NIOSH). According to this analysis
of workers compensation claims in the Supplementary Data System of the Bureau of Labour Statistics, there are approximately 1000 work related injuries each year due to excavation cave-ins. Of these, about 140 result in permanent disability and 75 in death [NIOSH, 1995]. Thus we can say that the trench excavation is one of the most hazardous construction operations.

Trench excavation work is basically the entire man-made process of moving earth, a heavy non-homogeneous material with dramatically variable engineering properties that can be controlled but not sculpted to a permanent form, for the purpose of making improvements to the land. Excavation work includes digging for the placement of concrete footings and walls, cutting and filling sections of embankments for a roadway, bridge, or dam and installation of underground utilities and tanks along with some types of soil stabilization methods. The hazard related to excavation varies greatly with the different types of excavation work.

Soil weighs 3000-4000 pound per cubic yard. If this dirt falls on a worker working in a trench, it causes suffocation and the death of the worker. Even if the worker is only partially buried, that is if the dirt reaches up to the chest, the pressure exerted on the chest makes the worker unable to breath and if immediate steps are not taken, it can lead to his death.
Trench collapses and excavation hazards need to be reduced or eliminated, so that these losses to the companies and workers are avoided. A trench collapse can affect many factors of the construction industry including direct and indirect costs. Direct costs include medical costs, worker’s compensation, compensation to the worker’s family in case of death, and the cost of property damage if the construction is not insured. The indirect costs include delays in the trenching operation and related activities, a decrease in work efficiency of an injured worker, the time lost off the job, the cost to replace and train a new worker, the impact on other workers, the cost to clean up the site, the time loss of the supervisor involved in accident activities, the cost of rescheduling the delayed work and the loss of time of the safety and administrative personnel due to their involvement in accident investigation, Occupational Safety and Health Administration (OSHA) fines, the cost of legal assistance, increase in the Experience Modification Rate (EMR), and damage to the reputation of the company in the market.

EMR- The construction insurance industry has developed the experience rating system. This experience rating system is used as an equitable means to determine the premiums for the worker’s compensation insurance. These rating systems consider the average worker’s compensation losses for a given firm from the type of work and amount of payroll. Based on this, the insurance industry predicts the dollar amount of expected losses to be paid by that employer in a designated rating period, usually three years. The rating for the companies is done by comparing the rates of losses for the firms doing
similar types of work, and the employer is rated against the average expected performance in each work classification. Losses incurred by the employer for the rating period are then compared to the expected losses to develop an experience rating. Worker’s compensation insurance premiums for a contractor are adjusted by this rate, which is called the experience modification rate (EMR). Lower rates, meaning that fewer or less severe accidents had occurred than were expected, result in lower insurance costs. A contractor’s EMR is adjusted annually by using the rate for the first three of the last four years. [www.bnl.gov]

Statistical analysis on the occurrence of trench accidents was carried out by Arboleda, Abraham, Wirahadikusumah and Irizarry in 2002. They collected information related to trench accidents from the different case studies and the sources like the Occupational Safety and Health Administration (OSHA) and National Institute of Occupational Safety and Health (NIOSH) and performed an analysis based on this collected information. Their study shows that the most common reasons for the occurrence of trench accidents are lack of planning at the beginning of the work, inadequate trench supervision, improper protection systems and lack of proper training. But the main reasons for the trench fatalities were inadequate or improper supervision at the job site and improper or missing soil condition evaluation.
The American Society of Safety Engineers (ASSE) launched an excavation accident prevention program in Georgia as well as across the country in 2004. According to Georgia officials, there were 98 trench accidents in the state in the year 2003, and five resulted in fatalities. To address this issue, new legislation aimed at strengthening the utility contractor licensing laws (House Bill 1300) was passed.

1.2 Objectives of the study

Due to the above mentioned fatalities and the direct and indirect losses involved, it is necessary that steps be taken to reduce the number(s) of accidents and fatalities related to the trench. A number of studies and analyses have been done by the Occupational Safety and Health Administration in creating rules and regulations. It is required that these safety rules and regulations be followed during the trench excavation activities. Regular site visits are made by OSHA to check whether the rules and regulations are being followed or not. OSHA has also developed safety programs and training for the construction industry. Thus each and every employee of the company including the site supervisor and the project labour has to attend such safety training and pass a test before the first construction work is carried out. This training is given on a regular basis to all the workers so that they can be taught the new techniques, rules and methods. Thus lot of efforts have been made by OSHA and the companies in improving the safety of the trench. Even though all this efforts are made in improving the safety of the trench, the fatalities related to the trench has not shown any significant downfall. This can be clearly
seen in Table 1. This thesis is an effort to help the project engineer and the supervisor(s) involved in trench excavation to recognize the overall safety performance related to a trench and take necessary steps required to achieve it. The goal was to prepare three different fuzzy logic models in visual basic software that would help evaluate the safety of a trench. This software will help to reduce the numbers of fatalities and losses associated with trench accidents.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>FATALITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>42</td>
</tr>
<tr>
<td>1999</td>
<td>43</td>
</tr>
<tr>
<td>2000</td>
<td>49</td>
</tr>
<tr>
<td>2001</td>
<td>57</td>
</tr>
<tr>
<td>2002</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 1.1: Trench fatalities with respect to time [1, 2]

1.3 Potential benefits of the study

This thesis contains the software program that helps to evaluate the overall safety performance of a trench. With the help of this software, the project engineer and the site supervisor will be able to evaluate the overall safety of the trench. The user (the project engineer, the site supervisor) after visiting the site enters the various conditions into the software. These are the conditions which he has seen on the trench excavation site. Once the user enters this information in the software programs, the software gives the overall safety performance of the trench in a graphical format. It just takes the user only a couple
of minutes to enter the conditions in the software program, by which the program gives
the results. The purpose in developing the software is to help the project engineers and
the supervisor evaluate the safety of the trench in a short time and make the construction
industry a safer place to work, where the loss of the human life and the losses occurring
to the company are minimized.

1.4 Method of study

Fuzzy set models have been used to develop the software. Trench safety evaluation
can seldom be expressed numerically. The evaluation of trench safety is done by using
linguistic terms like very safe, safe, fairly unsafe, very unsafe. The reason of expressing
the trench condition in the linguistic terms is because of dealing with the uncertainties of
trench safety. These terms are usually imprecise, not easily defined, but extremely useful.
The fuzzy set concept has been used to develop the software because it deals specifically
with the evaluation of the linguistic terms. The linguistic terms used in this study include
very good, good, poor, and very poor for describing the site condition and very safe, safe,
fairly unsafe, very unsafe for describing safety of the trench. Therefore, the thesis
capitalizes on the use of the fuzzy set concept to manipulate these terms. This concept
interprets in mathematical terms the linguistic variables of subjective appraisals of the
trench enabling and triggering events and their consequences. The triggering causes can
be considered as something beyond human control. They are out of the control of the
persons responsible for the excavation project. The enabling causes are the causes that
make the occurrence of the accident possible. These causes wait for the triggering causes to create the damage or destruction. Without the enabling cause, an accident cannot occur.

1.5 The fuzzy set models used

There are different fuzzy set models that can be used to analyze and evaluate the linguistic terms associated with the safety of a trench. Out of these, three fuzzy set models will be considered in this study. They are: (1) The Translational Model, (2) The Rotational Model and (3) The Angular Model.

The three different models are used because each model has its own features, advantages and disadvantages associated with it. These models have their own uniqueness in evaluating the safety of the trench. Different experts and user have different opinions about these models, and they use different models for evaluating the safety of trench. Here, the term experts means a person who has sound knowledge and experience in the trench excavation field and who is working for the company or may be hired by the company to evaluate the trench safety. The user can be a project engineer, project manager or the site supervisor who is in charge of the trench excavation procedure. Therefore, three models have been developed so that the experts who will evaluate the safety of the trench have the choice of using the software which suits them best.
The above mentioned method can be used as a tool for preventing accidents and reducing enabling and triggering events in order to achieve the desired safety level of overall trench performance.

1.6 Scope and limitations

This thesis includes statistical study and analysis of the data related to trench fatalities and accidents. It also contains the study and development of three different fuzzy logic models. These fuzzy logic models have been developed in the form of a software program in visual basic. The study is limited to trench safety. In particular it is limited to the analysis of the enabling and the triggering causes by using 3 different fuzzy logic models.

1.7 Organization of study

Chapter 2 explains the causes of the trench collapse. This chapter briefly discusses the enabling, triggering and procedural causes that results in the trench accidents. Chapter 3 shows the statistical data related to trench collapse. The statistical data are based on the information available from OSHA and NIOSH. The analysis of the statistical data points to the importance of this study. It contains data related to trench accidents with respect to various factors. The analytical study underscores the importance of this thesis and supported the development of the effective software models. Chapters 4, 5 and 6 explain the different fuzzy logic models. The user, according to his choice, can use any of the
three models. Chapter 4 is a discussion of a translational model. This is one of the three models which help in evaluating the overall safety of the trench. In this model, the user (the project engineer, the site supervisor, the expert or the project manager) has to enter the various enabling and the triggering conditions that he/she observe on the site. Once these conditions are entered in translational model software, the model gives the overall trench safety in a graphical format. The software with the translational model also has the "Matrix" button, which when clicked, displays the 11 x 11 matrices of enabling and triggering causes involved in trench accidents and their products. These matrices displayed in the software help in evaluating the overall safety graph, which is based on the final product of the enabling and triggering matrices. Chapter 5 explains the rotational model of the fuzzy logic concept. This is the second model which helps in evaluating the overall safety of the trench. This model contains a set of rules. The users have a choice in selecting among the set of rules according to their expertise. Once the user selects the rule of his choice, he enters the actual site condition(s) in the software, and the software returns the result of overall safety of the trench in a graphical format. Chapter 6 is the angular model. It describes the overall safety of the trench in the angular form. This model also gives the users an opportunity to select the set of rules to be applied. As with the rotational model, the user in the angular model selects the rules and enters the actual site condition. The model displays the overall trench safety in a graphical format. Chapter 7 contain the summary and conclusion, and includes recommendations based on findings.
CHAPTER 2

CAUSES OF TRENCH COLLAPSE

2.1 Introduction

Accidents occur due to three different causes. They are: (1) Triggering Causes, (2) Enabling Causes, and (3) Procedural Causes. An accident occurs due to one of the above mention causes or a combination of these causes. These events are briefly explained below.

2.2 Triggering Causes

Triggering causes are something beyond human control. They are out of the control of the persons responsible for the excavation project. For example, an earthquake or hurricane can be considered as a triggering cause which is sudden and which cannot be controlled by humans. Some of the major triggering causes for trench collapse are presented in Table 2.1.
Table 2.1: Triggering causes for trench collapse

2.3 Enabling Causes

Enabling causes are causes that enable the occurrence of the accident. These causes wait for the triggering causes to create damage or destruction. But without this enabling cause, an accident cannot occur. An example of an enabling cause is a worker’s fall from a broken plank because he is not wearing the body harness system. A triggering event caused the plank to break, but the worker fell because he was not wearing the body harness system. The major enabling events for the trench collapse are presented in Table 2.2.

Table 2.2: Enabling events for trench collapse
2.4 Procedural Causes

Procedural events are events related to the procedures used to perform the project. The procedural related problems involve the lack of or improper management, incomplete communication, problems related to contract terms or lack of proper safety codes, and inadequate funding. Procedural causes related to trench accidents are presented in Table 2.3.

The translational model has been developed using the enabling and triggering causes that are responsible for trench collapse. The procedural causes are not included in the evaluation of the trench safety performance because the procedural events are related to the fault in the management, the faults associated with the office. Fault in the design, failure in proper communication can be considered as the causes related to the procedural causes. The evaluation of the procedural events requires expertise in the management and law field which is totally different from expertise related to the trench safety evaluation.
<table>
<thead>
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<th>Table 2.3: Procedural causes for trench accident or collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FAILURE IN IMPLEMENTING A SAFETY PLAN</strong></td>
</tr>
<tr>
<td>- Risk avoidance plan</td>
</tr>
<tr>
<td>- Emergency response plan</td>
</tr>
<tr>
<td>- Safety inspection plan</td>
</tr>
<tr>
<td><strong>FAILURE TO IMPLEMENT EFFECTIVE EQUIPMENT MAINTENANCE</strong></td>
</tr>
<tr>
<td>- Equipment needed but not available</td>
</tr>
<tr>
<td>- Equipment not in good working condition</td>
</tr>
<tr>
<td><strong>FAILURE TO PROVIDE PROPERLY TRAINED WORKER</strong></td>
</tr>
<tr>
<td>- Untrained worker for equipment operation</td>
</tr>
<tr>
<td>- Untrained worker for excavation operation</td>
</tr>
<tr>
<td>- Workers skills not matching job requirement</td>
</tr>
<tr>
<td>- Untrained supervisor for trench operation</td>
</tr>
<tr>
<td><strong>FAILURE TO IMPLEMENT SITE MAINTENANCE</strong></td>
</tr>
<tr>
<td>- Material storage</td>
</tr>
<tr>
<td>- Equipment storage</td>
</tr>
<tr>
<td>Dirt is stored close to the excavation or equipment is placed close to the excavated area.</td>
</tr>
<tr>
<td><strong>CREATION OF IMPERMEABLE SURFACES</strong></td>
</tr>
<tr>
<td>- Highways</td>
</tr>
<tr>
<td>- Parking lots</td>
</tr>
<tr>
<td>- Building foundations</td>
</tr>
<tr>
<td>The impermeable surfaces listed above cause the redirection of runoff which results in a threat when the water table is low.</td>
</tr>
<tr>
<td><strong>REROUTING OF STORM WATER</strong></td>
</tr>
<tr>
<td>- Rerouting of storm water can cause soil piping.</td>
</tr>
<tr>
<td><strong>CREATION OF SINK HOLES</strong></td>
</tr>
<tr>
<td><strong>UNSAFE CONSTRUCTION PLANS</strong></td>
</tr>
<tr>
<td>- Zone overlapping in the scheduling process</td>
</tr>
<tr>
<td>- Sloping, shoring or benching improperly selected</td>
</tr>
<tr>
<td>- Sloping, shoring or benching improperly implemented</td>
</tr>
<tr>
<td>- Worker skills not matching job requirement</td>
</tr>
<tr>
<td>- Equipment improperly selected</td>
</tr>
<tr>
<td>- Improper soil inspection</td>
</tr>
</tbody>
</table>
CHAPTER 3

ACCIDENT REPORTS AND STATISTICAL DATA

3.1 Introduction

The incidence of fatalities and disadvantages associated with trench excavation can be seen in the Chapter 1. Trench safety is becoming an important issue. In spite of the efforts which are made to improve the safety of the trench, the trench accidents are still happening. The various statistical data collected from OSHA is presented in this chapter. This data helps us to understand why research in trench safety is necessary. The chapter contains statistical data related to trench accidents with respect to years of occurrence, the geographical location, hours of daily operation, the months when the accidents occurred, the ages of the worker involved, and the depth of the trench excavation.

3.2 Accident reports

Accidents that are related to the trench are discussed in this section. The descriptions of the accidents are intended to contribute to understanding of the importance of the study. The descriptions clarify understanding of the probable causes of the accidents. The information given in this chapter includes the type of work being carried out when the
trench collapsed, the conditions under which the accident occurred, and what the probable cause of the accident was.

1) "The man killed in pit collapse."

From *New York Times*, June, 1994

This article reports that a 52 year old man was killed when he was working in the trench and the trench collapsed. The trench was seven feet deep. He was trapped between the soil and the wooden stabilizing wall. The report states that the probable cause of the death of the worker was "suffocation".

The worker and his companion were attempting to repair drainpipes in a parking lot. The other worker managed to escape. A detective reported "He was only buried to his knees. His companion tried to get his friend out, but he couldn't do it." It took seven hours for workers to clear the collapsed dirt and stabilize the trench enough to recover the man's body.
2) “Manslaughter charge filed over death in trench collapse.”

From Los Angeles Times, October 26, 1994

This article reported that the Los Angeles County district attorney’s office filed a manslaughter charge against the plumbing subcontractor who allegedly failed to reinforce a 10 foot deep trench before its walls collapsed, killing one worker and injuring another. The charge against the independent sewer and plumbing contractor carries a maximum sentence of four years in state prison. The 51 year old worker died seven hours after he had been buried in dirt for 30 minutes. His co-worker suffered a broken pelvis while attempting to rescue him. The cave-in occurred along a 15 foot section of trench dug to replace a sewer line to a warehouse. Failure to reinforce the trench walls was “a clear case of cutting corners to cut costs”, stated the district attorney. Three days prior to the accident a Los Angeles city building inspector issued a warning to the general contractor about the lack of a protective system for workers in the trench. The general contractor did not comply with the inspector’s order. In the wake of the accident, the state’s division of OSHA fined the subcontractor $36,085 and the general contractor, $4,450.
3) “Toxic fumes kill three and injure three at Reynolds plant in McCook.”

From *Chicago Tribune*, June 1, 1995

The article reported that three men were killed and three others injured by toxic fumes that filled a pit they were excavating at a metal company plant in McCook, Illinois. The plant manufactures sheet and plate metal components for automobiles and aircraft. The men were excavating to lay a foundation for a new casting furnace when they were overcome at 7:45 am by “unknown noxious fumes”

4) “Echo Park trench cave-in kills construction worker.”

From *The Los Angeles times*, April 12, 1996

A 28 year old man was killed in trench after a cave-in buried him up to his chin. He was barely breathing when more than 40 fire-fighter, paramedics, and search and rescue team members arrived on the scene. However, the worker died a few minutes later due to the tremendous squeezing pressure inflicted on the body by the weight of the soil. It took fire-fighters more than three hours to recover the worker’s body from the trench.
5) “OSHA”: Fatal error repeated.

From *Engineering News Record*, February 5, 1996

The Occupational Safety and Health Administration has proposed fines of $100,000 against a small Connecticut paving contractor for alleged improper shoring techniques during a sewer line installation. The contractor is accused of using unsafe shoring methods similar to those used on another trench that killed a 57 year old worker three weeks earlier (October 12, 1995) on the same project.

In this October 12 accident, a worker was in a 13 feet deep trench that was shored with a 6 feet high shoring box augmented by steel plates. A cave-in shifted these steel plates and broke 8 inch water main. According to an OSHA spokesman, the worker was “crushed and drowned at the same time.”

6) “Two workers injured in ‘Big Dig’ accident.”

From *The Boston Globe*, November 30, 1996

Two laborers were injured after a 3 feet x 3 feet sheet of clay slid down and pinned the men underneath. One of the workers suffered a fractured right leg, a bruised chest and rib injuries. The other worker suffered minor injuries to his lower leg. The two men had been working in trench that was 8 feet deep x 5 feet wide x 15 feet long.
7) “OSHA fines two firms in job fatality.”

From *The Atlanta Journal Constitution*, July 20, 1996

OSHA has imposed a fine of $104,000 on a pipeline subcontractor for “serious” and “wilful” violations that resulted in the death of a Norcross, Georgia, man in January of 1996. The controlling employer is also facing penalties of up to $94,000. The victim died after being crushed by a piece of equipment dropped by a backhoe into the trench where he was working. Eight days prior to the accident, officials had ordered a halt to the construction work. The construction supervisor was cited twice for failing to halt the work, including a citation the day before the accident. A total of six serious violations were cited in the accident report, including failing to shore up the trench.

8) “Teen killed when trench collapses.”

From *The Atlanta Journal Constitution*, September 6, 1996

In Lawrenceville, Georgia, a 16 year old died when a trench collapsed and buried him under 5 feet of dirt. The boy was trapped under several hundred pounds of soil for about ten minutes as his father tried to dig him out with a backhoe. Nearby residents rushed to the site and dug furiously with their hands and shovels before his head and chest were freed.
CPR was administered, but did not succeed in reviving the boy, who later died at Gwinnett Medical Center. Fire officials found no protective systems in the trench, which was being dug to lay a new septic system.

A follow-up article dates September 7, 1996 stated that the absence of supports, recent rains had softened the soil, increasing the possibility of cave-in.

9) “Two firms facing fines in trench death.”

From *The Atlanta Journal Constitution*, October 7, 1998

OSHA cited two Stock Bridge construction firms and proposed fines totalling $244,000 for safety violations in a trench cave-in that killed a 25 year old worker. The employee was buried beneath tons of soil made unstable by rain before the accident. OSHA found evidence that neither company had taken proper precautions to prevent the July cave-in of a 19 feet deep drainage trench at the subdivision. OSHA’s Atlanta Regional Director stated: “Both employers were aware of the highly hazardous nature of trench work and knew this particular trench was unsafe but failed to take any action to protect workers whose lives were at risk. There is no excuse for their failure to follow trenching guidelines.” Both firms were cited for wilful failure to provide workers a protection system. The piping subcontractor faces additional penalties of $84,000 for
failure to train workers on the hazards of excavations and failure to provide a means of entering and leaving the trench.

10) “Safety citation issued.”

From The Houston Chronicle, July 19, 1997

The U.S Department of Labor cited a local construction company for 12 alleged safety violations in an accident in which a teenager was buried alive in a trench while laying sewer pipe. The company could be fined $30,000 for the violations found at the site where the 18 year old worker was killed. The worker was knocked off his feet by a heavy chunk of clay before the walls of the 13 feet deep ditch caved in on him.


From The Houston Chronicle, March 23, 1998

This article reported that local and federal officials are investigation the death of a 43 year old construction worker buried alive when the 18 foot deep trench in which he was working collapsed. The excavation was part of a sewer sanitation rehabilitation project just east of downtown Houston. Although a steel trench box was in place in the excavation, the worker was in the trench but outside of the trench box at the time of the cave-in. Co-workers on the street scrambled into the pit and frantically dug the dirt away
from the face of the man, who was buried about six minutes. When fire-fighters arrived, they found the man conscious and were able to feed an oxygen line to him. As rescue work was in progress, a second cave-in occurred, trapping two fire-fighters who were trying to help. The second collapse also covered up the victim, and he died a few minutes later.

The president of the company that employed the worker stated that this was the first fatality in the 43 year history of the company. “We are all devastated by it”, he said. “We operate extremely safely, and we pride ourselves on that.”

3.3 Statistics of accidents

The National Institute for Occupational Safety and Health (NIOSH) has stated: “Excavation cave-ins cause serious and often fatal injuries to workers in the United States [NIOSH].” An analysis of workers compensation claims for 1976 to 1981 by NIOSH [1] in the Supplementary Data System of the Bureau of Labor Statistics (BLS) by NIOSH [1] suggests that excavation cave-ins caused about 1,000 work-related injuries each year. Of these, about 140 injuries resulted in permanent disability and 75 in death. Thus, this type of incident is a major cause of deaths associated with work in excavations and accounts for nearly 1% of all annual work-related deaths in the nation. The data related to the rate of occurrence of the accidents per worker in each age group, rate of occurrence per worker for each foot depth and occurrence of the trench accidents per square mile are
very important for the studies, but cannot be obtained through OSHA or BLS. Some of the data that are obtained from OSHA, BLS and NIOSH that are equally important for the study are collected and incorporated in this chapter. The BLS data is summarized in Table 3.1.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>FATALITIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>42</td>
</tr>
<tr>
<td>1999</td>
<td>43</td>
</tr>
<tr>
<td>2000</td>
<td>49</td>
</tr>
<tr>
<td>2001</td>
<td>57</td>
</tr>
<tr>
<td>2002</td>
<td>34</td>
</tr>
</tbody>
</table>

Table 3.1: Trench fatalities with respect to time [1, 2]

The BLS data clearly suggests that even though significant steps are taken in improving the safety of the trench, fatalities related to the trench have remained consistent. The occurrence of trench accidents by month is shown in Figure 3.1. This table has been prepared by using the data available from the Occupational Safety and Health Administration (OSHA). Trench accidents appear to peak in October at 16% of the total, which according to the OSHA is most likely because of the work season and the rain, which causes water seepage in the soil and weakens soil stability. Figure 3.1 also shows a relative peak in March which has 10% of the total. According to OSHA, this is most likely because it is the end of the winter season and the beginning of spring season, which is the peak construction season. August has a high rate of 10% as well. That is the
time when the construction firm wants to complete excavation work and begin the concrete work before the winter sets in. Figure 3.1 also shows an unusual 10% peak of accidents in January, which might be due to the location of the excavation site in a warmer climate.

![Trench Accident by Months](image)

**Figure 3.1:** Total trench accidents occurrence by months (1996-1997) [1, 2]

Figure 3.2 shows trench accident occurrence with respect to worker’s age. The graph shows a peak between 26 and 30 years, which possibly according to the author, is because the largest numbers of workers fall in this age group. A peak is also observed at
the age between 46 and 50, which may be due to the worker’s attitudes, overconfidence and the age factor.

Figure 3.2: Number of trench accidents with respect to age [1, 2]

According to the data collected from the OSHA reports, 40% of the accidents reported involved workers working with water lines, sewer lines, and the other type of pipe installation, i.e., Standard Industrial Classification (SIC) code 1623, as shown in Figure 3.3.
The occurrence of trench accidents by the depth of the trench is shown in Figure 3.4. The figure shows that 37% of the time trench accidents have occurred at a depth of 0 to 5 feet. It is interesting to see that the maximum number of accidents occur at a shallow depth. According to the author, the main reason behind this is that the contractor or site supervisor does not understand the governing rule and if he understands the rule he does not follow it. The reason the site supervisor or project engineer does not follow or understand the rule, may be that he/she is not competent enough to recognize the danger associated with the trench. The rule states that trench protection is not required for a
depth less than 5 feet, if the ground is examined by a competent person and he states that the ground provides no indication of the potential cave-in.

Figure 3.4: Total trench accidents occurrence by trench depths- From OSHA’s Integrated Management Information System (IMIS) [www.osha.gov]

Figure 3.5 shows the occurrence of the trench accidents with respect to the hours of operation.
The Figure 3.5 shows that the greatest number of trench accident occurs in the afternoon, between 12 to 4 pm. According to Hinze and Bren (1997), it is possible that during the lunch break, the apparent cohesion of the trench walls has begun to relax. If the trenching work does not commence for another hour, the trench walls would be even more unstable. Moreover, it is important to consider that after 3:00 pm, the workers are prepared to leave the site and sometimes the importance of the safety procedure is underestimated because the labor hours are nearing an end. The graph also shows a peak in the morning between 8 and 10 pm. of 26%. OSHA states that before work is started in the morning, site inspection should be carried out by a supervisor who is competent in the field of trenching. According to Arboleda, Abraham, Wirahadikusumah and Irizarry view
the high percentage of accidents in the morning is possible if the morning inspection is skipped or not done thoroughly. A lower percentage of accidents are seen between 4:00 and 6:00 pm. The reason behind this is the work generally stops between 4:00 pm and 4:30 pm. The work is continued after 4:30 pm only when there has been a delay in the project or if it is necessary that the project is required to be completed early.

Table 3.2 shows the accidents with respect to geographical location. This data has been obtained from The National Institute of Occupational Safety and Health (NIOSH). The data displayed below show the accidents reported to NIOSH in the year 2001.

The data collected from the reports shows that the greatest number of trench accidents occurred in the state of California which had 9, followed by New Jersey, where 7 trench accidents were reported, but again the perfect comparison of the accidents by states cannot be done because the states differ in the total square mile area of construction work and the data per square is not available.

The accidents with respect to the occupation of the worker are shown in Table 3.3. This table shows that 61% of the fatalities were to the laborers and the construction workers. If the accidents in terms of gender are considered, 51 fatalities were to the males and 1 was to a female [10]. The reason why more male workers are injured is because most of the construction workers are male.
Table 3.2: Trench accidents with respect to geographical location

<table>
<thead>
<tr>
<th>STATE</th>
<th>REPORTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alaska</td>
<td>2</td>
</tr>
<tr>
<td>Arizona</td>
<td>2</td>
</tr>
<tr>
<td>California</td>
<td>9</td>
</tr>
<tr>
<td>Florida</td>
<td>1</td>
</tr>
<tr>
<td>Georgia</td>
<td>2</td>
</tr>
<tr>
<td>Indiana</td>
<td>1</td>
</tr>
<tr>
<td>Iowa</td>
<td>1</td>
</tr>
<tr>
<td>Maryland</td>
<td>4</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>4</td>
</tr>
<tr>
<td>Michigan</td>
<td>1</td>
</tr>
<tr>
<td>Minnesota</td>
<td>4</td>
</tr>
<tr>
<td>Nebraska</td>
<td>2</td>
</tr>
<tr>
<td>New Jersey</td>
<td>7</td>
</tr>
<tr>
<td>North Carolina</td>
<td>1</td>
</tr>
<tr>
<td>Ohio</td>
<td>1</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>1</td>
</tr>
<tr>
<td>South Carolina</td>
<td>1</td>
</tr>
<tr>
<td>Texas</td>
<td>2</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>1</td>
</tr>
<tr>
<td>Wyoming</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.3: Trench accidents with respect to the occupation [10]

<table>
<thead>
<tr>
<th>OCCUPATION</th>
<th>PERCENTAGE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laborer</td>
<td>44</td>
</tr>
<tr>
<td>Construction Worker</td>
<td>17</td>
</tr>
<tr>
<td>Foreman</td>
<td>12</td>
</tr>
<tr>
<td>Equipment Operator</td>
<td>6</td>
</tr>
<tr>
<td>Pipe Layer</td>
<td>4</td>
</tr>
<tr>
<td>Line Man</td>
<td>4</td>
</tr>
<tr>
<td>Subcontractor</td>
<td>2</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
</tr>
</tbody>
</table>
The table shows that the maximum affected group of personnel were the laborers, who contribute 44% of the total. According to the author, this is because trench excavation is done by the laborers and most of the time they are the persons who are working in the trench and exposed to the open walls of the trench. In the same way, the least affected group is the subcontractors with percentage of 2%. This is because they usually deal with the office work and seldom have to enter the trench.

Trench accidents with respect to fatalities reported by the companies have been classified according the Standard Industrial Classification –SIC, (OSHA, 2001). Table 3.4 shows the distribution by categories for the companies.

<table>
<thead>
<tr>
<th>SIC CODE</th>
<th>CODE DESCRIPTION</th>
<th>PERCENTAGE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1623</td>
<td>Heavy construction (Water, sewer, pipeline, communications and power lines)</td>
<td>40</td>
</tr>
<tr>
<td>1794</td>
<td>Excavation work</td>
<td>13</td>
</tr>
<tr>
<td>1611</td>
<td>Highway and street construction</td>
<td>6</td>
</tr>
<tr>
<td>4911</td>
<td>Electric services</td>
<td>6</td>
</tr>
<tr>
<td>4923</td>
<td>Natural gas transmission and distribution</td>
<td>4</td>
</tr>
<tr>
<td>Others</td>
<td>Additional categories with one report</td>
<td>21</td>
</tr>
<tr>
<td>N.A</td>
<td>Not available data</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3.4: Accident reports with respect to the companies [10]
The Table 3.4 shows that the greatest number of report are from the heavy construction companies, which are involved in water and sewer pipeline, communications and power lines. All these activities require the excavation of deep and long trenches.

The OSHA’s reports also contain the information pertaining to standard violations that occurred on the site and the respective recommendations that should be followed to avoid the same accidents in the future. Some reports include more than one recommendation. The Table 3.5 shows the most frequent recommendations made in the reports.

<table>
<thead>
<tr>
<th>SR. NO</th>
<th>DESCRIPTION</th>
<th>PERCENTAGE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Shoring-Shielding-Sloping</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>Competent person</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>Equipment improvement</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>Safety program</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>Job safety analysis</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>Equipment location</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>Worker age</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>Safety training</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Safety meeting</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>Miscellaneous</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 3.5: The OSHA recommendation with respect to the trench accident reports
Table 3.5 shows that the first five recommendations comprise 68% of the total. Thus it can be seen that these are the most frequently made recommendations that should be followed in accordance with OSHA standards in every trenching operation.

OSHA requires the presence of a competent person on the site during the trench excavation process, and defines the competent person as follows:

"The competent person is an individual who is capable of identifying existing and predictable hazards or working conditions that are hazardous, unsanitary, or dangerous to employees, and who has authorization to take prompt corrective measures to eliminate or control these hazards and conditions [1]."

Many a time the competent person is charged with more than one trench to inspect. This happens when there are many trenches being excavated on the same site and at the same time, or if it is a long trench, for example, a trench for laying pipes. It becomes difficult for the competent person to keep track of multiple trenches or a long trench. Moreover, many of the competent persons are not highly skilled at recognizing the dangers associated with the trench, especially after heavy rain.

Thus, the competent person requires some assistance for evaluating the overall condition of the trench. Software has been developed using the fuzzy logic to help the
competent person evaluate the overall trench safety. In this chapter, the translational model is used to help finding the overall trench condition. This translational model uses linguistic terms in the process of finding the overall trench safety. It displays the overall trench condition in wording as well as in graphical forms.

As shown in Table 3.6, various factors that contribute to trenching accidents were identified from the OSHA reports. Misjudgement of hazardous situations was identified in 39% of the instances, making it the most common risk factor. This reinforces the need to have a “Competent Analysis System” capable of correctly identifying risks so that action can be taken to reduce the probability as well as the severity of accidents.

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>NO. OF OCCURRENCES</th>
<th>% OF TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstable soil condition</td>
<td>7</td>
<td>15%</td>
</tr>
<tr>
<td>Misjudgement of hazardous situation</td>
<td>18</td>
<td>39%</td>
</tr>
<tr>
<td>Inappropriate handling of materials or</td>
<td>8</td>
<td>17%</td>
</tr>
<tr>
<td>equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overhead load hazard</td>
<td>7</td>
<td>15%</td>
</tr>
<tr>
<td>Failure to secure trench walls/ or</td>
<td>6</td>
<td>13%</td>
</tr>
<tr>
<td>protection not present</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>46</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 3.6: Identified factors associated with trenching accidents [1, 2]

Due to significance of the results shown above, the topic of the trench safety is selected to contribute to the safety of the trenches. In this thesis the software has been
developed using different fuzzy logic models. This software assists in determining the overall trench safety.

This software will help the competent person and the supervisor to evaluate the overall trench condition and determine whether steps are required to be taken to prevent trench collapse or evacuate the trench in emergencies before any of the fatalities occurs.
CHAPTER 4

EVALUATING TRENCH SAFETY USING THE TRANSLATIONAL MODEL

4.1 Introduction

It can be seen from Chapter 1, that the trench accidents and fatalities cause a great loss to construction companies in terms of direct and indirect losses. We also saw that it causes a death or disability to the workers working in the trench. We also looked at the causes of the trench accidents in Chapter 2. These enabling and triggering causes lead to the occurrence of trench collapse. The discussion of enabling and triggering conditions in Chapter 2 was a great help in developing the rules for the different fuzzy logic models. Moreover, the statistical analysis of trench accidents presented in Chapter 3 points to underscore the importance of the study and the models.

This chapter capitalizes on the use of a fuzzy set translation model to manipulate the descriptive terms. The translational model of the fuzzy set concept is used in this chapter to generate graphical displays, which provides a guideline in determining the overall trench performance.
4.2 Assessing the trench condition

In order to minimize trench accidents and failures, one should recognize the condition of the trench in relation to the enabling and triggering factors discussed in Chapter 2. Procedural causes will not be taken into account because it is out of the scope of this study. One reason for not using the procedural causes in evaluating the trench condition is that information regarding the procedural causes is not made accessible by a visit to a site to assess the trench conditions.

Assessment of trench conditions is often based on subjective judgement which is expressed using linguistic terms such as “Good”, “Very Good”, “Poor”, “Fair” and “Very Poor”, which is unsuitable in probabilistic assessments. To take the advantage of the plethora of these terms, the author employs the concept of fuzzy sets. Thus, a fuzzy set based on the possibility approach can be used to transform these linguistic terms into mathematical representations. For example, the supervisor of the project or the project engineer makes a site visit and studies various enabling and triggering causes. Based on his perceptions, the user tries to analyze all these condition in linguistic terms such as “Very Poor” (VP), “Poor” (P), “Fair” (F), “Good” (G), “Very Good” (VG). Based on the available information about the various enabling and triggering conditions and analysis of the conditions with linguistic terms, the user is able to analyze the overall condition of the trench, which is represented in graphical form. This can be a great help to the project
manager or the supervisor so they can understand the trench condition and take immediate steps to correct critical conditions.

Trench safety depends upon the condition of the trench in relation to the enabling events E, and the magnitude of the triggering events T. For this purpose the consequences of both categories of events were observed and their relations are presented in Tables 4.1 and 4.2.

<table>
<thead>
<tr>
<th>TRENCH SAFETY</th>
<th>TRENCH CONDITIONS</th>
<th>VERY POOR</th>
<th>POOR</th>
<th>FAIR</th>
<th>GOOD</th>
<th>VERY GOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Unsafe</td>
<td>E1,E2,E3,E4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unsafe</td>
<td>E1,E2,E3,E4</td>
<td>E1,E2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>E3,E4</td>
<td>E1,E2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safe</td>
<td></td>
<td>E3,E4</td>
<td>E1,E2</td>
<td></td>
<td></td>
<td>E1, E2, E3,E4</td>
</tr>
<tr>
<td>Very Safe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E1, E2, E3,E4</td>
</tr>
</tbody>
</table>

Note:
E1 = Poor soil condition with no shoring or sloping system
E2 = Inadequate trench depth with no shoring or sloping system
E3 = Inadequate shoring or sloping system provided
E4 = Inappropriate use of equipment or methods

Table 4.1: The safety of the trench vs. condition of enabling events
<table>
<thead>
<tr>
<th>TRENCH SAFETY</th>
<th>MAGNITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VERY HIGH</td>
</tr>
<tr>
<td>Very Unsafe</td>
<td>T1,T2,T3,T4</td>
</tr>
<tr>
<td>Unsafe</td>
<td>T1,T2,T3,T4</td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>Safe</td>
<td></td>
</tr>
<tr>
<td>Very Safe</td>
<td></td>
</tr>
</tbody>
</table>

Note:
T1 = Excess dewatering
T2 = Excess water seepage
T3 = Surcharge load
T4 = Vibration by equipment

Table 4.2: Magnitude of triggering event vs. the trench safety

The various enabling and triggering condition that are placed in the respective columns are based on the authors [Patel and Hadipriono, 2005] personal experience. According to the authors [Patel and Hadipriono, 2005], these four enabling conditions discussed in Table 4.1 are the enabling condition that have most frequently caused the trench collapse in the past [www.osha.gov]. These enabling conditions are categorized at different safety levels according to their severity, as shown in Table 4.2.

The enabling condition E1, which stand for “Poor soil condition with no shoring or sloping systems” is considered as critical for the occurrence of the trench collapse. If this
E1 is found to be very poor which means that the soil condition is very poor and on top of that a sloping system has not been provided for this poor soil, then the situation of the trench is considered as “Very Unsafe”. This “Very Unsafe” condition indicates a “Very High” chance for the occurrence of trench collapse. Thus, with E1 being “Very Unsafe”, it is kept in the first column, where the occurrence of the occurrence of a trench accident is considered as “Very High”. This is true for the conditions E2, E3 and E4. If all these enabling condition are “Very High”, then the condition of the trench is “Very Unsafe”. The safety of the trench increases with the improvement in the trench condition. Suppose that the trench enabling condition is E4, which states “Inappropriate use of equipment or methods” is “Fair” then the trench safety condition is “Moderate”.

The same is the case with the triggering conditions. Four different triggering conditions are considered in this study. According Patel and Hadipriono [2005], these four triggering conditions are the triggering conditions that have most frequently caused the trench collapse in the past [www.osha.gov]. These triggering conditions are categorized at different safety levels according to their severity, as shown in Table 4.2.

The enabling event-related performance ranges from “Very Poor” (VP) to “Very Good” (VG) and the results range from “Very Unsafe” (VU) to “Very Safe” (VS). For example, “Fair” (F) condition of the trench results in the “Moderate” (M) safety of the trench.
The magnitude of the triggering events ranges from "Very Light" (VL) to "Very High" (VH). For example if the magnitude of the triggering event of excess dewatering (T1) is "High" (H), this results in the "Poor" (P) safety of the trench with respect to T1.

The methodology of approximate reasoning, encompassing the fuzzy set concept, is capable of both coping with the fuzzy nature of the problem that may exist, and synthesizing objective knowledge and subjective judgments. Through its operations, the fuzzy set concept is capable of integrating the above uncertainties systematically in situations in which human ability may falter in the case of a very complex system.

It is essential to interpret the linguistic values into fuzzy sets. There are three categories of linguistic variables; the enabling events, which are related to the soil condition, the magnitude of the triggering events, and their results. The linguistic variables are presented with the fuzzy set values in Table 4.3. For example a poor soil condition without shoring and sloping may be represented as shown in the following:

\[
\text{Poor} = \{x = 0.0|f_G(x) = 1.0, \quad x = 0.1|f_G(x) = 0.9, \quad x = 0.2|f_G(x) = 0.7, \quad x = 0.3|f_G(x) = 0.6\} \\
= [0.0|1.0, 0.1|0.9, 0.2|0.7, 0.3|0.6]
\]  

(1)
where "|" is a delimiter and Poor is a subset of the universe of discourse $X$ for all $x \in X$.

The element $x$ indicates the level of condition, which may range from $x=0$ to $x=1$. The membership value, $f_G(x)$, is the corresponding degree of belief, which is highest for very good condition and which rapidly decreases for poor conditions.

The membership values of all variables using the term "very" are obtained from the following equation:

$$f_{\text{very } G}(x) = [f_G(x)]^2$$  \hspace{1cm} (2)

The membership values listed in Table 4.3 are based on the subjective judgement of the authors [Patel and Hadipriono, 2005]. The values listed are for the illustration purposes only.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Magnitude</th>
<th>Results</th>
<th>Values (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Poor (VP)</td>
<td>Very High</td>
<td>Very Unsafe</td>
<td>$[0.0/0.1,0.1/0.81,0.2/0.49]$</td>
</tr>
<tr>
<td>Poor (P)</td>
<td>High</td>
<td>Unsafe</td>
<td>$[0.0/1.0,0.1/0.9,0.2/0.7,0.3/0.6]$</td>
</tr>
<tr>
<td>Fair (F)</td>
<td>Medium</td>
<td>Moderate</td>
<td>$[0.4/0.7,0.5/0.9,0.6/0.9,0.7/0.7]$</td>
</tr>
<tr>
<td>Good (G)</td>
<td>Low</td>
<td>Safe</td>
<td>$[0.8/0.6,0.9/0.9,1.0/1.0]$</td>
</tr>
<tr>
<td>Very Good (VG)</td>
<td>Very Low</td>
<td>Very Safe</td>
<td>$[0.9/0.81,1.0/1.0]$</td>
</tr>
</tbody>
</table>

Table 4.3: Fuzzy set values for conditions, magnitude and results
4.3 The fuzzy set model

The authors have developed software that generates the overall condition of the trench. The software uses the linguistic variables describing the soil condition and the magnitude of the enabling and triggering events to generate the output.

Consider an example in which the supervisor visits the site and identifies the enabling condition of the trench and the magnitude of the triggering events. The resultant can be found by using Tables 4.1 and 4.2, and are shown in Tables 4.4 and 4.5.

<table>
<thead>
<tr>
<th>Enabling Event</th>
<th>Condition</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor soil condition with no shoring or sloping system (E1)</td>
<td>Very Poor(VP)</td>
<td>Very Unsafe(VU)</td>
</tr>
<tr>
<td>Inadequate trench depth with no shoring or sloping system (E2)</td>
<td>Poor(P)</td>
<td>Unsafe(U)</td>
</tr>
<tr>
<td>Inadequate shoring or sloping system provided (E3)</td>
<td>Fair (F)</td>
<td>Moderate(M)</td>
</tr>
<tr>
<td>Inappropriate use of equipment or methods (E4)</td>
<td>Very Poor(P)</td>
<td>Very Unsafe(VU)</td>
</tr>
</tbody>
</table>

Table 4.4: Trench- result vs. condition
<table>
<thead>
<tr>
<th>Triggering Event</th>
<th>Magnitude</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess dewatering (T1)</td>
<td>Very</td>
<td>Very Unsafe (VU)</td>
</tr>
<tr>
<td></td>
<td>High (VH)</td>
<td></td>
</tr>
<tr>
<td>Excess water seepage (T2)</td>
<td>Low (L)</td>
<td>Safe (S)</td>
</tr>
<tr>
<td>Surcharge load (T3)</td>
<td>Medium (M)</td>
<td>Moderate (M)</td>
</tr>
<tr>
<td>Vibration by equipment (T4)</td>
<td>High (H)</td>
<td>Unsafe (U)</td>
</tr>
</tbody>
</table>

Table 4.5: Trench- magnitude vs. result

Since the linguistic variables of “Condition” and “Magnitude” are used in a different universe of discourse, a fuzzy relation is used to associate them with their fuzzy set values. The condition and the result of the enabling events (E) are associated by their respective fuzzy set values. The membership functions of the relation RE1, for example, between the fuzzy subsets “Very Poor” (VP) and “Very Unsafe” (VU) of the trench in Table 4.4 can be found through use of the following equation:

\[
f_{RE1}(x_1, y_1) = f_{VU \times VP}(x_1, y_1) = \bigwedge_{(x_1, y_1) \in X \times Y} \left[ f_{VP}(x_1), f_{VU}(y_1) \right]
\]

where \( VP \subset X \) and \( VU \subset Y \), and where \( X \) and \( Y \) are universes associated with the condition and result. \( \bigwedge \) denotes the conjunction which corresponds to the intersection of the “Result” and “Condition” in the classical set theory. This yields the following matrix presented in Table 4.6.
The same kind of manipulation is used to obtain the membership values of the fuzzy relations between the fuzzy set values of the condition and results for all $E_i (i = 1, \ldots, 4)$ listed in Table 4.7.

The membership function of the total relation is obtained by taking the disjunction of all relations using the following equation:

$$ f_n(x_i,y_i) = \bigvee_{k=1}^{n} \left[ f_{R_k}(x_i,y_i) \right] $$

where $\bigvee_{k=1}^{n} R_k$ denotes the disjunction from 1 to n. This gives Table 4.7.
Table 4.7: Result x condition matrix

<table>
<thead>
<tr>
<th></th>
<th>0.0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result</td>
<td>1.0</td>
<td>0.9</td>
<td>0.7</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.9</td>
<td>0.9</td>
<td>0.7</td>
<td>0.6</td>
<td></td>
<td></td>
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<tr>
<td>0.2</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.6</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>0.3</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
<td>0.9</td>
<td>0.9</td>
<td>0.7</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0.4</td>
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<tr>
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<td>0.9</td>
<td>0.9</td>
<td>0.7</td>
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<tr>
<td>0.6</td>
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<td>0.9</td>
<td>0.9</td>
<td>0.7</td>
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<tr>
<td>0.7</td>
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<td>0.7</td>
<td>0.7</td>
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<tr>
<td>0.8</td>
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<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
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<tr>
<td>0.9</td>
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<tr>
<td>1.0</td>
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<td>0.7</td>
<td>0.7</td>
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</tr>
</tbody>
</table>

Equation 3 is also used to determine the membership values of the relations between the fuzzy set values contained in the “Magnitude” and “Result” of the triggering events, \( T_i \) for \( i = 1, 2, \ldots, 4 \) as listed in Table 4.8.

Table 4.8: Magnitude x result matrix

<table>
<thead>
<tr>
<th></th>
<th>0.0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude</td>
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<td></td>
</tr>
<tr>
<td>0.4</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>0.6</td>
<td>0.7</td>
<td>0.9</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>
where $M \subseteq Y$ and $M \subseteq Z$, where $Y$ and $Z$ are the universes associated with the result and the magnitude, respectively.

Similarly, the total relation of the “Magnitude” and the “Result” for the triggering events is obtained by taking the disjunction of all relation $RT_i (i = 1, 2, \ldots, 4)$. Equation 4 is used to give the results printed in Table 4.9.

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>0.0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>0.9</td>
<td>0.7</td>
<td>0.6</td>
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<tr>
<td>0.1</td>
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<td>0.9</td>
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<tr>
<td>0.9</td>
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<td>0.6</td>
<td>0.9</td>
<td>0.9</td>
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<tr>
<td>1.0</td>
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<td>0.9</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.9: Magnitude x result matrix

Tables 4.7 and 4.9 show that $RT \subseteq Z \times Y$ and $RE \subseteq Y \times X$ or, in other words, $RT$ and $RE$ are not in the same space. The integration between them can be performed through fuzzy composition in which both $RT$ and $RE$ are extended into a common space $X \times Y \times Z$. This can be done by repeating the membership values of $RT$ in space $X$ so
that \( RT^* \subset X \times Y \times Z \) and of \( RE \) in space \( Z \) so that \( RE^* \subset X \times Y \times Z \). The membership function of the composition \( RE \times RT \) is given by:

\[
f_{RT \circ RE}(x_i, z_k) = \bigvee_{y_j} \left[ f_{RT}(x_i, y_j, z_k) \wedge f_{RE}(x_i, y_j, z_k) \right]
\]

(5)

Thus, the above process for finding the membership function of \( RT \circ RE \) leads to the following expression:

\[
f_{RT \circ RE}(x_i, z_k) = \bigvee_{y_j} \left[ f_{RT}(z_k, y_j) \wedge f_{RE}(y_j, x_i) \right]
\]

(6)

\[\forall x \in X \]
\[\forall y \in Y \]
\[\forall z \in Z \]

By using Equations 5 and 6, the fuzzy composition \( RT \circ RE \) of Tables 4.7 and 4.9 results in Table 4.10.

In order to obtain the overall trench safety performance, the membership values in Table 4.10 are projected to the performance space. This is done through the use of the following equation:

\[
f_{T x}(x_i) = \bigvee_{z \in Z} f_{RT \circ RE}(x_i, z_k)
\]

(7)
where $T_x$ is the projection of the membership values on the performance space, $X$.

<table>
<thead>
<tr>
<th>RT $\cdot$ RE</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Magnitude</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.9</td>
</tr>
<tr>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>0.4</td>
<td></td>
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<tr>
<td>0.5</td>
<td></td>
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<tr>
<td>0.6</td>
<td></td>
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<tr>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.10: Magnitude x condition matrix

The largest membership value from each column in Table 4.10 is then chosen as the membership value of the trench overall performance, which gives:

$$T_x = [0.0|1.0, 0.1|0.9, 0.3|0.7, 0.4|0.7, 0.5|0.9, 0.6|0.9, 0.7|0.7]$$ (8)

This can be represented graphically as shown in Figure 4.1. Clearly, the graph shows a range of performance from “Moderate” to “Poor”. This provides a warning to the trench supervisor to improve the quality control procedures.
4.4 The computer program

A software program was developed to perform the mathematical calculations and produce the result as a matrix and graph. The software makes it easy to translate the linguistic terms into a mathematical representation and perform the calculations. Moreover, the linguistic value attached to the program and the enabling and triggering events mentioned in the program are based on the author’s experience. They can be changed according to the knowledge and the experience of the person or the expert using the software.

The software was developed using visual basic programming language. The program has a list of enabling and the triggering events listed on the form. The experts or the persons who wants to evaluate the overall performance of the site, has to visit the site, collect all the information mentioned on the form and attach a linguistic value to the event according to his personal experience. A range of linguistic values for each of the enabling and triggering events is given on the form, which has to be selected by the user, for each event according to his trench review and experience.
The software is shown in the Figure 4.1:

Figure 4.1: The translational model

The various common enabling and triggering conditions that cause trench collapse are described on the left hand side of the screen. The severity of the condition and the safety of the trench under that severity conditions is selected by the user. Thus, the software gives the user the ability to select the condition which he observes on the site and to enter
the safety performance of the trench according to his experience. He can even take the
data to the expert and allow the expert to select the appropriate description of the safety
performance of the trench under the conditions he observed. The top part of the screen
displays the overall safety performance of the trench in the graphical form.

This graph is displayed by using a matrix calculation, which can be seen by the user or
the expert by pressing the button “Matrix”. The screen looks likes Figure 4.2 shown on
the next page.
Thus, if the expert or the user has any doubt about the result or if he wants to check the overall calculation of the result, he can click on the matrix button and check the matrix calculation.

Once users collect the required information from the site, they enter the various conditions of the enabling and triggering events that were viewed at the site. Based on
their experience they will attach a linguistic value for each of these conditions, which range from “Very Unsafe” (VU) to “Very Safe” (VS). Once users have entered all the enabling and the triggering conditions and attached a linguistic value to a condition, they can view the RE and RT matrix and the composite matrix RT-RE by clicking on the matrix button. If users directly want to view the result, they can just press the “Result” which will give them the overall performance of the trench in the form of the graph. It will also describe the condition of the trench in words.

Example 1: Assessment of the initial overall trench safety performance

Consider an example where the site supervisor makes a site visit and finds the following enabling and triggering conditions on the site.

<table>
<thead>
<tr>
<th>ENABLING EVENT</th>
<th>CONDITION</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor soil condition with no shoring or sloping system (E1)</td>
<td>Very Poor(VP)</td>
<td>Very Unsafe(VU)</td>
</tr>
<tr>
<td>Inadequate trench depth with no shoring or sloping system (E2)</td>
<td>Poor(P)</td>
<td>Unsafe(U)</td>
</tr>
<tr>
<td>Inadequate shoring or sloping system provided (E3)</td>
<td>Fair (F)</td>
<td>Moderate(M)</td>
</tr>
<tr>
<td>Inappropriate use of equipment or methods (E4)</td>
<td>Very Poor(P)</td>
<td>Very Unsafe(VU)</td>
</tr>
</tbody>
</table>

Table 4.11: Trench- result vs. condition
<table>
<thead>
<tr>
<th>TRIGGERING EVENT</th>
<th>MAGNITUDE</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess dewatering (T1)</td>
<td>Very High (VH)</td>
<td>Very Unsafe (VU)</td>
</tr>
<tr>
<td>Excess water seepage (T2)</td>
<td>Low (L)</td>
<td>Safe (S)</td>
</tr>
<tr>
<td>Surcharge load (T3)</td>
<td>Medium (M)</td>
<td>Moderate (M)</td>
</tr>
<tr>
<td>Vibration by equipment (T4)</td>
<td>High (H)</td>
<td>Unsafe (U)</td>
</tr>
</tbody>
</table>

Table 4.12: Trench- magnitude vs. result

Figure 4.3: The overall performance of the trench case discussed in example 1.
The RE, RT and RT o RE matrix for the example discussed in example 1 can be displayed by using the program as shown in Figure 4.4.

![Figure 4.4: The RE, RT and RT \* RE matrix for the trench case discussed in example 1](image)

Figure 4.4: The RE, RT and RT \* RE matrix for the trench case discussed in example 1
Example 2: Assessment of the improved overall trench safety performance

Consider another example in which the enabling condition of the trench and the magnitude of the triggering events are as shown in Tables 4.13 and 4.14, respectively.

<table>
<thead>
<tr>
<th>ENABLING EVENT</th>
<th>CONDITION</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor soil condition with no shoring or sloping system (E1)</td>
<td>Good (G)</td>
<td>Safe (S)</td>
</tr>
<tr>
<td>Inadequate trench depth with no shoring or sloping system (E2)</td>
<td>Good (G)</td>
<td>Moderate (M)</td>
</tr>
<tr>
<td>Inadequate shoring or sloping system provided (E3)</td>
<td>Very Good (G)</td>
<td>Very Safe (VS)</td>
</tr>
<tr>
<td>Inappropriate use of equipment or methods (E4)</td>
<td>Good (G)</td>
<td>Very Safe (VS)</td>
</tr>
</tbody>
</table>

Table 4.13: Trench - result vs. condition

<table>
<thead>
<tr>
<th>TRIGGERING EVENT</th>
<th>MAGNITUDE</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess Dewatering (T1)</td>
<td>Medium (M)</td>
<td>Moderate (M)</td>
</tr>
<tr>
<td>Excess water seepage (T2)</td>
<td>Low (L)</td>
<td>Safe (S)</td>
</tr>
<tr>
<td>Surcharge load (T3)</td>
<td>Low (L)</td>
<td>Safe (S)</td>
</tr>
<tr>
<td>Vibration by equipment (T4)</td>
<td>Very Low (L)</td>
<td>Safe (S)</td>
</tr>
</tbody>
</table>

Table 4.14: Trench - magnitude vs. result
The results are shown in Figures 4.5 and 4.6.

Figure 4.5: The overall performance of the trench as discussed in example 2
Figure 4.6: The RE, RT and RT - RE matrix for the example in example 2
CHAPTER 5

EVALUATING TRENCH SAFETY USING THE ROTATIONAL MODEL

5.1 Introduction

The loss to constructions companies in terms of direct and indirect cost were learned earlier in Chapter 1. It has been seen earlier that the trench collapse can cause the death or disability of the workers working in the trenches. The trench accident reports and the statistical data have been explored previously in Chapter 3. The enabling and triggering causes lead to the occurrence of trench collapse. The enabling and triggering conditions as discussed in Chapter 2 was a great help in developing the rules for the rotational fuzzy logic model discussed in this chapter. Moreover, the statistical analysis of the trench accidents presented in Chapter 3 will strengthen understanding of the importance of the study and the models.

This chapter capitalizes on the use of the fuzzy set rotational model to manipulate the fuzzy linguistic terms. The rotational model of the fuzzy set concept is used in this chapter to generate graphical displays, which provide a guideline to determine the overall trench performance. The assessments by the experts result in production rules for use in a
knowledge-based expert system. The fuzzy set rotational model can be used to solve problems where conflict among the rules occurs. The model utilizes the *modus ponens* deduction technique for partial matching or development of new rules.

5.2 Assessing the trench condition

Assessment of the trench is usually performed by experts through subjective judgement in which linguistic values are frequently used. Although the judgement is accomplished by using linguistic values, these values can be represented by the fuzzy set concepts. In this study, the author is also acting as the expert judge. The expert judgement is used for assessing the values of the linguistic variables at various levels of the trench excavation. The result from this assessment is used to develop the production rules of the knowledge based expert system.

The knowledge based expert system (KBES) is the concept used to develop a computer program that attempts to embody the knowledge and decision making process of an expert(s). The KBES is a heuristic based approach rather than the numeric approach. It is based on the experience of the experts, rules of thumb and educated guesses. The advantages of the KBES are:

- Even if the data are incomplete, they are helpful in producing the answers
- It is possible with the KBES to explain the reasoning and logic behind the answer
- It also provides the capability to easily inspect the knowledge base
The disadvantage of the KBES is that the result produce by it may not always be correct.

5.3 Damage criteria and damage level

The author has developed a set of rules based on his personal expertise in the field of excavation. The set of rules can be different according to the experience and expertise of different experts. This set of rules was developed by the author through study and analysis of the various enabling and triggering conditions that are responsible for causing the trench collapse.

After the various enabling and the triggering conditions were studied, the trench condition was categorized in 10 different overall condition levels:

1) Absolutely Poor
2) Very Poor
3) Poor
4) Fairly Poor
5) Fairly Good
6) Good
7) Very Good
8) Absolutely Good
9) Undecided
10) Impossible
Out of these 10 condition levels, the author did not use the “Absolutely Good” and “Absolutely Poor” in developing the software. The author considered the term “Absolutely Good” and “Very Good” as the same. In the same way, the terms “Absolutely Poor” and “Very Poor” are considered to be the same. For this reason, each of the above two terms are combined and are not included in the developing the set of rules.

In the same way the author developed various safety levels the experts could utilize in evaluating the safety of the trench. They are:

1) Absolutely Safe
2) Very Safe
3) Safe
4) Fairly Safe
5) Fairly Unsafe
6) Unsafe
7) Very Unsafe
8) Absolutely Unsafe

Out of these eight safety conditions, the author did not use the “Absolutely Safe” and “Absolutely Unsafe” categories in developing the software. The author considered the term “Absolutely Safe” and “Very Safe” as the same. In the same way, the terms
"Absolutely Unsafe" and "Very Unsafe" were considered to be the same. For this reason each of the above two terms was combined and are not included in the developing the set of rules.

5.4 Fuzzy logic rules

A knowledge based expert system (KBES) is a system developed for assessing the safety of a trench. The KBES applies the knowledge base and inference mechanisms through the use of computer programs for problem resolution usually performed by experts in a specific field. The knowledge base includes the information acquired from expert[s] or other sources of information, such as historical or experimental data, concerning the values of functionality, reparability, and structural integrity. This information is collected by the expert, who accessed the site where the trench excavation is going on and evaluates the various enabling and triggering conditions of the trench.

The fuzzy set concept is then used to quantify the linguistic values of the variables of the damage criteria and to construct the rules. Assessment from the same group of experts may result in rules with the following cases:

1. Similar antecedents and consequents
2. Similar antecedents but different consequents
3. Similar consequents but different antecedents
4. Different antecedents and consequents.
In the case of similar antecedents and consequents fuzzy set operations need not be used. The total number of similar rules determines the weight of the damage levels in the rules. In the case where several rules have similar antecedents but different consequents, these rules can be combined. For example, consider a case in which there are five rules with similar antecedents but three of the consequents indicate that the safety of the trench is “Very Unsafe” or “SA is VU” and the two others indicate that the condition of the trench is “Unsafe” or “SA is U”. The combined consequents of rules 1 and 2 can be represented by the following:

CONS 1: Safety of the trench is Very Unsafe (VU)
CONS 2: Safety of the trench is Unsafe (U)

where CONS denotes the consequent

Two rules can have similar consequents and different antecedents, as is shown below:

Rule (Expert 1):
ANT 1: The Condition of the trench is Poor (P)

Rule (Expert 2):
ANT 2: The Condition of the trench is Very Poor (VP)

where ANT denotes the antecedent
5.5 Partial condition matching using fuzzy logic

Consider the following production rule:

If the trench condition after analyzing the various enabling and the triggering condition is “Very Poor” (VP) then the safety of the trench is “Very Unsafe” (VU). When a fact shows that the safety is VU, the consequent is then realized. However, when the value of Safety does not match exactly, e.g., the fact shows that “Safety is Unsafe”, then partial matching is in order.

This can be performed by the following fuzzy logic operation:

(1) Truth Functional Modification (TFM)

(2) Inverse Truth Functional Modification (ITFM)

(3) Modus Ponens Deduction (MPD)

This operation uses the BALDWIN TRUTH VALUES to describe the result. The membership functions of the Baldwin truth model are described in Table 5.1
<table>
<thead>
<tr>
<th>Truth Values</th>
<th>Fuzzy Set Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Fairly True</td>
<td>0</td>
</tr>
<tr>
<td>True</td>
<td>0</td>
</tr>
<tr>
<td>Very True</td>
<td>0</td>
</tr>
<tr>
<td>Absolutely True</td>
<td>0</td>
</tr>
<tr>
<td>Fairly False</td>
<td>1</td>
</tr>
<tr>
<td>False</td>
<td>1</td>
</tr>
<tr>
<td>Very False</td>
<td>1</td>
</tr>
<tr>
<td>Absolutely False</td>
<td>1</td>
</tr>
<tr>
<td>Undecided</td>
<td>1</td>
</tr>
<tr>
<td>Impossible</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.1: Baldwin membership functions
From the above table we get the following Baldwin Truth Model

![Baldwin Truth Model](image)

Figure 5.1: Baldwin Truth Model

**TRUTH FUNCTIONAL MODIFICATION (TFM)**

TFM was first introduced by Zadeh [11]. TFM is a logic operation that can be used to modify the membership function of a linguistic value in a certain proposition with a known truth value. Suppose Safety (S) of the trench is “Very Safe” (VS) and that condition is believed to be false. This proposition can be expressed as
P: (Safety is VS) is False (FA), VS ⊆ SA, FA ⊆ T

where, safety is a variable (universe of discourse), T is the truth space, and VS and False are the values of Safety and T, respectively. The symbol ⊆ denotes 'a subset of'.

Modification of this proposition yields

P': (SA is SA1): SA1 ⊆ SA

where, SA1 is the value of SA. A graphical solution is shown in Figure 5.2 where the fuzzy set VS and FA are represented by Baldwin's model and plotted in Figure 5.2a and Figure 5.2b. Note that the axis of Figure 5.2a is rotated 90° counter-clockwise from Figure 5.2b. This means that for any given element of VS, we can obtain the corresponding element of FA. Also, the membership values of SA1 can be found as shown by the arrowheads and plotted in Figure 5.2b.
INVERSE TRUTH FUNCTIONAL MODIFICATION (ITFM)

ITFM is a logic operation that can be used to obtain the truth values of a conditional proposition, P, is such as ‘Safety of the trench is Very Safe given that the safety is Unsafe”; then the proposition can be rewritten as

\[ P: (SA \text{ is } VS) \text{ (} SA \text{ is } U); \text{ VS, } U \subseteq S \]

The ITFM reassesses the truth of (SA is VS) by modifying this proposition to yield

\[ P': (SA \text{ is VS) is } T1; T1 \subseteq T \]
where, $T_1$ is the new truth value for ($S$ is $VS$). The truth value, $T_1$, can also be obtained through the graphical solution shown in Figure 5.3. Suppose "Very Safe" ($VS$) and "Unsafe" ($U$) are again represented by Baldwin’s model. The values $VS$ and $U$ are first plotted as shown in Figure 5.3b. Since the truth level is equal to the membership value of $VS$, they lie on the same vertical axis. Hence, for each membership value of $VS$, the corresponding element of $T_1$ is also known. Then too, since the membership value of $T_1$ equals that of $U$, for any given element of both $VS$ and $U$, we can find the corresponding element and membership value of $T_1$. The truth value, $T_1$ in Figure 5.3a is constructed by successively plotting the membership values of $U$ ($d_1$, $d_2$, etc.) from Figure 5.3b at each truth level. Note that the axis in Figure 5.3a is rotated $90^\circ$ counter-clockwise from Figure 5.3b.
Figure 5.3: Inverse Truth Functional Modification

MODUS PONENS DEDUCTION (MPD)

Modus Ponens Deduction (MPD) is a fuzzy logic operation whose task is to find the value of a consequent in a production rule, given the information about the antecedent. A simple MPD is: A implies B and given A, then the conclusion is B. Consider again the proposition ‘if the soil condition is Very Poor (VP), then safety is “Unsafe” ’ (If SC is VP, then S is U). However, suppose further information is available, i.e., ‘Safety of the trench is “Unsafe” (SA is U). This proposition can be represented by the following:
P: (SC is VP) ⊨ (SA is U)

P': (SC is P)

where the symbol ⊨ represents the implication relation between (SC is P) and (S is U).

This example can be conveniently solved through the following graphic representation. Through the ITFM, P and P' can be combined:

P": (SC is VP) is T1 ⊨ (SA is U)

We can obtain the truth value of (SA is U), i.e., T2, through the use of the implication relation operation introduced by Lukasiewicz. He incorporated the truth relation, denoted as the elements of T2 and T1. These relations, for different values of the elements of T2, are shown in Figure 5.4a as parallel lines. The intersections of T1 and T1 yield the membership values of T2. Subsequently, the truth value, T2, can be found and plotted as in Figure 5.4a. Now (SA is U) is T2 can be modified through the TFM process to give SA is SA1 in Figure 5.4b, which concludes that SA is “close to “Fairly Unsafe” (FU).

The MPD goes through 3 steps:

1) ITFM
2) LIR
3) TFM
Figure 5.4a

Figure 5.4b

Figure 5.4: The figure shows the ITFM
Figure 5.5: The figure shows the LIR
Figure 5.6: The figure shows the TFM

5.6 The software program

The software has developed in visual basic programming language. The various rules developed for this software are from the author's own experience. The software is very user friendly. It contains a set of rules that has been developed by the author. The user after making the site visit and looking at the various enabling and triggering conditions on the site and enters them in the software. The software offers options for the selection of the rule. The rule selection depends upon the user. One user might think that the trench condition is good so that the trench safety is “Very Safe” (VS) while another user might
think of it as “Fairly Safe” (FS). This depends upon the user's own experience and education. Once the user selects the rule, then he has to enter the trench condition that was actually observed on the site. After the user enters the trench condition and hits the “Result” button, the software gives the overall condition of the trench. The software performs this by following fuzzy logic operation:

1. Truth Functional Modification (TFM)
2. Inverse Truth Functional Modification (ITFM)
3. Modus Ponens Deduction (MPD)

The role of above three fuzzy logic operations has been previously discussed in this chapter. The software goes through the above mentioned rules in this order and then ultimately gives the final condition of the trench. The software does not show the step by step performance of the logic. In other words it does not display the TFM and ITFM produced by selecting the rule and entering the conditions. It only displays the final result the MPD.
The software program looks like this:

![Image of software program]

**MODUS PONENS DEDUCTION**

The left side of the software screen represents the rule and on the right side the user has to enter the actual trench condition that he has observed on the site. The graph will

Figure 5.7: The rotational model

The left side of the software screen represents the rule and on the right side the user has to enter the actual trench condition that he has observed on the site. The graph will
display the overall condition of the trench. Note that the axis on the left side graph is rotated $90^\circ$ counter-clockwise from the right side of the graph.

As discussed previously, the truth value for the condition is obtained by the use of the implication relation operation introduced by Lukasiewicz. The new truth value is found by the intersection of the truth value of the rule with the parallel lines shown to the left of the graph. This new truth value is used to find the overall condition of the trench, which is displayed on the right hand side graph.

Example 1:

Suppose the user, based on his own experience and education thinks that if the soil condition is Very Good (VG), then the safety is "Safe" (If SC is VG, then SA is S). The user makes a site visit and finds that the actual soil condition on the site is Fairly Good (FG). From this available condition and the rule, the software will give the overall condition of the trench. The above proposition can be represented by the following:

P: (SC is VG) $\Rightarrow$ (SA is S)

P': (SC is FG)
Now the result can be displayed by the software as follows. The green line displays the final overall safety performance of the trench.

![MODUS PONENS DEDUCTION](image)

Figure 5.8: The figure shows the result of example 1

We can see that the new truth line which is displayed in graph 1 on left side of the figure is obtained by the intersection of the parallel lines and the truth value T1. Now this
truth value can be modified through the TFM process to give the SA is SA1 in Figure 5.8, which concludes that the SA is ‘close to Fairly Good” (FG).

Example 2:

Consider another example in which the user, based on his own experience and education, thinks that if the soil condition is Poor (P), then the safety is “Very Unsafe” (If SC is P, then SA is VU). The user makes a site visit and finds that the actual soil condition on the site is Very Poor (VP). From this available information on the condition and the rule, the software will give the overall condition of the trench. The above proposition can be represented by the following:

\[ P: (SC \text{ is } P) \supset (SA \text{ is } \text{VU}) \]

\[ P': (SC \text{ is } \text{VP}) \]
Now the result can be displayed by the software as follows. The green line displays the overall safety performance of the trench.

![Image of MODUS PONENS DEDUCTION](image)

Figure 5.9: The figure shows the result of example 2

We can see that the new truth line which is displayed in the graph 1 on left side of the figure is obtained by the intersection of the parallel lines and the truth value T1. Now this
truth value can be modified through the TFM process to give the SA is SA1 in Figure 5.9, which concludes that the SA is ‘close to Fairly Good’ (FG).

Example 3:

Consider another example in which the user, based on his own experience and education thinks that if the soil condition is “Poor” (P), then the safety value is “Very Unsafe” (If SC is P, then SA is VU). The user makes a site visit and found that the actual soil condition on the site is Very Good (VG). From this available information on the condition and the rule the software will give the overall condition of the trench. The above proposition can be represented by the following:

\[ P: (SC \text{ is } P) \Rightarrow (SA \text{ is } VU) \]

\[ P': (SC \text{ is } VG) \]
Now the result can be displayed by the software as follows:

![Modus Ponens Deduction Diagram]

Figure 5.10: The figure shows the result of the example 3

As seen in the above figure the ALERT message has appeared on the screen. And it can be seen from the graph that the green result line is on the top of the right hand side graph. The green horizontal line at the top of the graph shows that the safety is
'UNDECIDED'. This can be clearly seen in Figure 5.1 'THE BALDWIN TRUTH MODEL'. The message says that 'the condition provided is incorrect or the project engineer should take necessary steps to match the condition with the rule'. This means the user should be more careful to select the correct rule. In this case the rule does not match the actual condition of the site, so either the user has not selected the rule properly or the description of the condition on the site is not appropriate and need to be corrected to match with the rule.
6.1 Introduction

The trench accidents are a significant source of loss to the constructions companies, in terms of both direct and indirect losses. Moreover, this can cause the death or the disability of the worker working in the trench. The causes of the trench accidents have also been considered in chapter 2. The two main causes of the trench accident are the enabling and the triggering causes. These enabling and triggering conditions discussed, have been a great help in developing rules for the angular fuzzy logic models. Moreover, the statistical analysis of the trench accident discussed in Chapter 3 should lead to greater understanding of the importance of the study and the models.

The notion of the fuzzy system was introduced by Zadeh in 1975 [12] can be applied as a useful means for describing situations where a result is imprecise. Since then, researchers have found numerous ways to utilize this theory to develop new mathematical methods of approximate reasoning.
Zadeh suggested a method for approximate reasoning. He demonstrated a problem that is transformed into a truth space, then the calculations are carried out in the truth space and the problem is transformed back from the space to give some result. The method was later described and modified by Baldwin and Blockley as Truth Functional Modification and Inverse Truth Functional Modification. In this chapter, the membership functions are described in terms of the fuzzy elements and fuzzy membership values.

This chapter discusses an angular fuzzy set model. The model uses an angle to determine a line that represents the linguistic value. Therefore, the membership value is a function of the angle \( \alpha \). This angular fuzzy set model can be applied to fuzzy logic modus ponens deduction techniques. In relation to these techniques, we employ fuzzy logic operations, such as the truth functional modification and inverse truth modification. A relatively simple calculation procedure is required to perform these operations. The conventional models that are represented graphically could pose difficulties in the interpretation of the graphs. The angular model, on the other hand, depends only on the angle. These angular models are solved numerically, and therefore are easier to interpret. Illustrations using this model and comparison with conventional models are presented in this paper.
6.2 Explanation of the fuzzy logic concept

There are two techniques where the fuzzy logic can be applied. They are:

1) Modus Ponens Deduction and
2) Modus Tollens Deduction.

Since the software has been developed based on the fuzzy modus ponens deduction technique, in this chapter, we will only describe an approximation of the reasoning in the fuzzy modus ponens deduction techniques.

The classical modus ponens relationship is commonly stated as: \([A \land (A \rightarrow B)] \rightarrow B\). Consider the following modus ponens propositions:

\[
\text{Ant. 1: } (\text{a is } A) \quad \implies \quad (\text{b is } B) \\
\text{Ant 2: } (\text{a is } A') \\
\text{Cons: } Q (\text{b is } B) \text{ is } \tau_B \text{ and } (\text{b is } B) \\
\tau_B \subseteq T (1)
\]

where, the symbol \(\implies\) represents the implication relation between (a is A) and (b is B); 'Ant' and 'Cons' stand for antecedent and consequent, respectively; a and b are the names of objects; A and A' are fuzzy sets in universe of discourse U while B and B' are
fuzzy sets in universe of discourse $V$; $Q (b \text{ is } B)$ means ‘the truth of (b is B)’; $\tau_B$ is the new truth fuzzy set value in truth space $T$; and the symbol $\subseteq$ denotes ‘a subset of’.

When we have the exact matching of the $A' = A$, then obtaining the result becomes easy. However, when the value of $A'$ does not match exactly with $A$, i.e. $A'$ is not exactly $A$, then the regular Modus Ponens Deduction technique is not too useful. For this type of condition, we have to introduce the Fuzzy Modus Ponens Deduction (FMPD) which is reduced to the classical modus when $A' = A$ and $B' = B$. The objective of FMPD is to find the value of $B'$.

In order to solve FMPD, fuzzy logic operations such as Truth Functional Modification (TFM) and Inverse Truth Functional Modification (ITFM) are to be employed.

Many fuzzy set models have been used to represent linguistic values. For example, Blockley’s model defined in a truth space is shown in Figure 6.1, and the membership functions for the linguistic values are illustrated in Table 6.1.
6.3 Angular fuzzy set model

The Angular Fuzzy Set Model (AFSM) defined in truth space is shown in Figure 6.2. The linguistic values are represented by lines with angle $\alpha$. 

Figure 6.1 Blockley's Model
Table 6.1 Blockley's membership functions

From the Figure 6.1, it can be seen that the horizontal axis, i.e. where $\alpha = 0$, represents a value Undecided (UN). This condition occurs when the rule and the actual condition on the site are totally opposite. The value of Absolutely True (AT) is indicated by line with a vertical angle $\alpha = \pi/2$, and the value of Absolutely False (AF) is represented by a line opposite to Absolutely True with $\alpha = \pi/2$. Both of the above mentioned terms, Absolutely True (AT) and Absolutely False (AF) are practically not possible. The positive values, such as Very True (VT), true (TR), Fairly True (FT), and so on, are represented by lines with angles between $\alpha = 0$ and $\alpha = \pi/2$. The negative values, such as Very False (VF), False (F), Fairly False (FF), and so on, are represented by the lines with angles between $\alpha = 0$ and $\alpha = -\pi/2$. Using this technique, we can define a continuous truth space $T$. This model can be used for performing FMPD. A simple calculation procedure is needed for this model.
Figure 6.2 Angular fuzzy set model
The table given below describes the angles for different safety conditions.

<table>
<thead>
<tr>
<th>Soil Condition</th>
<th>Abbreviations</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolutely Safe</td>
<td>AS</td>
<td>$\alpha = \pi/2$</td>
</tr>
<tr>
<td>Very Safe</td>
<td>VS</td>
<td>$\alpha = 3 \pi/2$</td>
</tr>
<tr>
<td>Safe</td>
<td>S</td>
<td>$\alpha = \pi/4$</td>
</tr>
<tr>
<td>Fairly Safe</td>
<td>FS</td>
<td>$\alpha = \pi/8$</td>
</tr>
<tr>
<td>Undecided</td>
<td>U</td>
<td>$\alpha = 0$</td>
</tr>
<tr>
<td>Fairly Unsafe</td>
<td>FU</td>
<td>$\alpha = -\pi/8$</td>
</tr>
<tr>
<td>Unsafe</td>
<td>U</td>
<td>$\alpha = -\pi/4$</td>
</tr>
<tr>
<td>Very Unsafe</td>
<td>VU</td>
<td>$\alpha = -3\pi/2$</td>
</tr>
<tr>
<td>Absolutely Unsafe</td>
<td>AU</td>
<td>$\alpha = -\pi/2$</td>
</tr>
</tbody>
</table>

Table 6.2 Different angles for different safety conditions

6.4 TFM using the angular model

TFM is a logic operation that can be used to modify the membership function of a linguistic value in a certain proposition with a known truth value. The principle adopted by Baldwin illustrates a problem that is transformed into the truth space. It can be described as the following:

If a proposition $\Omega$ can be allocated a truth value restriction, then

$$\Omega: (a \text{ is } A) \in \tau_A; A \subset U; \tau_A \subset T \quad (2)$$

where the truth restriction $\tau_A$ is the value of $T$. Modification of this proposition yields:
Ω: (a is A') is \( \tau_A; A \subset U \) \( \tag{3} \)

The membership function can be solved as follows:

\[ \Phi_A(z) = \Phi_{t \cdot A}[\Phi_A(z)] \] \( \tag{4} \)

where \( \Phi_A(z) \) and \( \Phi_A(t) \) are the membership functions of proposition A' and A, respectively, and \( \Phi_{t \cdot A}(t) \) is the membership function of truth restriction \( \tau_A \).

Suppose that the angles of A and \( \tau_A \) in AFSM, are \( \alpha \) and \( \beta \), respectively, as shown in Figure 6.3. The membership function \( \Phi_A(z) \) and \( \Phi_A(t) \) can be written as:

\[ \Phi_A(z) = z \tan \alpha \text{ and } \Phi_{t \cdot A}(t) = t \tan \beta \] \( \tag{5} \)
Introducing equation (5) into equation (4), we have:

\[ \Phi_{A'}(z) = \Phi_{tA} [z \tan \alpha] = z \tan \alpha \tan \beta \]  

(6)

So that \( \Phi_{A'}(z) = z \tan \gamma \)

where \( \tan \gamma = z \tan \alpha \tan \beta \)  

(7)
Using equation (7), we can obtain the modified membership function of a linguistic value by a simple mathematical calculation procedure. For example, suppose $\Omega$, the proposition 'the condition of the trench accident is Unsafe (U) is Fairly True (FT), we wish to calculate the condition of the trench. Using AFSM, the linguistic value $U$ and $FT$ can be characterized by $\alpha = \pi/4$ and $\beta = \pi/8$, respectively. Hence, equation (7) yields:

$$\tan \gamma = \tan (\pi/4) \tan (\pi/8) = \tan (\pi/8)$$

Assuming that the same characteristics of linguistic value are used in each space ($U$, $V$ and $T$), the angle $\gamma = \pi/8$ in space $U$ can be interpreted as "Fairly Unsafe" (FU). Hence, the TFM of the proposition gives: 'The condition of the trench is “Fairly Unsafe”.

6.3 ITFM using the angular model

ITFM, developed by Baldwin, is a logic operation that can be used to obtain the truth values of a conditional proposition. Suppose we have a proposition, gives:$\Omega$: (a is $A$), but is known from the given data that (a is $A'$). We can calculate the truth of proposition $\Omega$ as follows:

$$Q(a \text{ is } A' \text{ if } a \text{ is } A') = \tau_A; \tau_A \subseteq T; a, A' \subseteq U$$

(8)
where, \( \tau_A \) is the new truth restriction of the truth value for fuzzy set \( A \). The membership function of the new truth value,

\[
\Phi_{\tau_A}(t) = [\Phi_A(z)] = \vee_{z} [\Phi_{A'}(z)]
\]

(9)

in which \( \vee \) denotes that value where \( z \) is maximum. The proposition \( \Omega \) now becomes \( \Omega': (a \text{ is } A) \text{ is } \tau_A \). Therefore, the proposition described above can be written as:

\[
\Omega: (a \text{ is } A)/ (a \text{ is } A'); A, A' \subset U
\]

(10)

\[
\Omega: (a \text{ is } A) \text{ is } \tau_A; \quad \tau_A \subset T
\]

Suppose that the membership functions of \( A \) and \( A' \) are characterized by angles \( \alpha \) and \( \alpha' \) as shown in Figure 6.4.
The membership functions $\Phi_A(z)$ and $\Phi_{A'}(z)$ can be written as:

$$\Phi_A(z) = z \tan \alpha \quad \text{and} \quad \Phi_{A'}(z) = z \tan \alpha'$$  \hspace{1cm} (11)

Substituting equation (11) into equation (10), the membership function, $\Phi_{tA}(t)$, characterized by the angle $\beta$, yields:

$$\Phi_{tA}(t) = \Phi_{tA} [\Phi_A(z)] = \Phi_{tA} [z \tan \alpha] = z \tan \alpha \tan \beta,$$
and $\Phi_{tA}(t) = \bigvee_z [\Phi_{A'}(z)] = \bigvee_z [z \tan \alpha']$

so that $z \tan \alpha \tan \beta = z \tan \alpha'$. For $z \neq 0$, we have:

$$\tan \beta = \tan \alpha'/ \tan \alpha$$

(12)

and $\Phi_{tA}(t) = \tan \beta = \tan \alpha'/ \tan \alpha$

(13)

Equation (13) gives a very simple mathematical equation for the Inverse Truth Functional Modification. For example, suppose $\Omega$ is the proposition ‘the condition that the trench is Very Unsafe (VU)’, and we wish to assess the truth of $\Omega$ if we have the knowledge that ‘the condition of the trench is Unsafe (U) is True (TR)’. The linguistic value U and HI can be characterized by $\alpha = 3\pi/8$ and $\alpha' = \pi/4$, respectively. Through equation (12), we have:

$$\tan \beta = \tan \left(\frac{\pi}{4}\right)/ \tan \left(\frac{3\pi}{8}\right) = 0.41424$$

and $\beta = \pi/8$
Hence, the truth value is Fairly True, and the original proposition $\Omega$ can be written linguistically as: ‘Q (the condition that the trench is Very Unsafe given that it is Unsafe) is Fairly True’

6.6 Fuzzy modus ponens deduction

Consider again the proposition in equation (1). Through the ITFM, ‘Ant. 2: (a is A)’, in equation (1), can be combined to become;

$$\Omega: (a \text{ is } A) \text{ is } \tau_A \supset (b \text{ is } B) \quad (14)$$

The truth value of (b is B), i.e., $\tau_B$, can be obtained by modus ponens deduction. Mathematically, the membership function of the truth value $\tau_B$ is given by;

$$\Phi_{\tau_B} (y) = \vee_x [\Phi_{\tau_A} (x) \wedge \Phi_I (x, y)] \quad (15)$$

where $x$ and $y$ are the elements (truth levels) of the truth spaces $T$ and $T'$ of the propositions (a is A) and (b is A), respectively; $\Phi_I (x, y)$ is the truth implication relation function if the proposition (a is A) $\supset$ (b is B); and the symbol $\wedge$ denotes minimum or conjunction of $\Phi_{\tau_A} (x)$ and $\Phi_I (x, y)$. 

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For the AFSM, we need to define a new truth implication relation function $\Phi_i(x,y)$. According to Lukasiewicz's law, the implication relationship function of proposition A and A by traditional models, according to Giles, is:

\[ <A \supset B> = \sup \{ 0, <B> - <A> \} \]

where $<A>$, $<B>$ and $<A \supset B>$ are the membership functions of proposition A, B and $A \supset B$, respectively.

By Lucasiewicz theory, the membership function of the implication relation, by Angular Set Model, is given as:

\[ \Phi_i(x, y) = y - x \ (x \geq 0, \ y \geq 0) \]  \hspace{1cm} (16)

Substituting this implication relation function into equation (15), the membership function of the truth value $\tau_B$ can be obtained as follows.

Following Blockley, if a shorthand form of writing is adopted, for example, if we use A instead of (a is A), and B instead of (b is B), equation (1) can be rewritten, in a more general situation, as:
\[ [A \supset B] \text{ is } \tau_1; \ A, A' \subseteq U \]

\[ A' \text{ is } \tau_1; \ B, B' \subseteq V \]

\[ Q(B) \text{ is } \tau_1 \text{ and } B' \tau_B \subseteq T \]  \hspace{1cm} (18)

where \( \tau_1 \) and \( \tau_2 \) are the truth restriction of implication relation \( \Phi_1 (x, y) \) and of proposition (a is \( A' \)), respectively. In order to simplify the description, we use \( z \tan A \), \( z \tan A' \) and \( t \tan B \) to represent these functions \( \Phi_A(z), \Phi_{A'}(z), \) and \( \Phi_{A''}(t) \), respectively. Since a proposition is usually expressed by its membership function, we will use fuzzy sets to represent these functions, such as, \( A = \Phi_A(z) = z \tan A, \ A' = \Phi_{A'}(z) \), etc. Using the TFM and ITFM, the proposition \( A \) and \( A' \) can be combined as:

\[ Q(A/A') = \tau_A = \text{ITFM} [A/\text{TFM}(A', \tau_2)] \]

\[ = \text{TFM} \{ A/[A'\tan \tau_2] \} \]  \hspace{1cm} (18)

That is \( \tau_A = t \tan A' \tan \tau_2 / \tan A \)  \hspace{1cm} (19)

In which \( \text{TFM} \ (A', \tau_2) \) is the shorthand form of 'A' is modified by truth value \( \tau_2 \), and \( \text{ITFM} \ (A/A') \) is the shorthand form of 'Inverse Truth Functional Modification of proposition A given A''. Now the proposition, in equation (17), can be written as:
[A is $\tau_A \subset B$] is $\tau_1$;

$A \subset U; B, B' \subset V$

\[ Q(B) \text{ is } \tau_B \text{ and } B', \tau_B \subset T \]  \hspace{1cm} (20)

And $\tau_B$ can be calculated by equation (16). It can be rewritten as:

\[ \Phi_{tB} (y) = \lor \{ \Phi_{tA} (x) \land \text{TFM} [\Phi_t (x, y), \tau_1] \} \]  \hspace{1cm} (21)

Substituting equation (16) into equation (21), we have:

\[ \Phi_{tA} (x) = x \tan \tau_A = \text{TFM} [(y - x), \tau_1] \]

\[ = (y - x) \tan \tau_1 \]

And $x = y \tan \tau_1 / [\tan \tau_1 + \tan \tau_A]$  \hspace{1cm} (22)

So that we have

\[ \Phi_{tB} (y) = y \tan \tau_B = \Phi_{tA} (x) = x \tan \tau_A \]

\[ = y \tan \tau_1 \tan \tau_A / [\tan \tau_1 + \tan \tau_A] \]  \hspace{1cm} (23)
From equation (23) and knowing the truth of \( Q(B) \) is \( \tau_B \), the proposition \( B \) can be modified by TFM \((B, \tau_B)\) to give the value of \( B' \). That is:

\[
\Phi_{tB'}(z) = TFM(B, \Phi_{tB}) = \Phi_{tB}(z) \tan \tau_B = z \tan B \tan \tau_B
\]  

(24)

Combining equation (19), (23) and (24), we have:

\[
\Phi_{tB'}(z) = z \tan \tau_1 \tan A' \tan \tau_2 \tan B/ [\tan A \tan \tau_B + \tan A' \tan \tau_2] 
\]  

(25)

Equation (26) can be used to calculate the membership function of proposition (\( b \) is \( B' \)).

As an example of a *modus ponens* deduction, consider the following propositions: 'IF the condition of the trench is Very Good (VG) THEN its safety is Safe (S), this is True (TR)'. If it is True (TR) that the safety of the trench is Fairly Safe (FS), what is the conclusion?
Writing this as:

Condition is $G \supset$ safety is FS

Condition is $VG$

\[ Q \text{ (performance is GD)} = \tau_B \text{ and performance is } B' \]

Suppose that based on the AFSM, we have $\tan(S) = \tan(TR) = \tan(\pi/4)$, $\tan(VG) = \tan(3\pi/8)$, and $\tan(FS) = \tan(\pi/8)$. Through the use of equations (19), (23) and (24), we have:

\[
\frac{\tan \tau_B}{\tan \tau_B} = \frac{\tan(TR)\tan(FS)\tan(TR)}{[\tan(VS)\tan(TR) + \tan(FS)\tan(TR)]} = 0.146447
\]

and $\tan(B') = \tan(GD)\tan \tau_B = 0.146447\tan(\pi/4) = 0.146447$

so that $B'$ is between Fairly Safe $\alpha = \pi/8$ and Undecided $\alpha = 0$. If we replace:

'[Condition is $VG \supset$ Safety is S] is TR' by

'[Condition is $VG \supset$ Safety is S] is Absolutely True (AT)'

then we have $\tan(\text{AT}) = \tan(\pi/2]$ and
\[ \tan = \lim_{\theta \to \pi/2} \frac{\tan \theta \tan \phi \tan \Omega}{\tan \phi \tan \theta + \tan \phi \tan \Omega} \]
\[ = \tan (\pi/8) = 0.171573 \]

Thus, \( \tan B' = \tan (S) \tan B = 0.171573 \tan (\pi/4) \)
\[ = 0.171573 \]

Here it is assumed that the safety rules and the evaluation of the site conditions are done by the experts, the truth value for the rule and the condition of the trench is taken as True (TR) that is \( \tan(\pi/4) = 1 \). The software is prepared based on the consideration that the truth value of the trench condition and the set of rule is True (TR).

Suppose that based on the AFSM, we have \( \tan(GD) = \tan (\pi/4) \), \( \tan(VG) = \tan (VS) = \tan (3\pi/8) \), and \( \tan(FG) = \tan (\pi/8) \). Through the use of equations (19), (23) and (24), we have:

\(\tan \tau_B = \frac{\tan (FS) \tan (VG)}{[\tan (G) + \tan (VG)]} \)
\[ = 0.2925 \]

and \( \tan (B') = \tan (VG) \tan \tau_B = 0.2925 \tan (\pi/4) \)
\[ = 0.2925 \]
so that $B'$ is between Fairly Safe $\alpha = \pi/8$ and Undecided $\alpha = 0$. If we replace:

Consider another case in which:

'\{\text{Condition is VG }\supset \text{Safety is S}\}'

'\{\text{Condition is G}\}'

Suppose that based on the AFSM, we have $\tan (VG) = \tan (3\pi/8)$, and $\tan (S) = \tan(\pi/4)$. Through the use of equations (19), (23) and (24), we have:

$$\tan = \lim_{{AT \to \pi/2}} \frac{\tan (VG) \tan (S)}{[\tan (S) + \tan (VG)]}$$

$$= 0.785$$

Thus, $\tan B' = \tan (S) \tan \alpha_B = 0.785 \tan (\pi/4)$

$$= 0.785$$

6.7 The software program

The software was developed in visual basic programming language. The various rules developed for this software were from the author's own experience. The software is very user friendly. It contains the set of rules that were developed by the author. The user, after making the site visit and looking at the various enabling and triggering conditions
on the site enters the site condition in the software. The software offers the selection of
the rule. Rule selection depends upon the user. One user might think that the trench
condition is good so that the trench safety is “Very Safe” (VS) while the other user might
think of it as “Fairly Safe” (FS). This depends upon the users own experience and
education. Once the user selects the rule, then he has to enter the trench condition that
was actually observed on the site. After the user enters the trench condition and hits the
“Result” button the software gives the overall condition of the trench. The software
performs this by using three fuzzy logic operations. They are (1) Truth Functional
Modification (TFM), (2) Inverse Truth Functional Modification (ITFM) and (3) Modus
Ponens Deduction (MPD)

The role of above three fuzzy logic operations has been previously discussed in this
chapter. The software goes through the above mentioned rules in the order and then
ultimately gives the final condition of the trench. The software does not show the step by
step performance of the logic. In other words it does not display the TFM and ITFM
produced by selecting the rule and entering the conditions. It only displays the final result
which is the MPD.

The software looks like this:
If The Trench Condition Is:

S  Very Poor (VP)  

The Safety Is:
P  Very unsafe (VU)  

What If The Trench Condition Is:

S' Very Poor (VP)  

Then The Safety Is:
P'  

Result  

Figure 6.5: The angular model

The angular model can be seen in Figure 6.5. The rule is displayed on the lower left side of the form. The rule has a drop down menu, which means that the rule can be entered by the user according to his expertise. Here, the user may be an expert, an engineer or the supervisor. The advantage of this software is that the user governs the rule
according to his experience. Thus, a user is given a choice in selecting his rule in cases where good trench condition at a certain site may give poor safety result and visa versa.

The right side of the screen has a drop down menu, where the user can enter the actual site condition that was observed when he made the site visit. Once the user selects the rule and enters the actual site condition of the trench, the result is displayed in the graphical format on the top part of the screen. Along with the graphical display, the overall safety performance of the trench is also displayed in words, at the right corner of the screen.

Let us study some of examples to demonstrate the usability and performance of the software.

Example 1:

Suppose the user, based on his own experience and education thinks that if the soil condition is Very Good (VG), then safety is “Safe” (If SC is VG, then SA is S). The user makes a site visit and finds that the actual soil condition on the site is Fairly Good (FG). From this observed condition and the rule the software will give the overall condition of the trench. The above proposition can be represented by the following:
P: (SC is VG) \Rightarrow (SA is S)

P': (SC is FG)

Now the result can be displayed by the software as follows:

![Angular Fuzzy Set Model](image)

Figure 6.6: The figure shows the result of example 1

The Figure 6.6 displays the result which is ‘Between Fairly Good & Fairly Unsafe’.
Example 2:

Consider another example in which the user, based on his own experience and education thinks that if the soil condition is Poor (P), then safety is “Very Unsafe” (If SC is P, then SA is VU). The user makes a site visit and finds that the actual soil condition on the site is Very Poor (VP). From this available information on the condition and the rule the software will give the overall condition of the trench. The above proposition can be represented by the following:

\[ P: (SC \text{ is } P) \implies (SA \text{ is } VU) \]

\[ P': (SC \text{ is } VP) \]
Now the result can be displayed by the software as follows:

The Figure 6.7 displays a result which is 'Between Unsafe & Very Unsafe.'
Example 3:

Consider another example, example 3 in which the user, based on his own experience and education thinks that if the soil condition is Very Poor (VP), then safety is “Very Safe” (If SC is P, then SA is VS). The user makes a site visit and finds that the actual soil condition on the site is Very Good (VG). From this available information on the condition and the rule, the software will give the overall condition of the trench. The above proposition can be represented by the following:

P: (SC is VP) ⊃ (SA is VS)
P': (SC is VG)
Now the result can be displayed by the software as follows:

Figure 6.8: The figure shows the result of example 3

Figure 6.8 displays the result which is "Absolutely safe". This shows that if a wrong rule is selected by the user then the software would not notify the user for the wrong
selection of the rule. Instead, it will display “Absolutely Safe”. This means that the user is completely on the wrong track in selecting the rule and needs to change the rule, or that the site condition he has entered in the software is wrong.
CHAPTER 7

ADVANTAGES AND DISADVANTAGES OF THE DIFFERENT MODELS

7.1 Introduction

This thesis discusses three different fuzzy logic models. Each of these models helps in evaluating the overall safety performance of a trench. The models, prepared in the visual basic software, depend on the fuzzy set concept. All of these models have been discussed in detail in the previous chapters. The purpose of using three models is that each of these models has advantages and disadvantages associated with it. It is important that the user learn about the advantages and disadvantages of the software before they start using the models. The purpose of the following discussion of the advantages and disadvantages of the models is that the user can be aware of the features that comprise of the advantages and disadvantages of the models in making the decision of which of the models will be preferable for him.
7.2 Advantages and Disadvantages of the Translational Model

7.2.1 Advantages

The advantages of using the translational model are as follows:

The user has to select the appropriate enabling and triggering conditions. Thus the user does not have to evaluate these enabling and triggering conditions and make a decision as to whether the condition of the trench is safe or unsafe. Another important feature in this software is that the user does not have to select his set of rules. Both of these points turn out to be advantages when the user is not experienced or sufficiently competent in the field of trenching. Many times, the trenching is done by general contractors when they have to install piles or footings. They follow all the rules and regulations of OSHA, but they are not competent and enough experienced to evaluate the enabling and triggering condition by themselves. They fear hiring an expert because this requires a significant amount of money. In this case, the general contractor thinks that if he follows all the rules and regulations of OSHA, then the trench accidents cannot occur. However, this is not always true. There might be a case when there is rain, snowfall, or flooding at the site, and the contractor or the competent person does not have enough experience to evaluate the overall condition of the trench. At that time, the translational model would be a great help. In this software, the user, who might be the project engineer, the project manager, a competent person, or the site supervisor can just make a
site visit, note down the various enabling and triggering condition mentioned in the software and click on ‘result’. The enabling and the triggering condition mentioned in the software were selected by referring to the various trench accident cases and reading the report of the factors that contributed to the trench collapse. The enabling and the triggering conditions included in the translational model software are the main factors that have caused trench collapse in the past and can cause the trench collapse in the future. The author’s own experience in the field of excavation also played a role in selection of the enabling and triggering causes. Once the user clicks the “result” button, the software gives the overall safety of the trench in a graphical format. The software also describes the safety of the trench as a text message in the text box. Thus, if the user has no understanding about reading the graph, the performance displayed in the form of text helps him to understand the condition of the trench and take the necessary steps. Another advantage of the software with the translational model is that if the user feels that there is an error in the result displayed, he can click on the matrix button on the software, and a new window is opened which shows the 11 x 11 matrix with the enabling condition, the triggering condition and the multiplication of the enabling and triggering condition. Thus, from the values printed in the matrix and from the reassurance of the matrix products, he can understand the logic behind the final result.
7.2.2 Disadvantages

The disadvantages of the translational model are as follows:

With the translational model, the user has to select from among the enabling and the
triggering conditions listed in the software. Even though the enabling and the triggering
conditions included in the software are the most common causes, they do not cover all the
enabling and the triggering conditions that affect the soil safety. Covering all the enabling
and the triggering conditions in the software is not possible. Thus, the user has to analyze
only those enabling and the triggering conditions that are mentioned in the software.
Moreover, the user does not have command of selecting his own set of rules according to
his expertise. The membership value for each and every cause is fixed and it cannot be
changed by the user.

7.3 Advantages and disadvantages of the Rotational Model

7.3.1 Advantages

The rotational model is the second fuzzy logic model used in the thesis. The
advantages of using the rotational model are as follows:

When a situation occurs where partial matching of a condition is required the
translational model fails to provide the answer. In such case, the \textit{modus ponen deduction}
technique of the rotational model can help the user evaluate the partially matching conditions associated with the trench. Moreover, the user does not have to go through the trouble of entering each and every enabling and triggering causes associated with the safety of the trench. Instead, the user can just make a site visit, look at the enabling and triggering factors, and decide whether the condition that he saw can be considered as very poor, poor, fairly poor, fairly good, good or very good. Here, the user is also given a chance to prepare his own set of rules according to his expertise. Thus, the user can create his own set of rules and evaluate the enabling and triggering conditions according to his expertise. Once the user does that, the rotational model gives the overall safety of the trench in a graphical format. As compared to the translational model, it has the advantage that the user takes the command of the decision concerning rules. Moreover the user can evaluate all the enabling and the triggering conditions that he thinks are important to the trench safety. Thus, the user can make his choice for the enabling and the triggering condition instead of having to select from among the specific enabling and triggering conditions mentioned in the translational model. One more advantage of the rotational model is that if the user tries to enter a trench condition which is not consistent with the rule that he selected then the model gives an undecided condition result. It also displays the message which says that the user (the project engineer, site supervisor or project manager) should check the rule. If he did not make any mistake in the selection of the rule, then he has to make changes in the site condition so that it will correspond with the rule. This is helpful when the user, by mistake, selects a set of rules which is not relevant
to the site condition. If the model displayed a result based on this erroneous selection, the user would get a wrong overall condition of the trench. If the user followed the guidelines for this condition, this might cause the fatality of the trench, which according the model should not happen.

7.3.2 Disadvantages

The disadvantages of the rotational model are as follows:

The user has to select his own set of rules according to his expertise in the field of trench excavation. He also has to evaluate the various enabling and the triggering conditions of the trench and decide whether the overall condition can be considered as very poor, poor, fairly poor, fairly good, good or very good. Many times, the project engineer or the site supervisor involved in the trenching operation is not expert enough to make the right decision. Evaluating the condition incorrectly gives a wrong result, thus making the software not useful. Moreover, when the user selects a set of rules which is not appropriate for the site condition, the software gives the undecided condition result. Thus, if the user wants to evaluate the trench condition with the opposite set of rules, it is not possible with the rotational model. For example if the user selects the rule for the “poor” soil condition and wants to obtain the safety of the trench for a “very good” trench condition, the software result displays the “undecided” condition with a message to the project engineer to check the rule or to improve the site condition.
The result looks like this:

Figure 7.1: The rotational model showing the undecided condition
7.4 Advantages and Disadvantages of the Angular Model

7.4.1 Advantages

The third and final model discussed in the thesis is the angular model. The advantages of the angular model are as follows:

The angular model only depends on the angle for the final result. It allows the user to take command over creating his own set of rules and creating his own enabling and triggering conditions to determine whether the condition of the trench should be considered very poor, poor, fairly poor, fairly good, good or very good. It has an advantage over the rotational model because, even if the user enters a rule that is inconsistent with the site condition, it produces a result, which means that if the user selects a rule for fairly poor and wants the overall safety of the trench for a very good condition of the trench, it is possible using the angular model. A relatively simple calculation procedure is required to perform the operation. The same is not true for the rotational model. In this model, if we try to enter a trench condition which is inconsistent with the rule, the “undecided” condition result is displayed.
The disadvantages of the angular model are as follows:

The user has to select his own set of rules according to his expertise in the field of trench excavation. He also has to evaluate the various enabling and triggering conditions of the trench and decide whether the overall condition can be considered as very poor, poor, fairly poor, fairly good, good or very good. Many times, the project engineer or the site supervisor involved in the trenching operation are not expert enough to make the right decision. Evaluating the condition wrongly gives a wrong result, making the software unreliable. Moreover, when the user selects a set of rules that is not consistent with the actual site condition, the angular model displays a result. Taking action according to this result can be harmful when the user by mistake has selected the wrong set of rules. The software model does not give the undecided condition, instead, it gives a result, which in certain cases can prove dangerous and lead to trench fatality. For example, if the user by mistake selects the set of rules which is for the poor condition of the trench instead of the set of rules for the very good condition of the trench, the angular model displays a result which may not be the accurate one.
The result looks like this:

![Angular Fuzzy Set Model](image)

Figure 7.2: The angular model result with an opposing set of conditions
Moreover, another disadvantage of the angular model is that when the user selects the exactly opposite condition for evaluation, the condition reaches infinity or negative infinity. A sample calculation is shown below:

\[ \tan \tau_B = \frac{\tan (\text{Very Unsafe}) \tan (\text{Good})}{[\tan (\text{Poor}) + \tan (\text{Good})]} \]

\[ = \frac{-2.41 \times 1}{[-1 + 1]} \]

\[ = \infty \]
The result looks like this:

![Angular Fuzzy Set Model](image)

**Figure 7.3:** The angular model with exactly opposite rule and soil condition
CHAPTER 8

SUMMARY, CONCLUSION AND RECOMMENDATIONS

8.1 Summary

This thesis discusses the various losses associated with trench accidents and fatalities. It describes the various enabling, triggering and procedural events that cause trench fatality. It has also shown statistical data concerning trench accidents with respect to hours of operation, the months of occurrence, the depth of the trench excavation, the geographical location and the age of the workers. This discussion is important because it creates understanding of the importance of the study and has been helpful in developing a solution to the problem. The thesis continues with a brief discussion on the three fuzzy logic models which can contribute to the evaluation of the overall performance of a trench in terms of safety. The three fuzzy set models discussed in this thesis are: (1) The Translational Model, (2) The Rotational Model, and (3) The Angular Model.

The translational model follows the non-deterministic possibility approach, which involves a subjective appraisal using qualitative data. The deterministic approach cannot be used because it requires specific data related to the trench collapse. As there is not a
fix cause of trench collapse, this approach cannot be used. The translational model helps to transform the linguistic terms into mathematical representations. This translational model allows the user to select from among various enabling and triggering conditions listed in the software, and the software displays the result for the overall safety performance of the trench in a graphical format. It also displays the performance result in the form of a text message. There is a special feature for the user, which allows the user to click on the matrix button and for an 11 x 11 matrix display of the enabling event, the triggering events and the product of both the matrix of these events as the final result.

The rotational model is based another fuzzy set concept which helps in evaluating the safety of the trench. The knowledge based expert system (KBES) is used to develop the rotational model. This knowledge base helps to acquire the information from experts, historical or experimental data or other sources. The fuzzy set concept is then used to quantify the linguistic terms for the variables associated with the site conditions, which helps to create the rules. Thus, in the rotational model, the user according to his expertise can create a set of rules according to his expertise to find the overall safety of the trench.

The third model discussed in this thesis is the angular fuzzy logic model. The angular fuzzy logic model can be applied to fuzzy modus ponens deduction techniques and in relation to this technique, the fuzzy logic operations such as the truth functional modification and inverse truth functional modification can be employed. The angular
model depends totally on the angles so it is possible to solve the conditions numerically. Because of this the angular model is easier to interpret. The software allows the user to select a set of rules and the actual site condition he observed on the site. Once the data is entered and the "Result" button is pressed, the software displays the overall performance of the trench in angular format.

Each model has particular advantages and disadvantages associated with it. The advantages and disadvantages of each model are briefly discussed. The user (the site supervisor, project manager, project engineer or the expert) can refer to the advantages and the disadvantages of each model and decide on the model that he thinks is the most suitable for him.

8.2 Conclusion

Most trench collapse cases have been attributed to the existence of enabling and triggering events. The conventional deterministic and non-deterministic probabilistic approach in assessing trench condition seems to be impractical and insignificant since a considerable amount of subjective information is used during the evaluation of the trench condition. Since qualitative terms are frequently used in evaluating the trench condition, the fuzzy set concept can be employed to translate these terms into quantitative measures. The three fuzzy logic models developed in this thesis will help determining the overall safety of a trench. All of these models are based on the fuzzy set concept. These methods
can be used to assess the trench condition and prevent trench collapse. The model has a significant benefit for users (the trench inspector, supervisor, foremen, project manager, project engineer, and others), who can determine the overall trench condition without understanding the complex fuzzy set theory.

This thesis has shown how one may assign specific terms and their membership values to review the overall performance of a trench, the frequency of the external events that could trigger a trench collapse, and their consequences. Manipulations of these values results in an assessment of the overall performance of the trench, which can be used to determine the trench’s safety. If the overall performance of the trench is found to be inadequate, the enabling and triggering factors can be reviewed and improvement in specific area(s) can be suggested. Further manipulation can then be undertaken to modify the assessment of the overall trench performance.

The software is a new reliable way to find the safety of the trench. By using this software, it becomes easy for the project engineer or the site supervisor to evaluate the trench safety. It takes a few minutes to find the safety of the trench; even if the site supervisor or field engineer gives a call to the project engineer to narrate the site condition the project manager from his office can find the safety of the trench and take necessary action based on the result. Looking at the reports of trench fatalities and the death of the workers was necessary in the development of a method that is easy for the
user to operate to find the overall condition of the trench. The fuzzy logic concept used in
the thesis is the best concept for evaluating the linguistic terms. The aim of this thesis is
to make it possible to avoid the death of workers and the direct and indirect losses
occurring to the company as a result of the trench accidents. This is a step towards
making the construction industry a safer place to work.

8.3 Recommendations

There is scope to expand the current study by evaluating more cases and making
corrections in the software to make it more compatible and user friendly. Future
advancement can be made by evaluating unique and extreme trench conditions and then
making the software compatible with that type of condition too. The software still
requires that the site supervisor or the competent person make an evaluation based on the
linguistic terms associated with trench collapse. Often, the competent person is not
knowledgeable enough to evaluate these linguistic terms. Thus, the advancement can be
made, by providing theory explaining which types of conditions can be considered
“Safe”, “Very Safe”, “Fairly Unsafe” and “Unsafe”. Thus, even if the user does not have
enough knowledge about evaluating the trench, the detail explanation would help him in
determining the appropriate linguistic terms.

In the same way the fuzzy logic models can be used for developing software for other
types of accidents similar to accidents related to the trench, for examples accidents
related to electrocution, scaffolding, formwork erection, and concreting. Assessment of all these operations is done using linguistic terms. Thus, this fuzzy logic models can be of great use to evaluate the safety associated with all construction activities.

Based on the referrals to the cases of trench accident and review of the reports by experts, it seems that more safety rules and regulations should be introduced in term of trench excavation. The safety rules and regulations should be developed by study of the various trench accident cases to determine the factors that cause the trench collapse. Along with the development of new rules, care should be taken that these rules are followed by all the construction companies. For this purpose the regular inspection should be arranged by OSHA.

There is no fixed rule for the competent person who is employed to ensure trench safety. When four or five trench excavations are going on at a site, only one competent person is assigned to inspect all the trenches. This makes it virtually impossible for the competent person to take great care and give his attention to all the trenches equally. This especially affects the situation when there is heavy rain or snow at the construction site. Continuous inspection of the trenches is required at that time, which is not possible for one competent person. So a specific rule regarding the assignment of the competent person is required.
LIST OF REFERENCES


