A NEW PREDICTION AND PREVENTION APPROACH FOR TRENCH EXCAVATION CAVE-INS

By

Krupesh S.Kakkente

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Construction Management

2012

ABSTRACT

A NEW PREDICTION AND PREVENTION APPROACH FOR TRENCH EXCAVATION CAVE-INS

By

Krupesh S.Kakkente

Existing safety protocols imposed by OSHA are supposed to reduce the accidents; however there are high risk factors associated with trench excavations. The thesis explains the reasons for existence of hazards and injuries due to the lack of a predictive and preventive application in the field of trench excavation. The research aims to explore trench cave-in patterns and understand how to prevent accidents by implementing finite element method. Trench cave-ins are simulated and the patterns of failure are seen. A new protocol for trench excavation is proposed and a proof of concept using systems dynamics approach is also developed to evaluate the impact of implementing a new safety program within a construction company.

Keywords: Trench Excavation Cave-Ins, Finite Element Method, Systems Dynamics, Safety Program.

To

most important of them all, Mom, Dad, and little Sis.

ACKNOWLEDGMENTS

Truth be told, one could hardly ever ask for a friendlier and mentor of a supervisor than Dr. Armagan Korkmaz. The relentless effort put into the thesis by him supported me through the very beginning concept of this project until the very end, made it a project that was both very dear to him and myself. I would like to thank Dr. Sincem Korkmaz for having a nurturing demeanor towards my ideas and introducing me to Dr. Armagan Korkmaz who shared my excitement for Finite element sciences. She pushed me to refine and perform research in a disciplined manner, for which I will always be grateful.

I would like to sincerely thank Dr. Tariq Abdelhamid for inviting me to the Construction Industry Research and Education Center (CIREC) at MSU. I am thankful for all the support which helped me through tough times personally. Special thanks to Ankur Desai, Naveen Nerwal and Don Schaffer for helping focus on my vision through the writing of this thesis and helping make the time at CIREC a wonderful one. I am thankful to god for giving me the most loving family, who have helped me to stand where I am today. My loving mother and father who stopped at nothing to give me the best there is, while my adorable little sister who supported and encouraged me to work hard and live happily at every stage of my life. Great friends who stepped in at all the times both good and bad for me, and inspired me to be sucsseful- Rahul and Kavitha . And finally a shout out to Guarang Shrikhande for helping through the inception of the idea till the very end in helping with editing the thesis. Thank You.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction

1.1 Overview

The construction industry, with 7.2 million wage and salary jobs and 1.8 million self-employed, was one of the Nation's largest industries as reported by the United States Department of Labor (BLS, 2008). Earnings in construction are higher than the average for all industries. Construction also offers the opportunities for individuals who want to be self employed. Construction is one of the most lucrative and prospering industries worldwide; however it is also one of the most hazardous in existence. As reported by the European Union Statistical Information Instititution construction is the most land based work sector after finishing industry (Eurostat, 2010). Data from the U.S. BLS show that many construction trades workers experienced a work-related injury and illness rate that was higher than the national average. Table 1.1 shows the rate of accidents that have been caused only due to excavations and trench cave-ins (BLS, 2008).

Table 1.1: Deaths Due to excavations and trench cave-ins (BLS, 2008)

Year	Deaths
2001	36
2002	34
2003	48
2004	41
2005	44
2006	28

Occupational Safety and Health Administration (OSHA) identifies trenches as one of the most hazardous construction work conditions. The usual conditions under which the person dies as determined by the investigations is mainly due the soil pressure that bears over the chest of the construction worker, which prevents the chest from expanding and contracting, resulting in death due to suffocation. 1.5 m^3 of soil can weigh between 18kN to 27kN; Soil burying a person under these pressures can kill the worker in less than 3 minutes (Landscape Management, 2009).

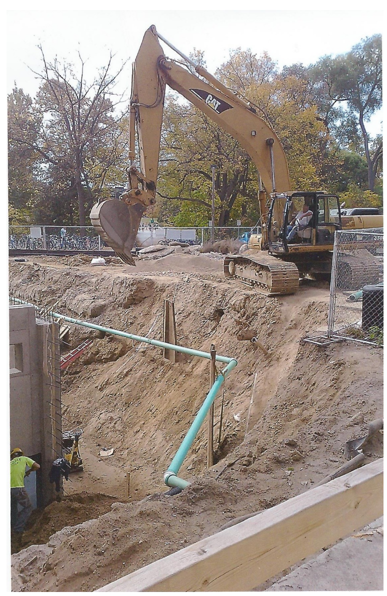


Figure 1.1: Trench Soil Cave-in "For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of

The costs arising against a contractor in the event of such hazards are tremendous. Generally trench excavation contracts are subcontracted by small size landscape service or utility firms who can run out of business with any such occurrence of fatalities to their workers. In the occurrence of such an accident, the contractor will have to bear the costs of OSHA investigation and legal fees; in addition he should be faced with increased insurance premiums, loss of time, increased costs of repair to the construction, the need to hire new workers and train them and potential loss of customers. OSHA has safety programs for proper execution of trenching work; however it is found that in many instances injury and death still occur in spite of such programs. The need for a methodology to predict such hazards and help save lives and help small size construction companies to grow has risen.

1.2 Research Rationale

The lack of effectiveness of current safety programs is identified within the thesis. Most of the trenchc excavation cave-ins have been identified to occur due to lack of implementation of required types of shoring methods to prevent soil cave-ins. Since the contractors performing excavation jobs are often tied up critically to their limited funds and low bids; they avoid the implementation of required safety conditions and shoring systems to maintain profit margins. The goal of the research is to recognize a tool which can foster safety in trench excavations by predicting the trends of trench failures and developing a guideline to make it easy for adoption by the construction crews. The thesis helps to realize a relatively easy-use tool which can help predict soil strata behavior during the execution of a trench excavation and to prove the usefullness and ease of implementing finite element method as a an effective tool for safety programs in trench excavation. A benefit of using the finite element based safety program is that it can provide for protection against legal claims in occurence of accidents.

FEM is used in geotechnical analysis and predicting soil behaviors. FEM has been extensively applied to the tunnel construction fields. FEM is also accurate in simulating in situ stress states, fluctuations of shield pressures, changes in construction process, and deformations of ground surface due to tunneling exercises (Ongsuksun et al., 2009). To provide an average excavation contractor with a relatively easy method to perform static soil prediction simulations of subsurface conditions in a trench is the ultimate goal of the current research. The result will be a process which can involve a preliminary investigation of the site, transferring the results of the site investigation into a finite element prediction tool. The tool enables prediction of excavation cave ins that may occur due to the trenching operations, live weight soil pile placed around the trench, the vibrations occurring onsite due traffic of trains and also due to changed conditions of rain storms and existence of high water table at site. The thesis focuses on understanding causes of trench excavation soil failures and methods predicting these failures for prevention.

Systems dynamics (SD) simulation was the solution first invented in 1950 by Forrester to solve the problems of dynamic complexity (Davis and O'Donnel, 1997). The concept of dynamic complexity can be explained as the unintended results that occur as a result of simple interactions or decisions but have the most counterintuitive results. Most companies and managerial teams have fallen prey to the occurrence of dynamic complexity as very though out decisions have yielded promising results in the short term, but over the long run the same system yielded to failure. Dynamic complexity arises not from the factors in the system that affects the end user but they way in which the factors related to each other (Davis and O'Donnel, 1997).

The reason for opting SD in the thesis is to understand how the implementation of new safety protocol can affect the change in working of a construction firm related to majorly trench excavations. Organizational safety culture, especially its definitions, dimensions, and enablers, as well as the development of tools for assessing and monitoring its health, have been give due importance in the recent years in order to identify areas for safety performance improvement (Choudhary et al., 2007). The lack of importance to such factors have caused sufficient risk and fatalities to human lives. Sherif and Chinda (2011) designed a causal model to simulate the interactions and relationships among Construction Safety Culture (CSC) enablers, as well as the potential impact of each enabler on safety goals over a period of time. The model with the help of other systems dynamics models could be tailored to suit the needs of the research.

1.3 Research Objectives

The present thesis aims to provide the following as the results for the construction industry:

1) 1) Realize the Computer program which can be used to predict trends in trench excavation cave-ins.

2) Organize a methodology to help the easy adoption of the prediction strategy in the industry by the construction crews for trench excavation safety.

3) Analyze the risks associated with implementing a new safety protocol and understanding the implications for the construction firms.

1.4 Thesis Overview

The thesis involves 7 chapters. In the first Chapter problem statement is laid out. The research rationale helps further the transition of the problem into understanding briefly how the problem is reallly justified; and how it is aimed to help the construction industry become a safer place.

The literature review covers the grounds on aspects of the thesis. Related research works are divided into modules for easier flow and transition of the paper.

In Chapter 3, the approach to solve the problems as outlined in the thesis are detailed in here. The steps taken to model a simple trench cave-in under homogenous conditions are also included within the chapter

In Chapter 4, FEM simulations which predict the failure of soils when not being safely executed are compared with Benched Trenches in FEM- ABAQUS models for verification. The results prove the effectiveness of simulating trench conditions.

In Chapter 5, implementation of FEM approach in safety program is a need for safety programs implemented on a regular basis in the construction industry. The change need to be brought up requires the various team players associated with trench excavation.

Chapter 6 helps to understand the impact of the behavioral change in an organization that could occur with the implementation of a new safety program.

Chapter 7 summaries the goal and objectives and achieved results of the thesis. The future recommendations are also given here.

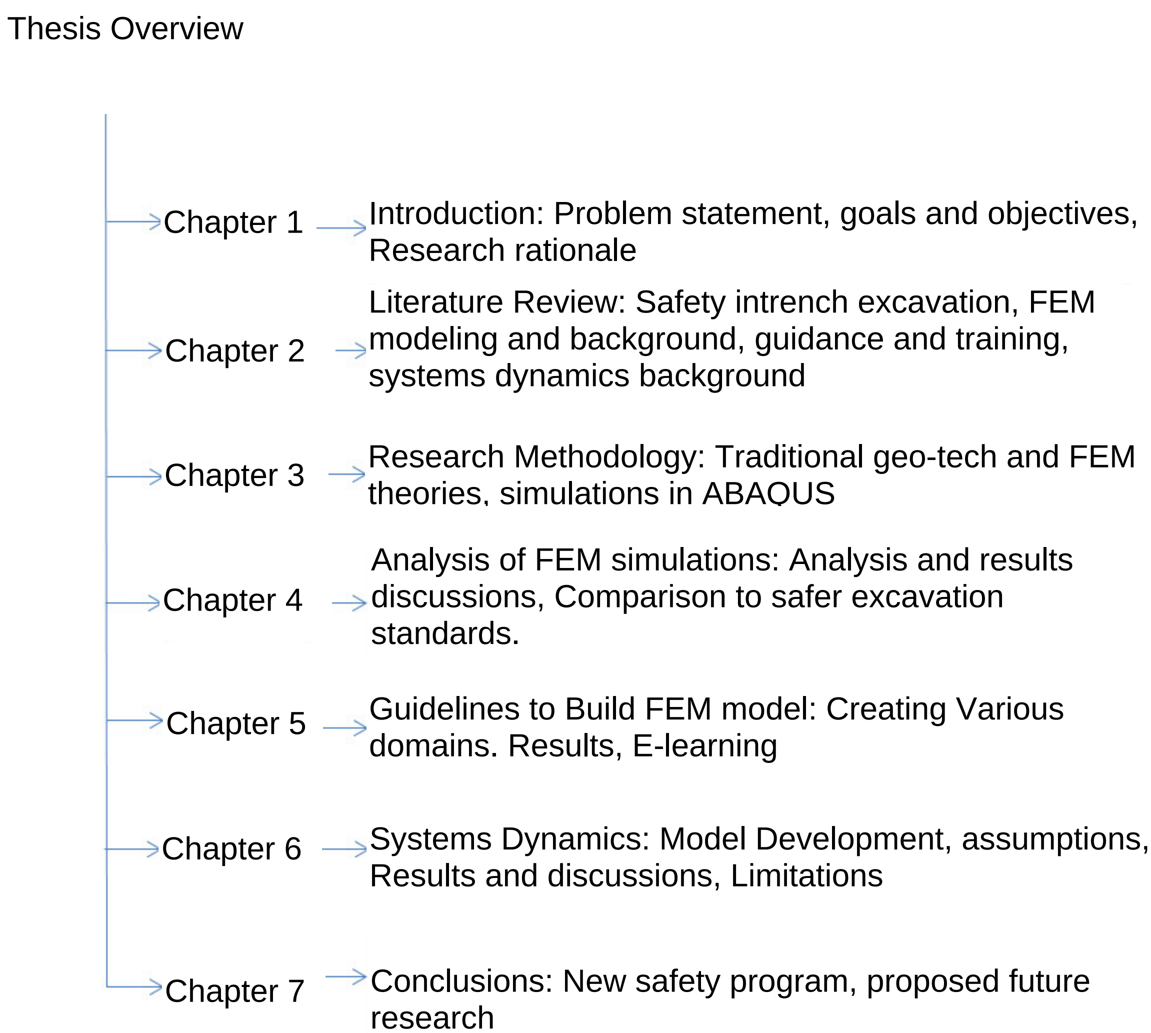


Figure 1.2: Thesis Overview

Chapter 2

Literature Review

Chapter 2 outlines the literature review conducted in order to identify the various factors that owe to unsafe conditions in the trench excavation sequences of construction. In the chapter, the finite element method, its applications and backgrounds are provided. Implementation of new strategies or policies that can change organizational behavior is discussed. In the thesis, current practices and existing knowledge are the foundation upon which new FEM based approach is developed. The traditional geotechincal conspets and FEM concepts which have been used in the research are included in the chapter three.

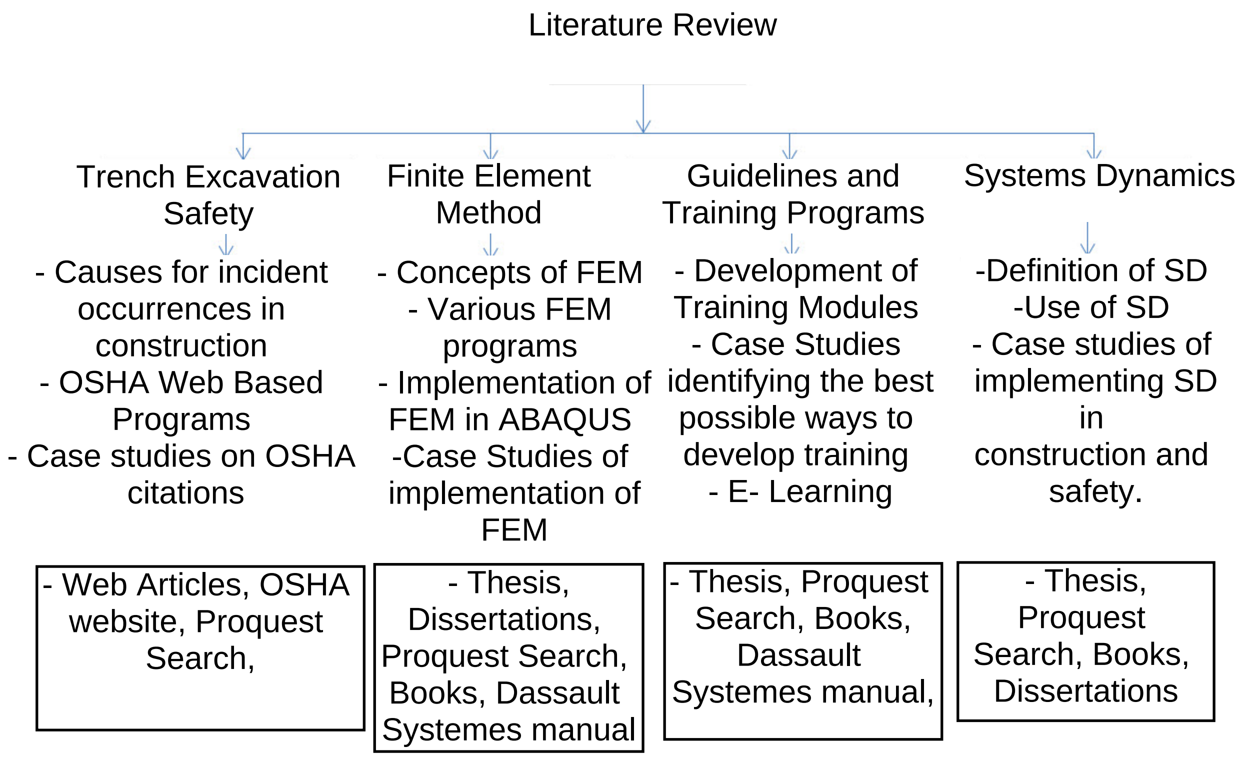


Figure 2.1: Frame-work for Literature Review

2.1 Safety in the Construction Industry Focusing on Trench Excavations

Construction safety researchers have postulated several accident causation models which cite the reasons for hazards and their occurrences. Some of the root causes, as identified by Abdelhamid and Everett (2000) are management deficiencies, workers' attitude and training. The element of unpredictability of the subsurface conditions also mounts to a significant amount risk to the construction work. For example the work that is expedited in the onset of a rainy day can lead to various unpredictable subsurface conditions that can change due to the increased rate of excavation and piling up of large amount of soil along the trench lines.

The use can be easily given as an example to cause a cave in and can endanger the lives of the workers inside the trenches. Another potential threat of cave-ins has been observed in case of deep trenches being excavated along road pavements and along railway tracks (GIT, 2010).

OSHA has designed a web based Training Program. NIOSH Trench Safety Awareness (2010) illustrates the four types trench collapse. Although many of these programs allow to understand the reasons and safety precautions to follow in the event of a cave in; none of them can help predict any of the types of soil collapses on the site. Death toll has far exceeded the numbers it should have ever reached as of today.

Research conducted by Arboleda and Abraham (Carlos and Abraham, 2004)found that ”When cave-ins occurred, 49% of the fatalities occurred in projects with costs under $250,000 and 73% of the fatalities in projects with costs under $1,000,000. Also, 31% of the accidents occurred in projects with fewer than 10 workers and costs under $250,000, i.e., when the project is smaller, the likelihood of a trench cave-in is higher”. The research provides sufficient evidence as to why most excavation contractors fail to follow the OSHA safety requirements while performing trench excavations and it can be inferred that an inexpensive tool to predict such hazards of cave-ins during excavation can prove to significantly reduce the everlasting death toll.

U.S. OSHA has stated that ”Without training a person cannot possibly be qualified for to supervise trench and excavation work” (Prentiss, 2004). It falls to the management to get the appropriately trained personnel to maintain a safe working site. OSHA also requires a supervisory member of the excavation team to have an 8 hour course that may vary based on experience. The training consists of modules that inform the personnel of hazards associated, the probabilities of being buried alive and the causes due to which trench cave-ins occur. However they are not well equipped with a method to predict such hazards in spite of the training. The training and safety protocol if followed in detail may in fact help avoid a large number of such incidents; but, it is because of becoming complacent in a work environment which leads to instances of lack of needed attention to detail at trench examinations for cracks.

The human tendency to become comfortable at a work environment is a very dangerous reason for many construction accidents. The situation needs a major behavior modification in the work force, which is not a logical attainable solution. Hence the alternative is to have computers come to the aid of mankind and help monitor such situations and predict them.

OSHA Reported Incidents and Implications are complied below as three case studies.

2.1.1 Case study 1

The event of an incident OSHA takes up to six months for its investigations, levying fines of up to $7,000 for hazards an employer should have been aware of or $70,000 for willful disregard of or indifference to regulations. The agency's inspectors are also told, while on route, to various locations on the job to stop and check out any work sites they pass with signs of trench work that lacks proper shoring (Rotstein and Gary, 2004). Another Heavy violation was cited and fined $510,750 for inadequate trench safety. Such incidents afore mentioned can easily put construction companies of mid size completely out of business therefore reinforcing the requirement of an innovative and cheap means of predicting trench cave-ins.

2.1.2 Case study 2

July 27, 2006 a trench cave-in occurred at Christiansburg, Virginia when two workers who were working for construction company got into a trench where no safety precautions were taken. The company said the workers were preparing to connect a new sewer line to an existing one. The existing line was busted, however, and water began filling the trench. One of them who has been doing site work for 30 years, jumped into the 3.5 m deep trench to try to set a pump to get the water out, company declared that the employees just got excited (Shawna, 2006). This statement simply shows the unnerving implications of worker's complacency on jobsite can have for the human safety.

2.1.3 Case study 3

OSHA's national statistics report an average of 30 to 50 cave-in deaths annually. it was maintained that the numbers are hardly a fraction of the actual incidents that occur every year; while these numbers could very well be three or four times higher (Shawna, 2006). In owner of a concrete company was operating a backhoe and managing the excavation for a new sewer line. Two employees were laying sewer pipe in an unprotected excavation approximately 2.5m deep and 1.5m wide. The sides of the excavation were nearly vertical. As the owner was digging the trench, he placed the spoils along the north edge of the excavation. Prior to the fatal collapse, two employees were in the trench when soil broke loose from the north side and they had to run toward the east end of the excavation to avoid being buried by a cave-in. They narrowly escaped being buried in the soil. They cleared up the soil and continued to work and nearly 10 minutes after resuming the work another cave-in occurred burying the two workers. One of the employees was killed in the accident and the other worker was seriously injured. The company received a combined total of three alleged willful violations with a proposed penalty of $99,400 and two alleged serious violations with a proposed penalty of $4,200, for a total proposed penalty of $103,600 (US Fed News, 2011).

2.2 Finite Element Method

The literature presented below shows the potential of implementing FEM approaches to predict and prevent trench cave-ins. One of the previous researches conducted has been to predict subsurface soil behaviors for tunneling projects that led development in numerical techniques which have been successful in simulating the sub-surface conditions in 3-D. Successful verification of the FEM simulations is carried out in a centrifuge model (Meguid et al., 2008). The numerical method that has been proved to be most effective in such simulation and predictions is FEM.

One such application of FEM has been used to predict slope stability (Swan and Seo, 1999) for heavy geotechnical construction related problems and to prevent hazards that could occur due to heavy downpours and changing water table conditions that could put roads and transportation related projects into jeopardy. Different types of soils and moisture conditions prevailing in these soils have different stress-strain properties. Hence it becomes highly difficult to model all these different types of soil behaviors and help predict their failures during a trenching exercise (Adhikary Guo, 2009).

ANSYS (2011) integrated civil FEM module is used in the research studies for predicting soil behaviors and the performance of trench excavations (Xiujuan et al., 2008). The studies use the soil's modulus of elasticity and Poisson's ratio of the proposed site in order to model the settlement that could occur on the event of construction of the oil tank and also the settlement that could occur due to filling up of the tank by using ANSYS civil FEM. Once the soil deformation was studied, the simulation offered results on how to design and build the tank. Another research conducted by Xi cites the use of ANSYS to simulate the seepage flow or subsurface flow of water through soils (Xi et al., 2008). Xi's study serves as a good resource of information to predict the movement of ground water and its effects on soil properties.

The finite element method is used to obtain values of stresses developed within the structure, on the nodes of each FE. In FEM, the system is meshed in finite members instead of driving equations. The meshed members are solved considering the entire system. The accuracy of the stress output is related to the FE meshing and the density of the realized grid. The boundary conditions of members are superposed to form the equations in the matrices in the system. In Figure 2.2, the continuous system can be seen (Bathe, 1967; Zienkiewicz and Taylor, 1967).

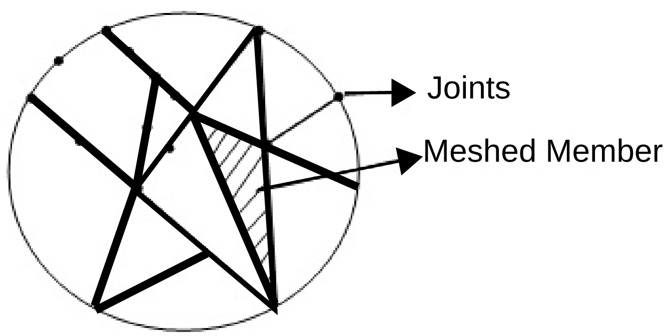
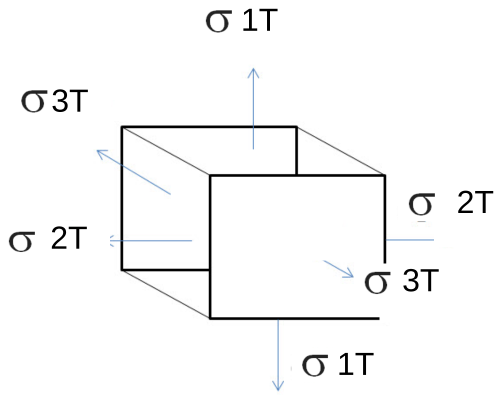
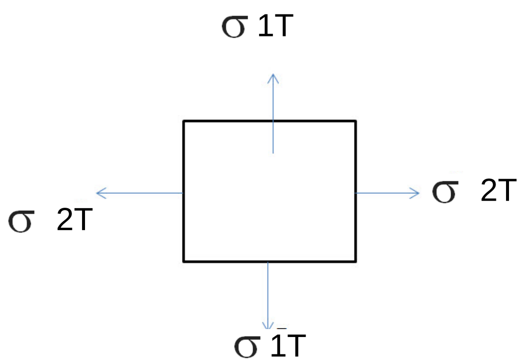


Figure 2.2: Continuous System and Finite Member

Calculation of the effect of the eliminated principal stress on the remaining two was made using the Hooke's law. In Figure the principal stresses are shown for a tri-axial stress state, while in Figure 2.3 its equivalent biaxial stress state is presented after elimination of the principal stress (Syrmakezis et al., 2006).



((a)) 3-D



((b)) 2-D

Figure 2.3: Stress states in 3D and 2D

For a three-dimensional stress state, the strains on plane $(1, 2)$ are equal to(Syrmakezis et al., 2006):

$$\varepsilon_1^T = \left[\sigma_1^T - \nu \cdot (\sigma_2^T + \sigma_3^T)\right]/E \qquad \varepsilon_2^T = \left[\sigma_2^T - \nu \cdot (\sigma_1^T + \sigma_3^T)\right]/E \tag{2.1}$$

$$\varepsilon_1^B = \left[\sigma_1^B - \nu \cdot \sigma_2^B\right]/E \qquad \varepsilon_2^B = \left[\sigma_2^B - \nu \cdot \sigma_1^B\right]/E \tag{2.2}$$

$$\sigma_1^B = \sigma_1^T - \nu \cdot \sigma_3^T/(1-\nu) \qquad \sigma_2^B = \sigma_2^T - \nu \cdot \sigma_3^T/(1-\nu) \tag{2.3}$$

$$\sigma_2^B = \sigma_2^T - \nu \cdot \sigma_1^T/(1-\nu) \qquad \sigma_3^B = \sigma_3^T - \nu \cdot \sigma_1^T/(1-\nu) \tag{2.4}$$

$$\sigma_1^B = \sigma_1^T - \nu \cdot \sigma_2^T/(1-\nu) \qquad \sigma_3^B = \sigma_3^T - \nu \cdot \sigma_2^T/(1-\nu) \tag{2.5}$$

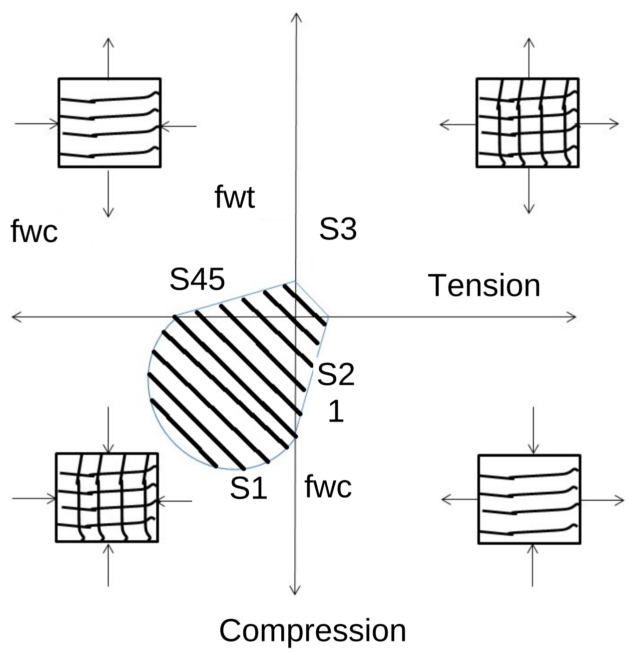


Figure 2.4: The modified Von-Mises Failure criterion

The modified criterion can be expressed in a three-dimensional system, where, plane of direct stresses is perpendicular to the third axis and represents applied shear stresses on the node, resulting in the semi-empirical failure surface, presented in Figure 2.4, for zero shear stress level (Syrmakezis et al., 2006).

Some of the element types used in FE analysis are eight-node brick element (C3D8 and F3D8) C3D8R and F3D8R, Twenty-node brick element (C3D20 and F3D20), Four-node tetrahedral element (C3D4 and F3D4) etc. (Dhondt, 2010). The most common and more accurate of these elements for sweep meshing techniques is C3D20R, a quadratic brick element with reduced integration (2x2x2 integration points). The Figure XX shows the element of C3D20R which is chosen as an ideal element choice for the simulations in the research because of its adaptability to various geometry.

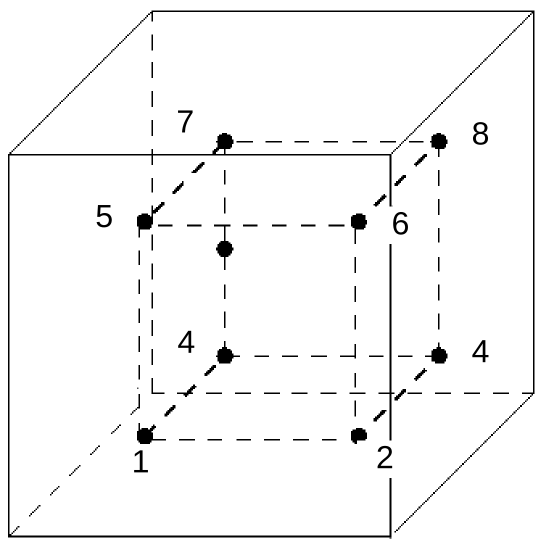


Figure 2.5: 2x2x2 integration point scheme in hexahedral elements

2.2.1 Case studies of application of FEM

There are considerable number of studies available for analysing the danger associated with deep excavations using FEA; however the same implementation in the shallow excavations lacks effort. Bentler et al. (1998) worked one developing adjustments to Sage, a FEM program developed at Virginia Tech for analysis of soil interaction problems. In the process to develop and understand the performance of deep excavation they studied files performances of the excavations for two main reasons. One of which was gain insight into the experiences gained during design and construction of real excavations. The researchers learned that a great deal could be learned about the behavior of deep excavations when careful observations of construction activities, site conditions were made. The second reason was for reviewing field performance variables was to learn about factors that couldn't be modeled analytically. Such findings bring in the understanding of how to approach the modeling of shallow excavation projects.

The literature review conducted brought to light detailed case histories of trench excavation cave-ins of how and why they occurred. Such data provides the insight of how the construction work was being executed prior to the fatalities or unfortunate incidents occurred. The data is critical to understand why the contractors were neglecting the safer practices. Most of the times even though shoring systems are onsite they are not in place where they have to be. Such practices could be taken into account for negligence and model the trenches in FEM as unprotected cave-ins.

Tamano et al. (1991) conducted studies to understand the mechanical behavior of ground heave due to 21m deep excavation in Osaka. The research team developed 2-D FEM models and compared the heave values of the model to the base heave values. The results of the study showed astounding comparability. Significant heave was found to have occurred 50m below the 21m excavation.

Finno et al. (1992) observed the ground movements adjacent to deep excavations made through soft Chicago clay. The research team studied the effects of deep foundation installation, cycles of excavation and bracing, and strut removal on observed movements. The researchers concluded that construction activities can change the stress in the ground and should be taken into account while estimating ground movements. Their findings primarily translated to the understanding that finite element analyses to predict excavation performance are limited by the ability to model construction activities.

Lee et al. (1998) monitored the corner effects on the behavior of a strutted excavation for the immigration building in Singapore. The researchers compared the 2-D and 3-D finite element wall movements and settlements of the excavation site to the field measurements of the same variables and found astounding comparison between the models and the real world measurements. Lee et al found that 3-D analyses seemed to agree more with the field measurements than 2-D analyses.

Finite element analyses may become imperative in conditions where in high-rise buildings exist next to a proposed excavation site. Such a case study was reported by Brassinga et al.(1991) where the team studied the response of a high-rise building next to a braced excavation in soft soils in Rotterdam, Netherland. Significant consolidation was found to have occurred after continuing settlements with the progress in time of excavation process. The researchers concluded that major reason for the consolidation was due to dewatering.

A similar instance can easily occur in steel shored or braced trench wall and the case could potentially mean shift in the braced trench laterally. Although the incident may not cause fatal threats to the workers, however it can impose a significant risk to the construction project itself where a repair work of an existing pipeline can potentially burst or collapse due to the lateral movement. The lateral movement as discussed before can be caused due to the removal of soil and increased lateral pressure from adjoining building.

The literature review for deep excavations follows to show that the following parameters are critical to performing a FEM analysis: type of soil and its mechanical behavior; construction method; construction sequencing; initial soil stresses; ground water conditions; support system; workmanship/ quality of construction; excavation geometry. The Osha Technical Manual (OTM) categorises soil in two four types. Type A is stable rock or cohesive soils with unconfined compressive strength of 144kPa or greater. Type B soils are unstable rock or soils having unconfined compressive strength of greater than 48kPa and less than 144kPa. Type C soils are granular or sandy soils which have a compressive strength of 48kPa or less. Type D is usually made up of layered geological strata.

2.2.2 Modeling in ABAQUS

The ABAQUS program was one of the first FEM programs to introduce an allowance for researchers to add elements and materials models. ABAQUS/Explicit is a special-purpose analysis module that uses an explicit dynamic finite element formulation (Dassault Systemes, 2009). It is suitable for modeling transient dynamic events, such as impact and blast problems, and is also very efficient for highly nonlinear problems involving contact conditions, such as creating simulations and also helps in modeling continuum problems (Tee, 2005).

2.2.3 Development of FEM model to determine earth pressure in trench rescue shoring systems

LaBaw et al. (2009), in their research developed a method to predict the earth pressure in trench rescue operations for the rescue team safety. The team created a 3-D linear elastic finite element model to examine the effects of different trench rescue shoring components on earth pressure. ABAQUS/Standard 6.7 was used to in the parametric studies and also to determine the earth pressure on rigid retaining wall by comparing the model results twit theoretical vertical and horizontal earth pressure. The model accuracy to predict the load transfer of the shoring system through multiple layers of materials and varying properties was also examined.

Half of the symmetric problem was modeled with a 3-D linear elastic model. The model consisted of three parts: soil, panel and strong back. All three parts were assumed to be solid and homogenous with elastic isotropic material properties. The soil was also given a density variable to account for the effects that could arise from gravity. Interaction between the strongback and the panel was locked and didn't allow for any movement.

Internal piston pressure was set at 1378.951MPa, 5171.067MPa, and 10342.9MPa, producing loads on the strut base of 5.8kN, 10.5kN, and 22kN respectively. Meshing in Abaqus assigned 820 elements to the panel, 300 elements to the strongback and 130000 to 140000 elements to the soil. Boundary conditions were only assigned to the soil.

The resulting analysis of the FEM model paralleled the calculated vertical stress and horizontal earth pressures. The FEM analysis brings valuable insight to the methodology to construct FEM models for the goals of modeling trench excavations. The models are built and detailed in the research methodology.

2.3 Guidance and Training Program for Trench Excavation Related Industry Professionals

The literature review so far concludes that the lack of ability to predict trench soil behaviors have been a major cause for majority of the cases of trench excavation injuries and fatalities. The ability to provide such a training program on a large scale industry such as construction would need a very rapid process dispersion of information. In order to achieve such a progression over a wide variety of end users the best means to develop a quick training program would be the method of developing an e-learning and e-training program.

2.3.1 Case study 1

Organizations must continuously learn update themselves to survive in a highly competitive market, such instances is very much seen in most technology driven industries. But in construction where aging knowhow and procedures still seem to precede the latest and most efficient methods of performing construction exist, the need for a faster way of spreading knowledge is critical. With an approximate number of 884,300 construction establishments in the United States as projected by BLS National Employment Matrix, 2008-2018, it is a vast territory to cover for training very quickly. In order to cover the ground of varying ages and localities within the U.S., the internet provides as the easiest source to provide the training across the country. Nivar, (2009) described distance learning as a modality by which instructor and learner are separated by time, space or both simultaneously. In order to keep up with market stiffness and competition and to favor company reputations organizations now expect employees to rapidly gain new knowledge, skills, and abilities.

As a result companies have turned to training that is available at any time required, and unimpaired in time with respect to quality and easy to schedule learning opportunities (Sims et al., 2008).

A key concept extracted from Norman's research work, was that of universal usability; which is an approach that provides a feasible solution to attending instructional design needs for the continuously growing population within the academic and work areas (Norman, 2004). This concept implements a universal design that may include and help accommodate the older and less experienced users and at the same time younger and more experienced users.

"While there is certainly a population that has grown in tandem with technology (touch screen devices, voice recognition devices and others) which are young and computer experienced, there are others that do not share the same common ground and computer experience, the aging (baby boomers and older adults). This disadvantage when combined with a large amount of physical and cognitive declining functions of the elderly, may difficult the adoption and assimilation of technology. Therefore, making questionable the effectiveness and quality of e-Learning and e-training modules for this special age group" (Nivar, 2009). Marcia's research aimed at determining a universal design guideline that can be applied when designing online course for a 25 year old learner and at the same time suitable for a leaner ageing at 65 years. Results of the study aimed at achieving high user satisfaction and information recall, while maintaining low levels of disorientation and task overload. Marcia's research concluded with significantly positive results from the following the approaches of implementing filming techniques employed in the creation of training video primarily affecting the recall capacities for all age groups. Narrative content had the most positive impact. The numerical modules showed inconsistent recall by the different age groups depending on the end user and their backgrounds. Finally the layout arrangements and preferences also had a significant impact on a successful e-training module.

2.3.2 Case study 2

Rene et al. (2004) offered guidelines for a leaner led instruction, the design of learner controlled training, and the creation of workplace conditions which help manifest learner led training. The reason of the researchers to choose e-learning is as a medium of propagating education is because it allows training to reach diverse and geographically dispersed workforce in a cost efficient manner; which is highly a reflection of the construction industry. Also other advantage include where training programs can be structured so that learners have the opportunity to collaborate remotely on training tasks. Also e-learning may be designed so that trainees follow a structured program individually. Learner control refers to a mode of instruction where some decisions are allocated to learner preferences. Learner control as of today has evolved to include instruction design elements, including the content, pacing, context, sequence, method of presentation, task difficulties. These options are previously instructor controlled and the flexibly of these options being available to the diverse e-learning population makes e-learning tremendously successful.

Preparing the trainees for learner led instruction was a major focus of the study where the researchers reasoned that trainees who are given control over their training are often poorly equipped to use that control. The various guidelines leading through the study are understanding learner control, giving the end user enough time to learn, calibrating the expected results and feedback, offering help, understanding the varying needs of the diverse user base and continuously evolving to include all recommendations, designing just the right amount of user control, allowing trainees to skip tasks as needed, Identifying user progress etc.

Effectiveness of the e-learning programs can be impacted by organizational factors, such as corporate culture and incentives. This is because if the organization does not provide a learner led training program the trainees might be reluctant to learn more than that can be anticipated and training programs can be rendered useless. The team also reasoned that following such guidelines might run to be more expensive than that of traditional training programs the learning outcomes might be overcome the costs might be recovered from improved productivity and better skills of the trainees and employees.

2.4 System Dyanmics

Zemke (2001) stated that ”Looking at how systems really work can be enlightening -or a wake-up call” . The corporate culture of most construction companies already incorporate safety in pristine importance. The fatality rate for excavation work is 112 % higher than the rate for general construction. BLS data show that 271 workers died in trenching or excavation cave-ins from 2000 through 2006. Even though the safety protocol implemented and other management decisions made to keep the trench excavations from ever happening, they are from being able to deplete these instances. The use of systems thinking and systems dynamics come into play in such situations, where, even though the corporate decisions made after careful thought and financial risk assessments to stop cave-ins from occurring, they are still faced with risks. The maxim as illustrated above have been attributed various times as an eye-opener to managers who assume that by changing just one part of a complex problem will cure the entire system of its ailments (Zemke, 2001).

Systems dynamics modeling was born at the hands of engineering and management Professor Forrester at Massachusetts Institute of Technology (MIT) in 1950's (Sheriff and Chinda, 2011). The approach of ”systems thinking” takes into account the synergies of human conduct in business, industry, government, community and other such soft but usually ignored factors into systems modeling and applies systems modeling to discover emergent properties or unexpected behaviors from the system's reaction to policy change or other such instances. The reason for such unexpected behavior to arise through these simulations is the length of time the behaviors of the systems is put to test at. The human reaction to systems and policy changes is very difficult to predict and even more so in the construction industry which is extremely diverse, dynamic and highly susceptible to economic downturns.

An organization must be able to highlight the areas for safety improvement to progress iteratively through different levels of cultural maturity (Sheriff and Chinda, 2011). Sherif et al. developed a casual model which aimed not only assist organizations in appropriately assess their current construction safety standard (CSC) maturity level, but also depict the potential effects of the enablers to achieve the pre-determined safety goals. The researchers used Systems dynamics modeling specifically designed to focus on policy analysis and design. The EFQM (2000)excellence model was adopted as a conceptual framework. To study the development of systems dynamics models for furthering construction safety a few cases were studied.

2.4.1 Case study 1

David O'Donald (1997) explained the use of system dynamics a way to look at business, by focusing on what is happening outside the organization and what is happening inside. It is a tool that is updated and in tune with modern concepts of business management with a focus on stakeholder requirements, empowerment of employees and the learning organization while making sure that the decisions are clearly linked to improving the stakeholder value. The process laid down by the research team has four stages and is based on systems thinking. First stage is to create a clear statement of objectives. The team proposed that "sustainable success can only be achieved through maintenance of confidence and support of all stakeholders". The statement has deeper meaning which goes to explain that traditional objectives that meet the requirements of the providers of capital might not be enough in the future to obtain objectives to greet the organization with success.

The second and subsequent stages require that new measures must focus on the factors which lead to success in addition to the measurement of success itself. Hence the second stage creates a map of the dynamic links between business activities and the objectives. The various relationships include cause and effect, delay, feedback etc.

The third stage goes on to map the activities are critical and also identify the key performance drivers. This map is usually a computer generated system dynamics model of the map. The research team postulated that running computer simulations can yield new insights and reveal unexpected limits to growth.

The fourth stage indentifies the ways to develop the measurement of key performance indicators. There are two ways to approach this, one of which is to measure the driver itself, but is seldom possible. The other is to measure the influencing proxies. Careful examination of the influence diagram would help identify these proxies and other variables to be measured.

2.4.2 Case study 2

Sherif and Chinda (2011) investigated interactions among five key enablers of construction safety culture. The team proposed methods for system dynamics modeling of Construction Safety Culture (CSC). The model was developed on the basis that improving the enablers will inevitably improve the safety performance in construction. In reality, System dynamics modeling with the developed index from this research is postulated, to be able to help organizations to plan the most effective safety implementation process to achieve their safety goals within a planned time frame.

The conceptual model is based on the adoption of European Foundation for Quality Mangement (EFQM) excellence model. The model follows the same assumption of the casual model as assumed in the model. Five enablers identified in the study are leadership, policy and strategy, people, partnerships and resources, processes (EFQM, 2000). The approach for the model was to develop safety improvement matrix where a weighted score for each enabler was obtained and then combined to achieve overall score. It is imperative that the approach requires examining the safety culture holistically; otherwise it would be impossible to determine the influence of the enablers. A CSC casual loop diagram was proposed which consisted of seven elements to explain the links between Enablers, Goals and the CSC index.

The sensitivity analysis of the model on close observation of the increasing rate of five enablers' values at early stages discovered that the Lds was the weakest enabler. Hence to expedite the Enablers' value and to achieve higher CSC figures the companies should employ better attribute focusing on bettering the leadership attribute. The researchers concluded that the developed CSC index meets the required goals and objective assist in construction safety improvements.

2.4.3 Case study 3

Owaba and Adebayi (2006) postulated that system dynamics approach helps in evaluating a safety program (SP) performance and allows more complex relationships between elements of the SP (accident causing factors, accident prevention activities and output) and also helps in identifying the dynamic relationships between the elements in addition to just the statistic relationships of the elements. As a part of the study the researchers followed the modeling strategy developed by Forrester (1973) and Burns (1975) to measure SP performance measure. The following steps are religiously followed as part the research: 1. Definition of system boundary, 2. Specification of set of quantities, 3. Delineation of causal diagram, 4. Delineation of flow diagram, 5. Determination of model equations from the diagram, 6.

Implementation of simulation from the model equations using computer program. Using a set of mathematical equations and the influence diagram a software program was used to create a manufacturing safety program simulator.

The developed safety program simulator was applied to a bottling manufacturing company to achieve the objectives of the research study and verify the working of the model. The literature review conducted for the study showed that soft drink industry had the highest rate of serious injuries and illness and the companies continue to be subject to high incident rates due to the labor intensive nature and exposure to hazardous operational condition. Data was collected through sources such as from production clinic, safety and administrative department of the establishment through vetting records, questionnaires and interaction with heads of various departments. Investigations were also carried out to see budgeting allocations committed by the safety department. Direct and indirect cost elements associated to the accidents were also identified. The amount dedicated to the safety programs was discovered to be quite significant.

The model developed consisted of two major parts dynamically linked: 1. Accident causing, 2. Accident prevention. The model was built to understand the dynamic relationships between the elements of the safety program and depict the future trends. The model was able to successfully simulate the safety conditions through the years of 1991 to 2004 and these results coincided with the recorded incidents within the company. The fluctuations in the effectiveness of the SP was majorly due to varying financial constraints of the company over the years due to net profit and was also found to directly proportional to the monetary conditions implemented towards safety programs in the company. The software program used to develop the simulator was Vensim PLE software and the simulator was found to be effective in facilitating the decision making of the planner of SP.

Chapter 3

Research Methodology

Chapter 3 describes the methodology that is used in the present thesis. Three different simulations are developed to show simple cases of trench excavations using the Abaqus CAE 6.9 software program (Abaqus CAE 6.9). The data for the different cases are obtained from a geotechnical website that has a summary of geotechnical soil properties for various types of soil such as very soft clay as shown in Table 3.1, gathered from the US Army Corps of Engineers EM 1110-1-1904 (Robert, 1990). Plaxis 3D is a FEM suite which has the similar capabilities of ABAQUS and would have better suited the research objectives. The use of ABAQUS was fostered by easy availability of the program within the learning laboratories.

Table 3.1: Summary of varios soil properties (Robert, 1990)

Soil Type	Young's Modulus (Es) (kPa)
Very soft clay	480-4,800
Soft Clay	4,800-20,000
Medium Clay	20,000-48,000
Stiff Clay	48,000-96,000
Sandy Clay	24,000-192,000
Clay Shale	96,000-192,000

3.1 Traditional Concepts of Soil Mechanics

In order to understand the parameters required to be input for the FEM simulations and the assumptions made for the same, there is a need to understand the principles of soil mechanics. Stress -strain behavior of soils are governed by two principles namely: the principle of effective stress and the principle of steady state deformation (Poulos, 1989). The effective stress can be explained as the load F transmitted through the soil at a normal direction to the cross-sectional area, A, divided by the area. $\sigma = \frac{F}{A}$

The effective stress principle implies that the pore fluid pressure should have no effect on the stress strain properties of the soil and also that, the strength of un-cemented soils will be zero if the effective stress remains zero. Steady state deformation can be defined as a unique steady state line given for any soil which is the locus of points at which the soil mass can strain continuously at constant: void ratio, shear stress, effective normal stress, and strain rate (Poulos, 1989). The factors that influence stress strain behavior are soil composition, structure, state, loading method. The Figure 3.1 shows the typical stress strain behavior for soils.

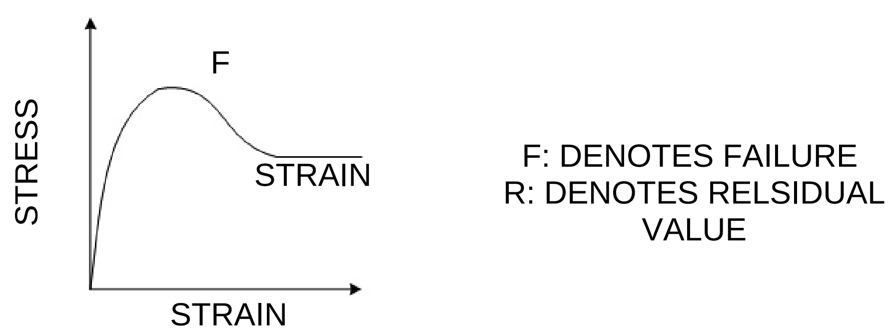


Figure 3.1: Typical Stress Strain curve for soils

The traditional geotechnical mathematical models such as Mohr-Coulomb Model are sufficient to accurately predict the types of shearing effects that soils could be experiencing. The Figure 3.2 depicts the concept of Mohr-Coulomb Model.

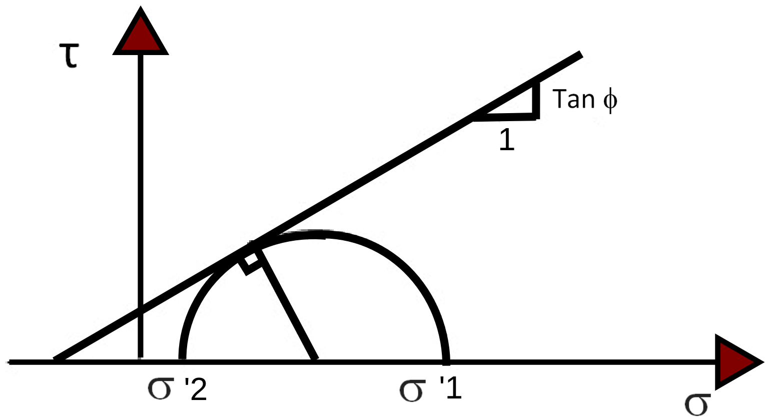


Figure 3.2: Mohr-Coulomb Soil Modeling

Computer programs utilize these models to help geotechnical designers to predict slope stability as detailed in the Literature Review. The concept of Mohr-Coulomb model is widely used in geotechnical analysis of problems. The Mohr-Coulomb failure theory results in a linear envelope that is obtained from a plot of the shear strength of a material versus the normal stress applied. The shear stress at the point where the coulomb line touches the Mohr's circle of stress is where the failure shear stress lies. Plaxis is one such computer program that is extensively used for geotechincal analysis and includes the modules for Mohr-Coulomb models, Linear Elastic models etc. (Plaxis, 2011).

For Modelling purposes in the research and use of Abaqus software for the FEM simulations, the problem of studying trench failure patterns is studied as a continuum problem. The choice of element is discussed in the Literature Review Chapter. The assumptions of Boundary conditions and types of soils etc are mention in the Research Methodology. 2D versus 3D based FEM simulations would yield different results. One of the objectives of the Thesis in future studies is to perform simulations for dynamic loading; In such scenarios it is important to perform 3D FEM simulations hence the research is completed using the 3D extruded trench sections.

3.2 Methodology

Three different cases are investigated to show the value of implementing finite element method in trench excavations. To simplify understanding of the concept the following cases are developed:

1. Trench with homogenous soil conditions
2. Trench with two layers of soil over lap
3. Trench with failure crack growth.

Figure 3.3: Research Methodology

Figure 3.3 breifly describes the various steps taken to approach the problem described in the thesis. Traditional methods of mathematical calculations such Mohr-Coulomb failure envelope are applicable to problems as stated in the thesis. The use of the research is targeted for the construction contractors and trench excavation teams onsite. Geotechinical designers would still approach these problems with traditional getoechnical approach as they are designers of such systems. But the FEM tool is used herewith to provide for lack of visualising hazardous conditions and predicting the same.

The various activities conducted to follow through the research are: 1) Identifying the need for the research, setting goals and objectives for research. 2) Conducting literature review to support the need for the research (Case studies, Major reasons for trench cave-ins, Methods to perform FEM simulation and analysis). 3) Short listing of types of simulations to be conducted to express the importance and visual effectiveness of the simulations. 4)

Completing three FEM simulations. 5) Analyzing simulations and understanding development guideline for performing future FEM simulations. 6) Implementing system dynamics to understand the impact of change in safety protocol for a construction company. 7) Conclusions. The Figure 3.4 captures the details of the steps through conception of the idea to completion of thesis.

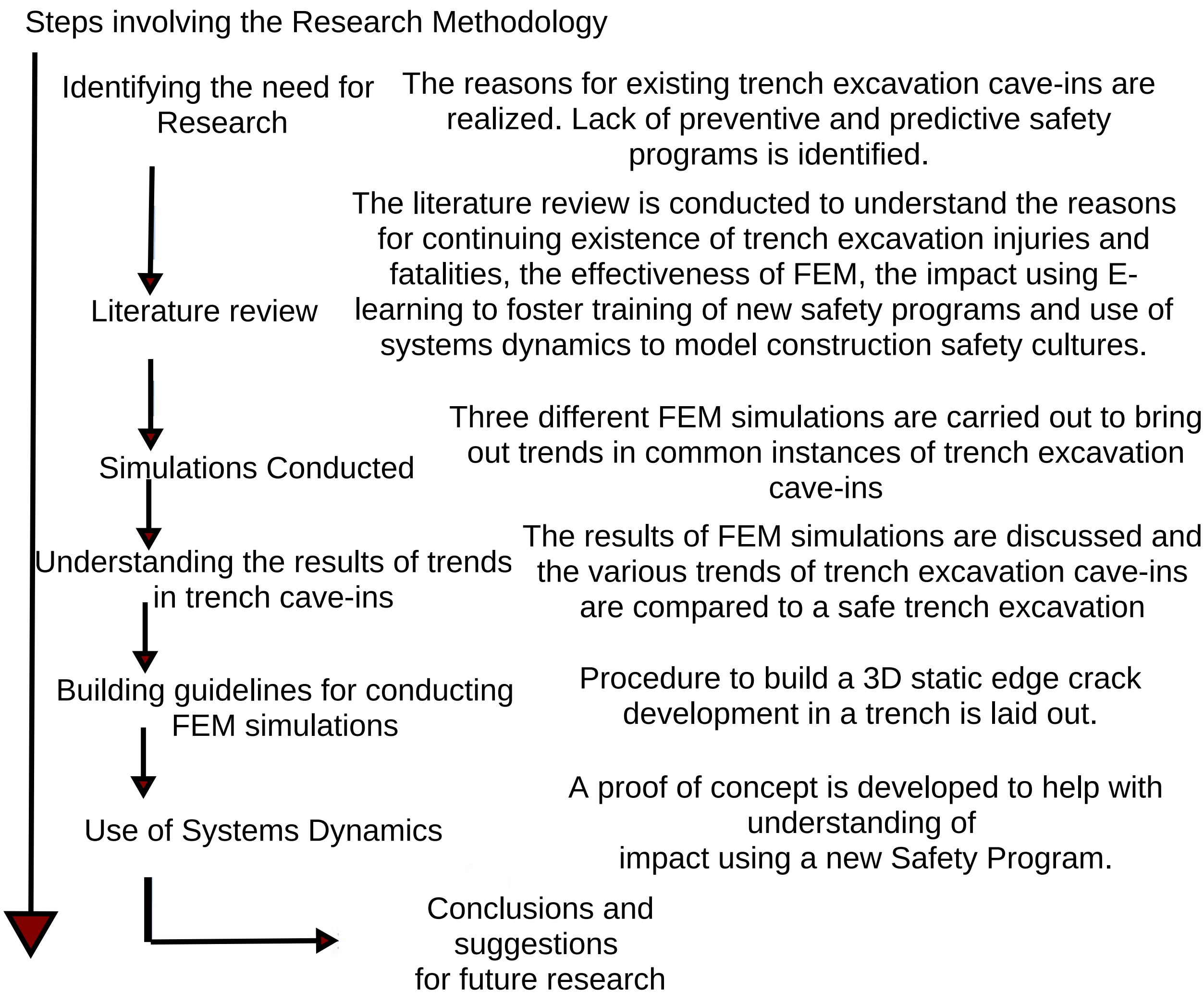


Figure 3.4: Research Methodology

3.2.1 Trench with homogenous soil conditions

Building ABAQUS simulation for homogenous soil failure began with defining the geometrical shape of the trench. The Figure 3.5 shows the dimensions of the trench, base width= 1.0m, left bank = 3.0m, trench width =3.0m, right bank= 3.0m; extrude depth of 0.3m. The dimensions input in the system was scaled down by 10 percent to have smaller FEM models and faster simualtions. This step would not have an impact on the stresses and magnitudes in the simulation beacuse the units are maintained in proportion.

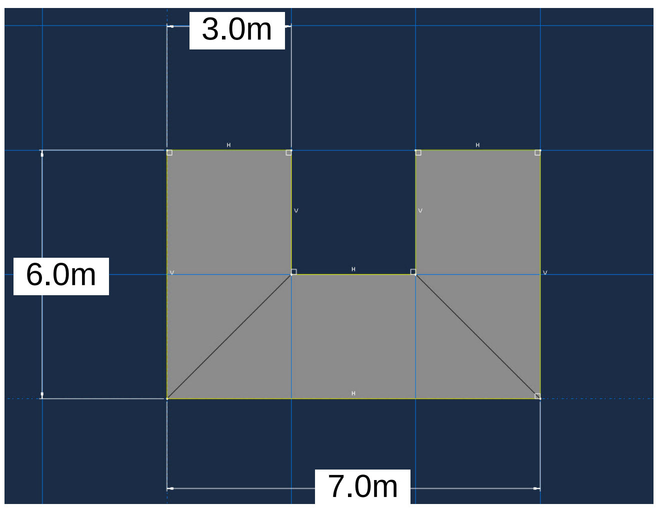


Figure 3.5: Geometry of Trench Section

The model was constructed to be a single part. The part was assumed to be solid 3D deformable and homogenous with elastic properties. In order to incorporate the mechanical properties of the soil, the research focused on homogenous soft clay soil properties with Young's modulus of elasticity (Es) 15MPa. To keep the problem simple, the soil was assumed to be un-drained and various complex parameters of pore pressures etc were ignored. Figure 3.6 is the result of a 3D extruded trench part. A 3D model is more suited to the thesis since a 3D approach is found to have better impact in the productivty of crews and their understanding of the job and related hazards. The Poisson's ratio that needed to be fed into ABQAQUS is 0.25.

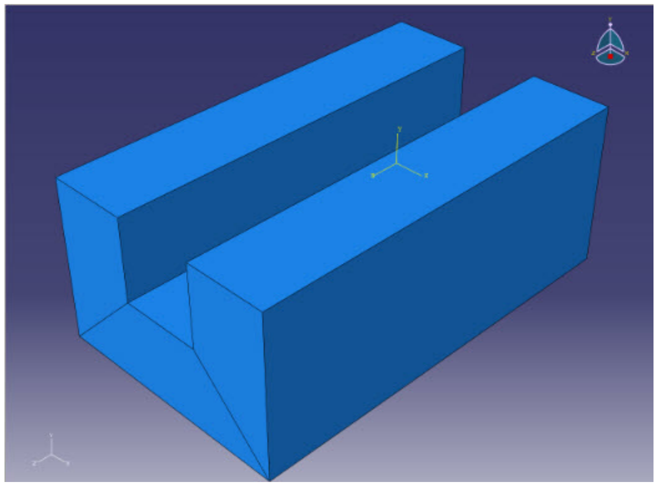
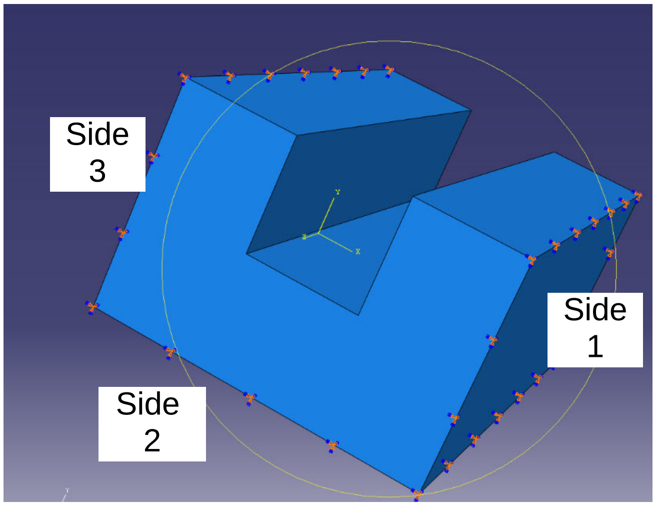


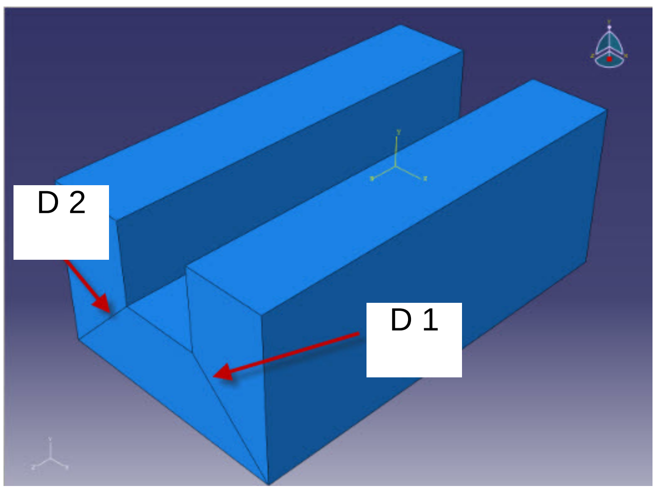
Figure 3.6: 3D Extruded Trench Section

Following steps are taken to create the section for the homogenous trench. Once the section has been created the part needs to be assigned the section properties. The section properties are completed the next step is to proceed to assembly module. The created trench part is selected and assigned Dependent mesh. Next, the steps for running the FEM simulation featuring the surcharge loads is selected to be static, general. The load is applied in the form of uniform pressure applied to both walls of the trench. Desired output which needs to be measured is selected as reaction forces and strain displacements.

Proceeding to selection of boundary conditions,outer walls of the trench were selected(side1, side2, side 3) to be fixed by 6 degrees of freedom using symmetry/ antisymmetry/ encastre for the trench load step. The type of boundary conditions chosen is encastre. The resulting boundary conditions are shown in Figure 3.7 (a).



((a)) Boundary Conditions



((b)) Partition Domain

Figure 3.7: Boundary Conditions and Cell Partition

The trench part needs to be sectioned in order to obtain the meshed part. The cutting planes chosen to simplify the object were diagonals at D1 and D2 is also shown in Figure

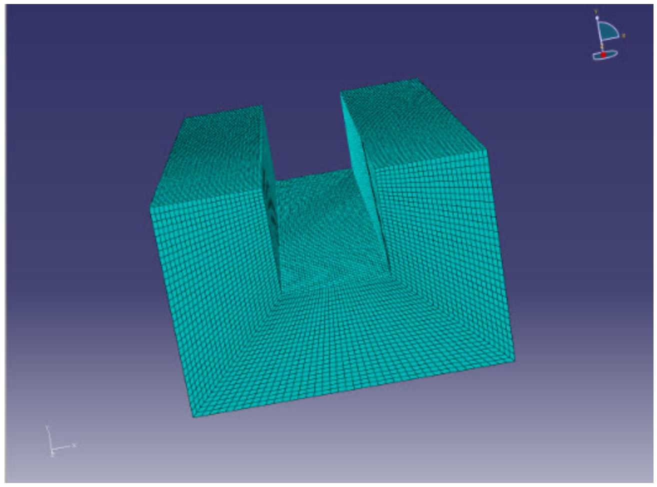


Figure 3.8: Meshed Trench

3.7 (b). The process divides the trench part into three different sections. Once the part is sectioned, the loads are given into the simulation model. The loads assumed are indicative of surcharge loads on trench walls due to excavated soil placement within 0.6m of the trench walls and heavy machinery etc. The load is applied as a uniform pressure at 0.015MPa.

The part is now ready to be assigned mesh properties. First the part is seeded at 0.003 and then meshed using quadratic reduced integration C3D20R hex element type. The C3D20R element is a general purpose quadratic brick element. The resulting meshed part is depicted in Figure 3.8. The homogenous soft clay trench is now ready to be submitted for analysis of part deformation due to the subjected loads. The mesh deformation of the trench is shown in Figure 3.9 and the contour deformation of the trench section is seen in Figure 3.10.

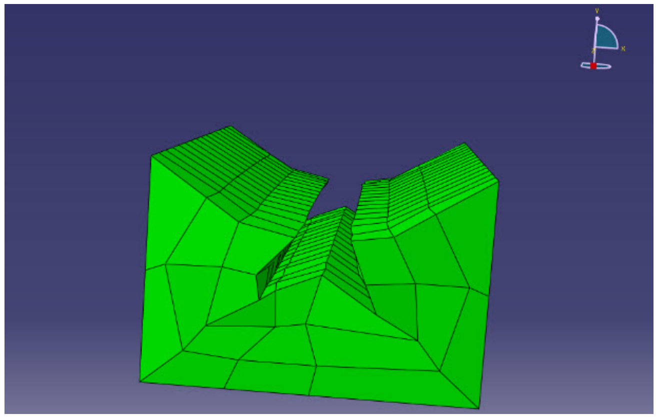


Figure 3.9: Mesh Deformation

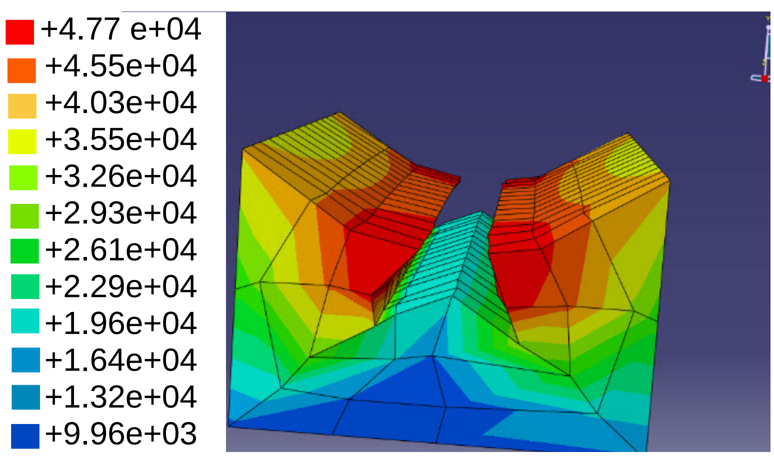


Figure 3.10: Mesh Deformation Contour

3.2.2 3D edge crack in trench

The research adds more complexity to the case done previously by simulating a static edge crack development in the trench. This is the main reason for the cave-ins to occur in most situations. Using ABAQUS simply will not yield the most realistic results unless the attempt to model realitic conditions is performed. To achieve crack growth we manually feed a cracked domain to the FEM model to predict how much failure can occur due to given loading conditions, or surcharge and machinery near trench walls.

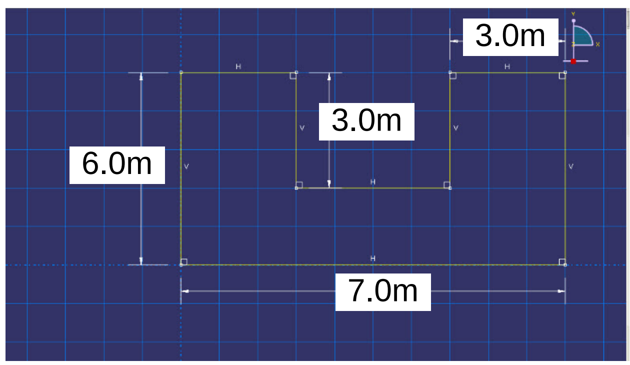
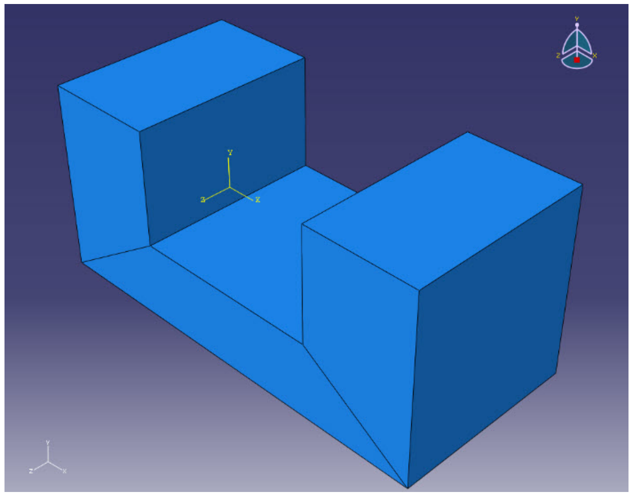


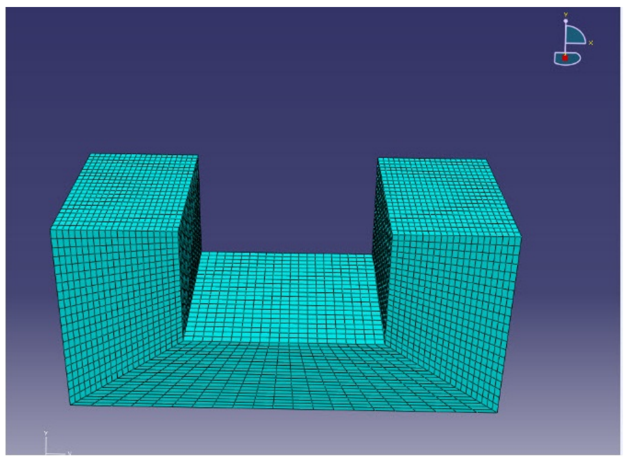
Figure 3.11: Geometry of Trench

The model follows a similar procedure as the previous one, as seen above the researcher begins with modeling the geometry of the trench as seen in Figure 3.11. The model is built as a 3D deformable solid. The size of the trench is base width= 1.0 m, left bank= 3.0 m, trench width=3.0 m, right bank= 3.0 m; extrude depth of 0.3m. The material properties are assumed to be that of the soft clay hence Young's Modulus is 15MPa and Poisson's ratio is taken to be 0.25.

The resulting model appears now as in Figure 3.12 (a). In the next steps the researcher assigns damage for traction separation laws and enters a value of 5MPa for Maxps Damage. The option for damage evolution is selected and displacement at failure is selected restricted



((a)) Extruded Trench model



((b)) Meshing Results

Figure 3.12: Trench Extrude and Meshing Results

at 1. The trench part is then assigned sections and meshing is completed as hown in Figure 3.12(b). For meshing sequence the researcher inputs Seeds at 21 number of elements running along the edges and structured Hex mesh is performed.

To create the crack domain a new separate part is created named as crack which is modeled as a 3D planar, deformable part; which has a base feature of shell and extruded to the same size as the trench 0.03. A line is drawn 0.24m away from the trench wall on the right wall. The depth of the crack is given as 0.24m. Resulting extrusion is now visible as seen in Figure 3.13.

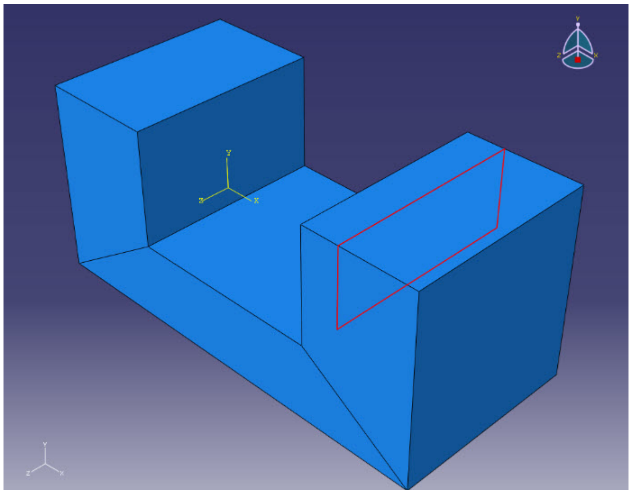


Figure 3.13: Crack Placement in Trench Domain

It is important to carefully configure the interactions between the crack and the trench parts. From the interactions menu choose the special module which consist a package for crack. Then, using XFEM type a crack interaction is created by choosing the un-cracked domain versus the crack domain by specifying the crack location. The crack growth interaction is modeled in the interactions menu selecting the XFEM crack growth module. The interactions between the crack and the trench domain are completed.

The loads are enforced as a uniform pressure on the cracked trench wall. The magnitude for top pressure is given as 0.0115MPa. Figure 3.14 represents the top pressure applied over the trench.

The final step is to set the boundary conditions; which is very similar to the previous simulation. Outer walls of the trench (side1, side2, side 3) were decided to be fixed by 6 degrees of freedom using symmetry/ antisymmetry/ encastre for the trench load step. The type of boundary conditions chosen is Encastre. The resulting boundary conditions are shown in Figure 3.15. The model is now ready to be submitted for analysis. Submitting the

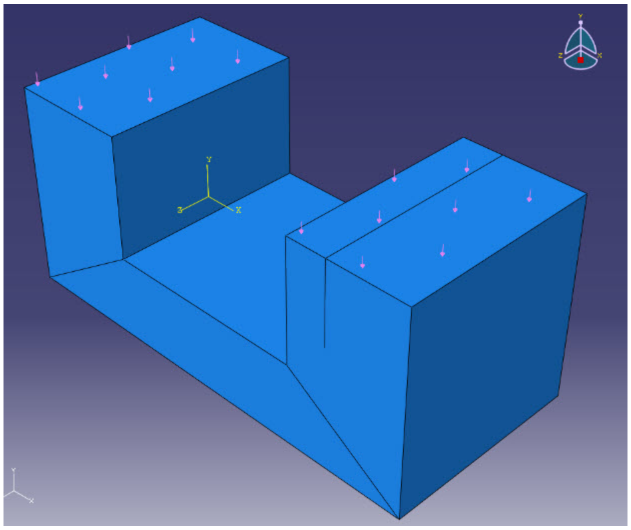


Figure 3.14: Loads Applied to Top Surfaces

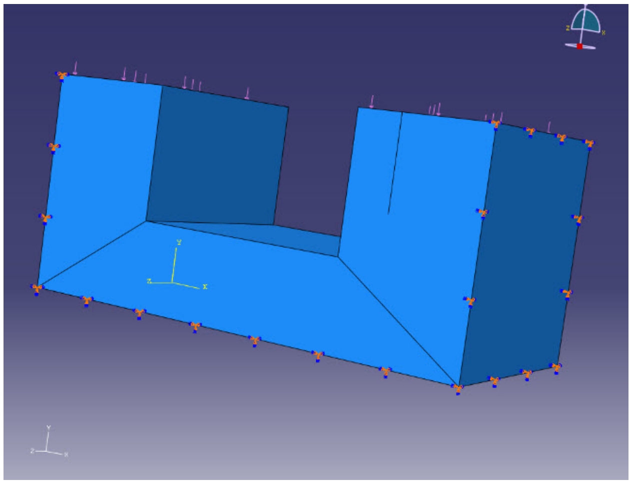


Figure 3.15: Boundary Conditions

model for analysis yielded the following results as depicted in Figure 3.16.

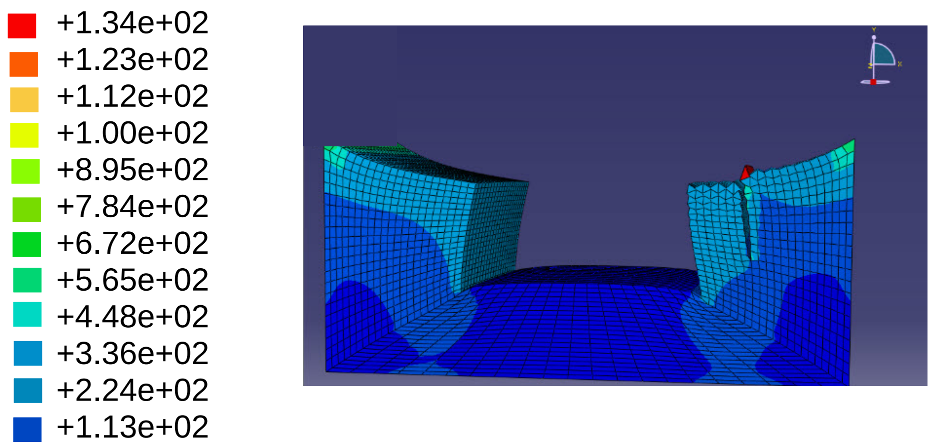


Figure 3.16: Resulting Failure

3.2.3 Trench simulation with 2 layer soil

Building the ABAQUS simulation for multi-soil trench began with defining the geometrical shape of the trench. The objective was to bring in some realistic components of trench excavation compared to the homogenous simulation in Section 3.2.1. Soft clay and very soft clay were chosen as the two types of soil mediums to be simulated. Figure 3.17 shows the dimensions of the trench, base width= 5.0 m, left bank = 2.0 m, trench width =1.0 m, right bank= 2.0 m; extrude depth of 0.02m

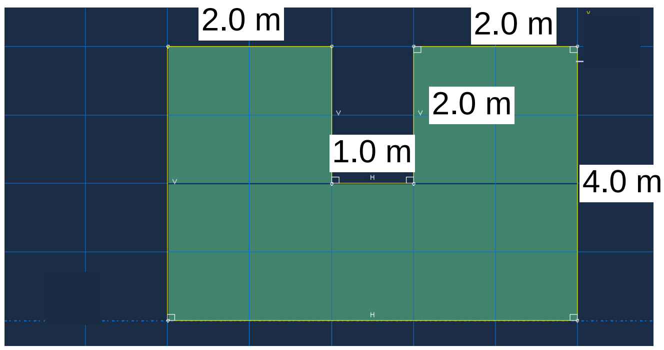


Figure 3.17: Geometry for The Two Layered Soil Trench

The model was constructed using a single part and then partition into symmetrical sections as show in the Figure 3.17. The walls of the trench were considered to be soft clay and the layer of soil acting as base of the trench was considered to be very soft clay. Both different soils were considered to be un-drained and homogenous in nature for reasons of simplicity.

The material properties assigned to the top layer of soil for Young's Modulus =15MPa and Poisson's ratio of 0.20. The material properties assigned to bottom layer of soil for Young's modulus of elasticity =20MPa and Poisson's ratio of 0.25. Section properties to both the layers of soil were assigned separately. Boundary properties were assigned in a similar manner as the previos simulations. 6 degrees of freedom using symmetry/ antisymmetry/ encastre for the trench load step. The type of boundary conditions chosen is Encastre. The resulting boundary conditions are shown in Figure 3.18.

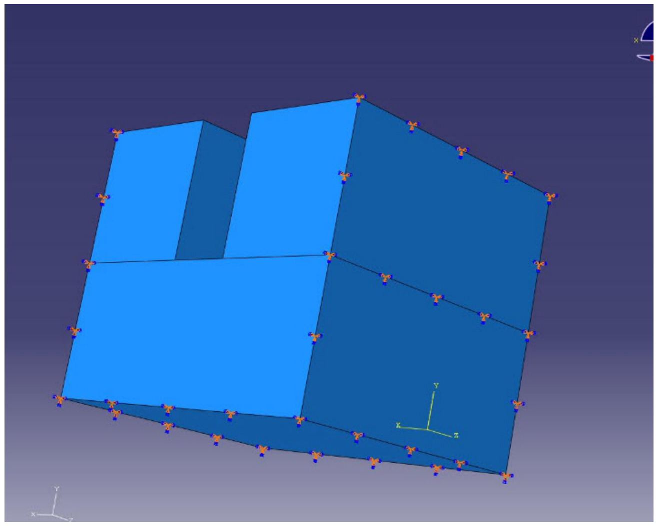


Figure 3.18: Boundary Layer Conditions

This particular trench simulation does not need to be partitioned because the two divided parts make it easy for meshing and does not cause any conflicts in structured meshing. The boundary conditions fixes both parts of the trench walls and the and the base of the trench along the same axis so as to allow for realistic boundary condtions.

The trench part becmoes ready for loading conditions. A uniform ramped pressure was simulated to be applied at a value of 0.025MPa. As mentioned previously, the loads assumed are to be indicative of surcharge loads on trench walls due to excavated soil placement within 0.48m of the trench walls and heavy machinery etc. The resulting Figure 3.19 shows the loading conditions on the top surfaces and the boundary conditions that have been applied to the trench section.

The trench part is now ready to be meshed. A similar mesh sequence as the homogenous trench simulation Section 3.2.1 is adopted here.

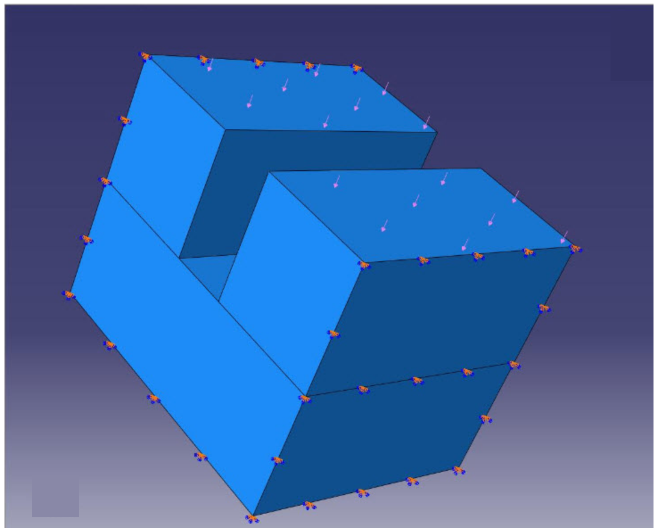


Figure 3.19: Loading Conditions

The mesh is completed using quadratic reduced integration C3D20R hex element type. The resulting meshed part is depicted in Figure 3.20.

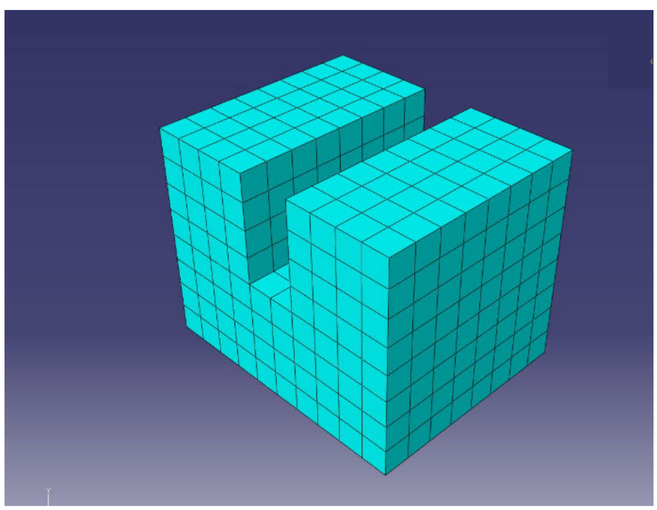


Figure 3.20: Meshed Multi Soil Layer Trench

With the completed mesh the analysis starts. The results obtained are shown in Figure 3.21. The results of the simulations are discussed in the Analysis part of the thesis. The

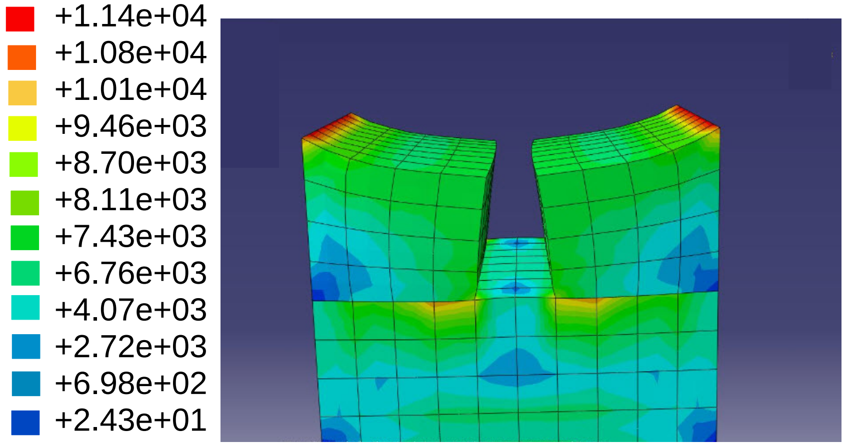


Figure 3.21: Results of Soil failure

comparison of the model to realistic construction aproach is performed in the Chapter 4.

Chapter 4

Analysis of FEM Simulations

Chapter 4 includes the analysis of the FEM simulations performed for modelling trench cave-ins. The results of the FEM simulations are compared to real situations of construction practices involving trench excavation practices. To approach the problem ABAQUS based FEM models were built to compare safe practices implemented in construction by modeling trenches that are considered to be safe, such as, sloped trenches and benched trenches.

4.1 Analysis of Results of ABAQUS FEM Models Discussed in Research Methodology

In order to establish the reliability of the FE models as discussed in the Research Methodology the results of stress failures for the three different simulations are developed. The results are displayed in the form of Von Mises' graphs for the stress failure which helps invisualizing the failures and can give insight to the different types of failure patterns that could occur in a trench subject different surcharge, loading conditions, soil properties etc. In order to identify the consistency of the results the researcher identified stress failure patterns and comparison to be the most effective means to identify critical failure points or yielding patterns.

The method to compare such results was developed by checking the stress values at certain nodes along the Y axis versus the distance along path. The distance implies the actual distance along the path in the single coordinate direction specified. The graph results prodcued as a part of the analysis helps identify critical loactions where stress intensity may be unusually high or cracks developped and the flow of stresses around the cracks. There are emergent trends which can be analyzed using such graphs as well.

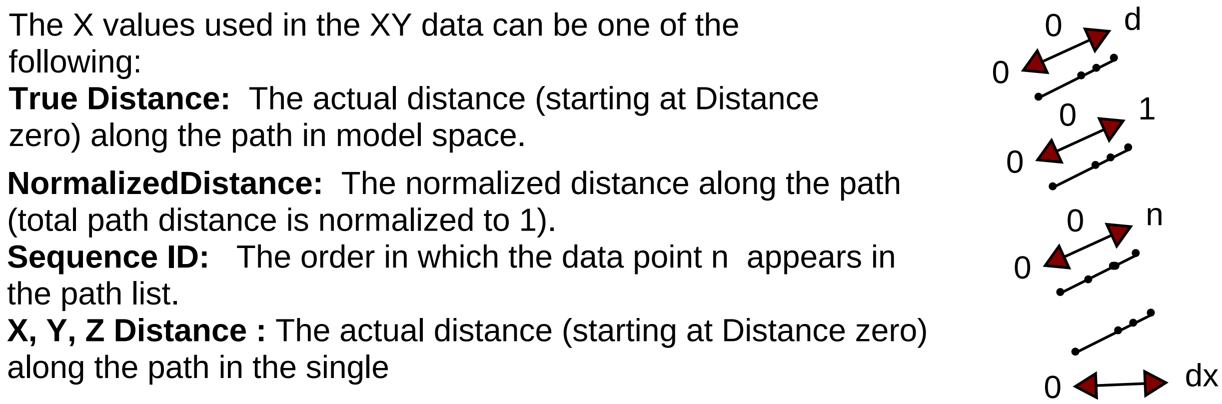


Figure 4.1: X Values Definition

The first model as designed in the FEM simulation section was trench with homogenous soil conditions. The results as shown in Figure 4.2, are displayed in graphic contour of S, Mises stress induced graphs. The S, Mises results are a derived from Von Mises stress; which is a geometrical combination of all stresses acting at a particular location, in this case the nodal elements. The various stresses included n such results usually are, normal stresses in all three directions and all three shear stresses.

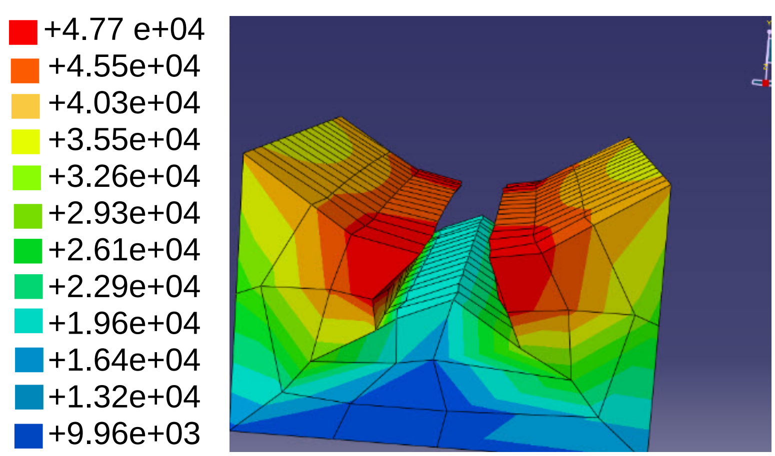


Figure 4.2: Result of Stresses in Trench With Homogenous Soil

The results of the simulation are, as observed in the Figure 4.2, compression of the soil would have resulted in a cave in, if decided to be dug without shoring systems or other modes of trench protection such as backing or benching the trench. Results such as these clearly show the significance of finite element simulation and the advantages of predicting soil behavior prior to trenching. In order to understand the stress flow patterns in such trench failure cases a stress output graph was generated.

A path was selected along the vertical axis of the trench along the front face of the trench. The path was critically chosen since it follows along the nearest nodal points to the trench wall. Apart from the trench edges themselves the chosen path would depict the highest stress patterns as seen in Figure 4.2. Nodes are selected for analyzing the stress patterns stating at node 157, 425, 235, 79, and ending at 193 as shown in the Figure 4.3.

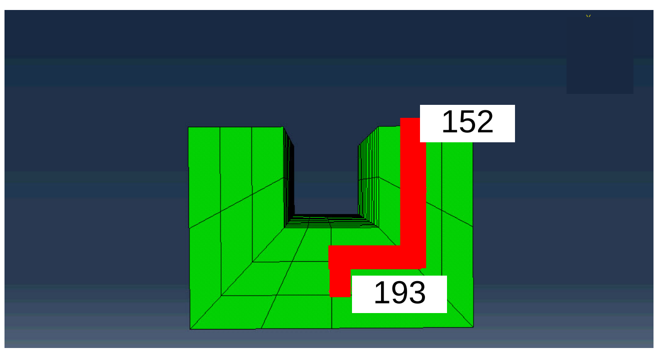


Figure 4.3: Path Selected for Stress Plots

The stress versus distance along path yielded the following results as shown in Figure 4.4. along the various nodes selected to measure the stress patterns, the graph relates perfectly along to results seen in Figure 4.2 The maximum stress is experienced at the top surface where the top pressure is exerted and the shearing action occurring owing to the typical boundary conditions applied. The stress within the nodes of the trench takes a gradual dip through the increasing depth of the trench. A huge dip in the stress is observed as the path now moves into the base of the trench where stress pattern is going to be very low since the top pressure is mostly going to affect the trench walls and not the bottom part of the trench.

Generating such graphs shed more light into detailed analysis of trenches where cracks appear or can be predicted or in deep trenches to analyze how various types of soils encountered need to be treated, and to ascertain the type of shoring needs.

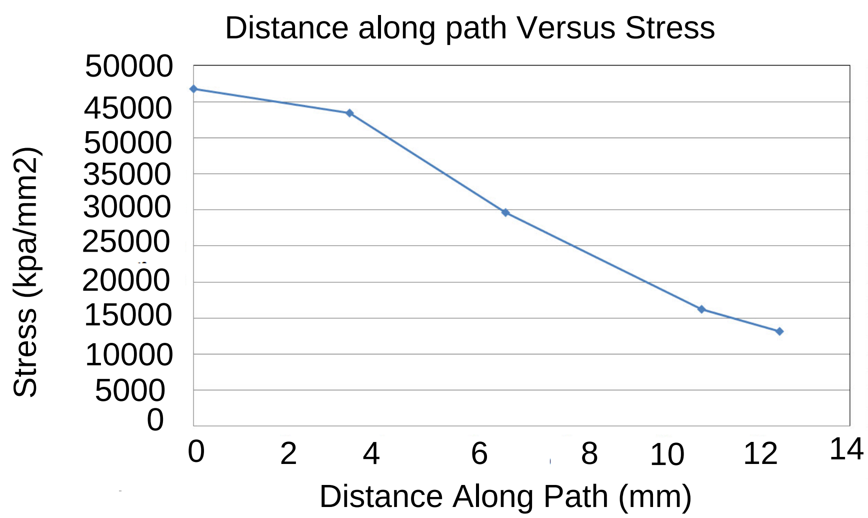


Figure 4.4: Stress Versus Distance along Path

Results of the simulation run for trench with a crack growth phenomenon the results are important to analyze in three different paths. This is owing to different stress flows through the trench model. The Figure 4.5 shows the end result of a crack growth phenomenon in a trench placed critically 0.12m away from the trench wall.

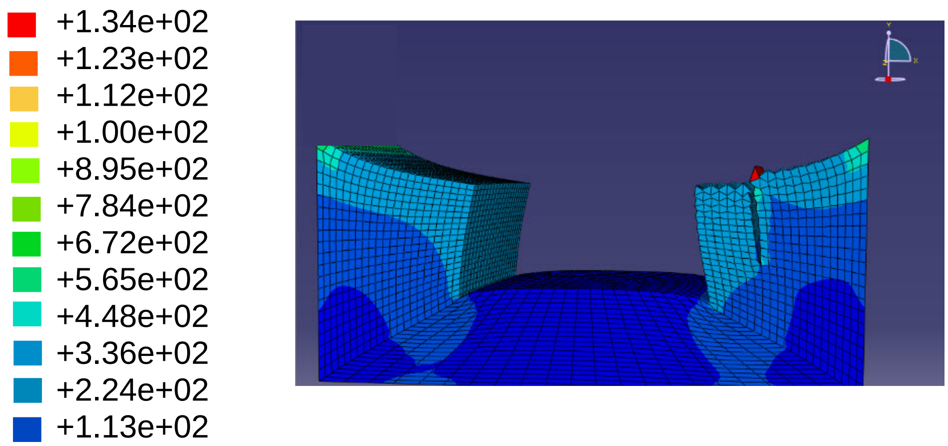
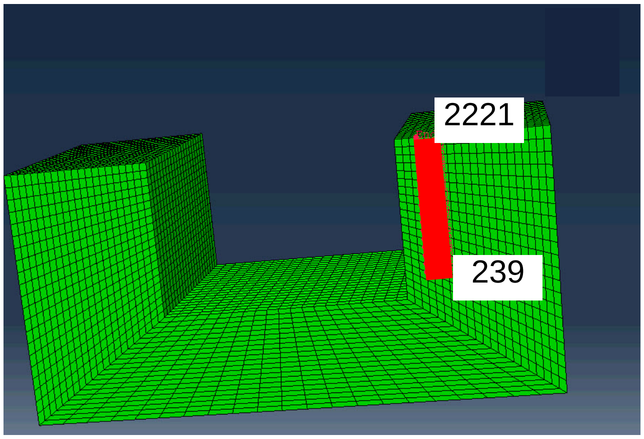


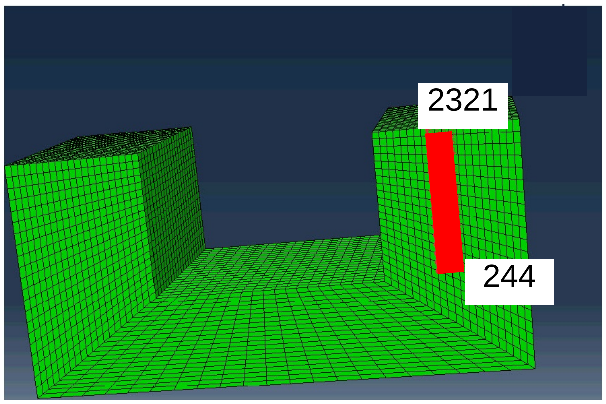
Figure 4.5: Trench Stress Results in Crack Trench Simulation

In order to understand the stress distributions across the trench, three different paths were selected to analyze the failure occurring in the trench. This is important since stress patterns can be different on the left side of the crack plane and the right side. Also there can be a different stress pattern showing on the left trench wall section. The hypotheses can be inferred from carefully analyzing the result of trench fatigue in Figure 4.5. However for scientific understanding and verification of such a hypothesis the stress plot versus the true distance along path was run.

The first stress pattern was plotted on the left side and away from the crack plane along the nodes starting at 2221, and ending at 239 as shown in Figure 4.6 (a) and the second stress pattern was plotted along the right side of the crack plane as shown in Figure 4.6 (b) along the nodes start at 2321, and ending at 244.

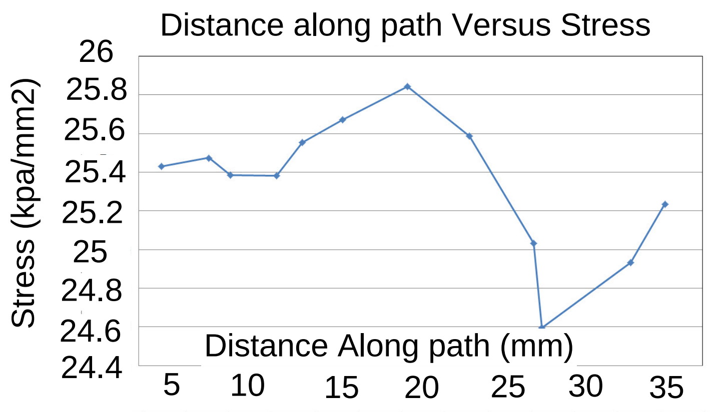


((a)) Node Selection Path 1

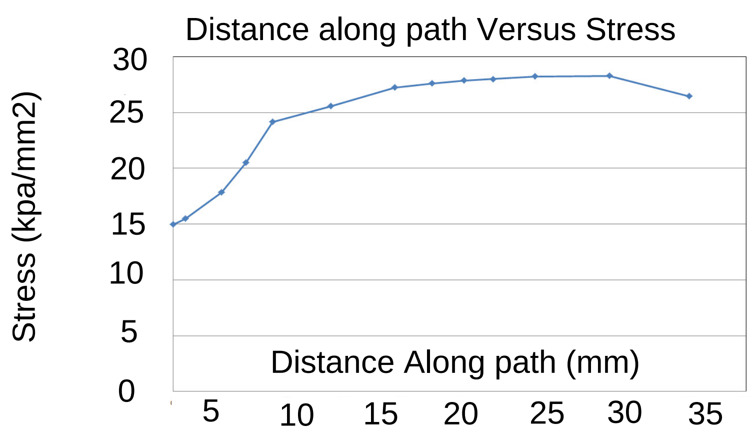


((b)) Node Selection Path 2

Figure 4.6: Selected paths for Stress Plotting



((a)) Stress Result 1



((b)) Stress Result 2

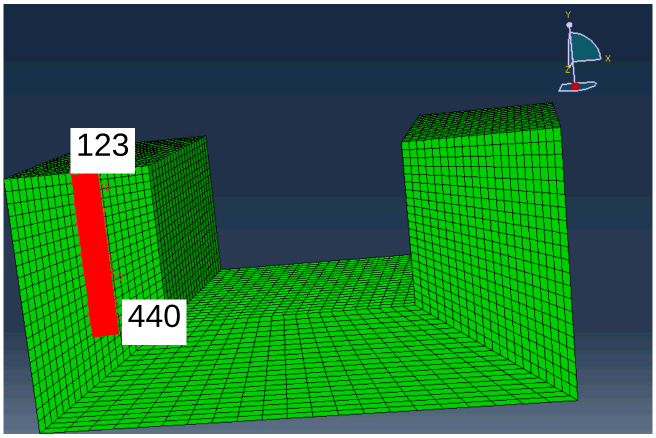
Figure 4.7: Results of Stress Plots

The results of the stress plots along path A and B are shown in Figures 4.7 (a) and 4.7 (b) the graphs for these instances were created from bottom up of the trench section.The approach was taken in order to capture the increase in stress patterns from bottom up of the trench sections along crack propagation plane. Since the method of crack development was modeled to be static a very interesting result was observed. In Figure 4.7(a) at the stress was tending to 0 at the starting node 2221. As the path progressed to nodes above, stress values shot up, and at then dipped suddenly. This pattern is noted as a result of the trench section being split away from the main domain as a result of the crack propagation. The dip in stress was noted owing to yielding of the soil. As the path progressed beyond the cracked plane stress was noted to increase but at a lower level because the cracked plane still was being exerted to some forces due to surcharge from top pressure loading.

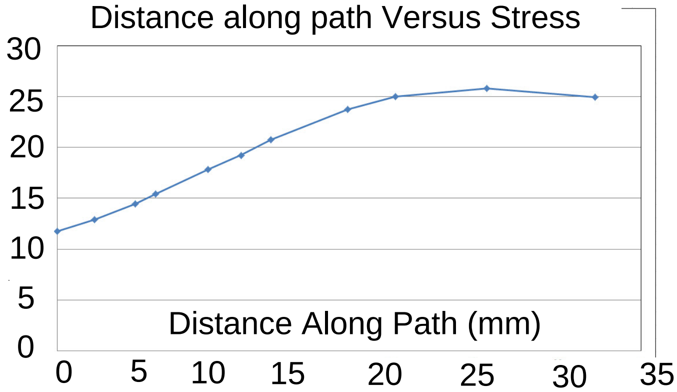
In Figure 4.7(b) a very curious pattern was observed in the trench where the stresses experienced were close to 0 at the bottom of the trench. However at the crack plane the elements shared a part of the forces experienced by the cracking plane and forces from the main domain of the trench. The wave pattern indicates the nodal elements experiencing varied forces between the two bodies of the trench. However the wave pattern observed was increasing in nature, which implied that although the different nodes were experiencing varied forces; the subsequent nodes were experiencing a gradually incremented value of force. This is consistent with the finding in the contour deformation results of the trench fatigue.

The third graph plotted was to understand the behavior trench on the left trench wall section as shown in the Figure 4.8.

The findings of the stress plot in Figure 4.8 (b) is consistent with the previous findings where the stress gradually increases from the bottom to the top of the trench. It is important to realize the findings where the stresses experienced on a section of trench where crack formation is found compared to the section where no cracks are developed. The cracks are forced to exist in the trench. In realistic conditions, there can be two very different soil conditions in existence on both walls of the trench. It can be important to model the crack formation in the weaker and strong soils to compare the hazardous conditions that may develop due to surcharge loading or change in moisture conditions. The trench section also clearly portrays the phenomenon of bulging in the bottom section of the trench. Such phenomenon is commonly found in realistic trenching situations. That is attributed to many hazards and instances in trenching activities. The approach can help in protecting workers



((a)) Node List 3



((b)) Stress Result 3

Figure 4.8: Nodes Path Selected and Results of Stress Plotting

and keep excavations safer by the performing FEM simulations.

The third FEM simulation involving two different soil layers have the results as shown in the Figure 4.9.

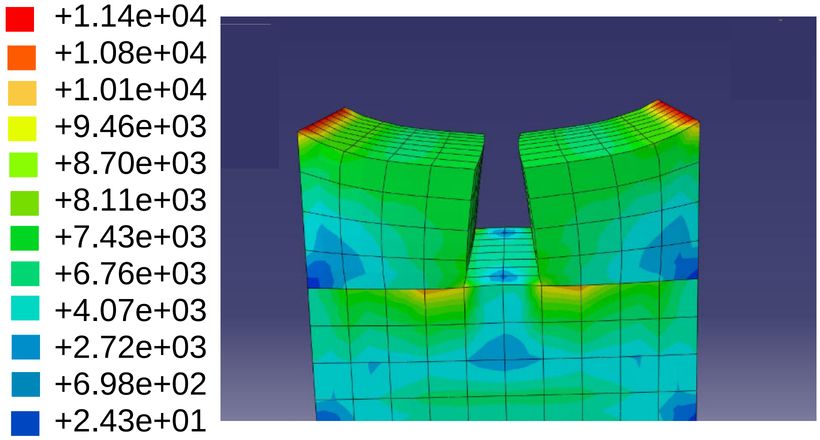
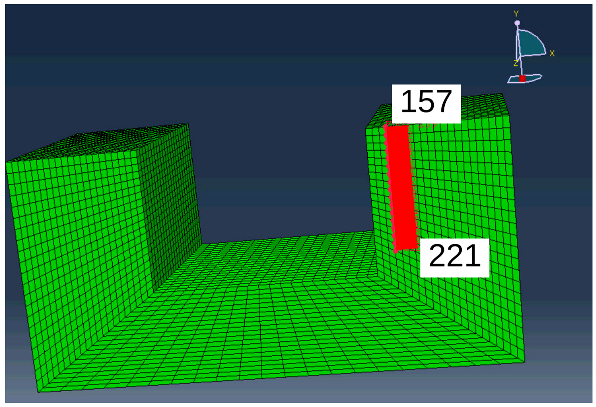


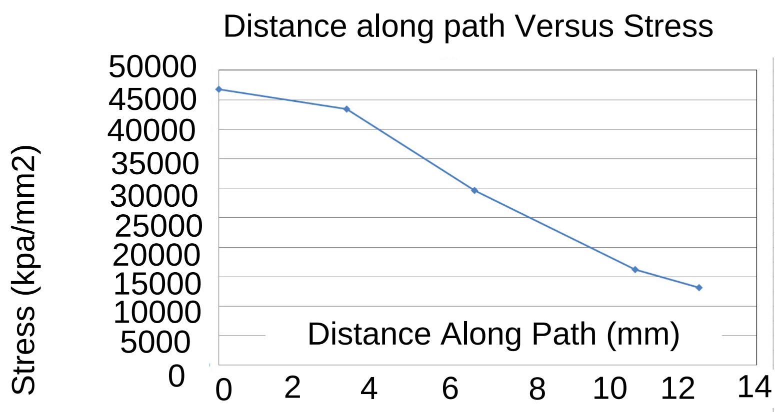
Figure 4.9: Fatigue In Trench with Two Layers of soil

The stress plots for this trench was performed starting at node 123 at the top of the trench wall section moving towards the bottom ending at node 440. Figure 4.10 shows the path for stress plot.

In the stress plot as seen in Figure 4.10, the stress reduces from top of the trench section to the bottom of the trench section. There is a downward slope and a sudden upward slope observed in the graph at the true distance of 0.55m along the selected path. This was an unexpected emergent result of the simulation. The explanation of the case is that the stresses at the dip abruptly between the nodes that act at the interaction layer of the two soil elements. Since the bottom part of the trench is simulated to be of a stronger material property than the top layer the transition of stresses from the top layer to bottom layer diffuses some of the forces. The forces arising through the heaving action which is in the negative direction of the path of stresses happens to be of a similar value at the layer interactions and hence there is a cancellation of forces at the point. As the nodal path



((a)) Node List



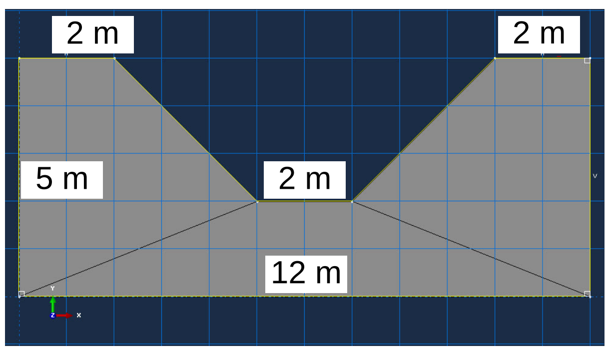
((b)) Stress Result

Figure 4.10: Nodes Path Selected and Results of Stress Plotting

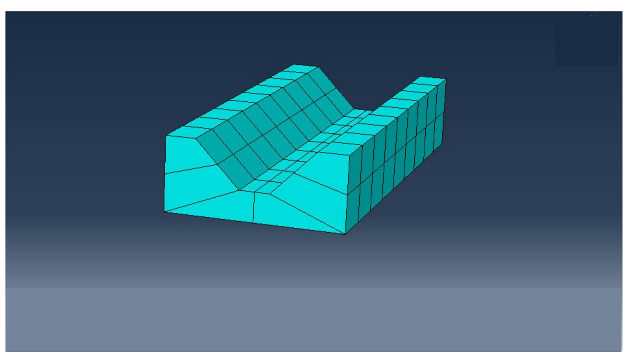
continues downward an increase can be seen in stress compared to the immediate previous elements.

4.2 Comparison of The Results to a Safe Practice of Trench Excavation

To understand how efficient the current safe practices in construction, a model was created which simulated a trenching for hard clay type of soil. OSHA recommends sloped excavation as a safe practice for type B layered soils which have mechanical properties enduring the soil to be excavated without shoring systems required if the trench walls are sloped. A simulation that features a scenario that assuming a Type B soil which allows for a 1:1 slope for excavation is constructed. The geometry and the meshed trench are shown in Figure 4.11.



((a)) Geometry for Sloped Trench



((b)) Meshed Trench Part

Figure 4.11: Geometry of Slope and Meshed Part

Similar soil properties, loading condition and boundary conditions as discussed in Research Methodology Section has been applied in this simulation. The research focused on homogenous soft clay soil properties with Young's modulus of elasticity (Es)= 15kPa and Poisson's ratio of 0.25. The outer walls of the trench are chosen to be fixed by 6 degrees of freedom using symmetry/ antisymmetry/ encastre for the trench load step. The type of boundary conditions chosen is encastre.

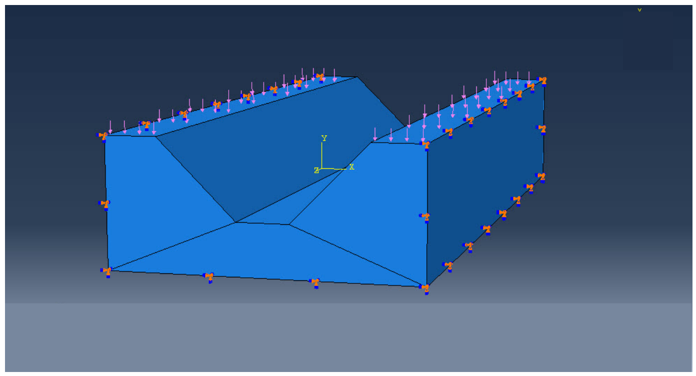


Figure 4.12: Boundary Conditions and Loading Conditions

The loads assumed are indicative of surcharge loads on trench walls due to excavated soil placement within 0.24m of the trench walls and heavy machinery etc. The load is applied as a uniform stress at 12 kPa. The resulting mesh deformation is shown in Figure 4.13.

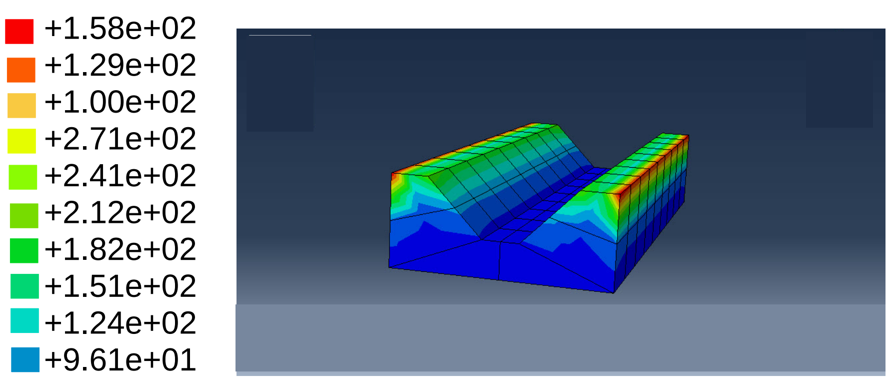
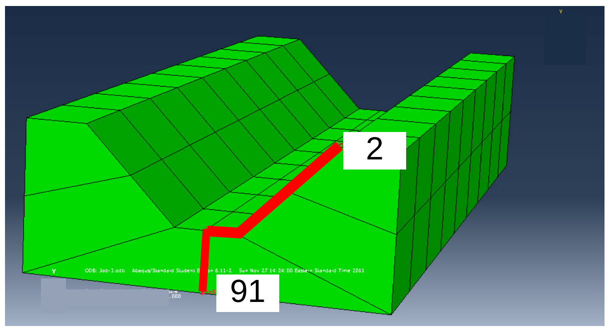


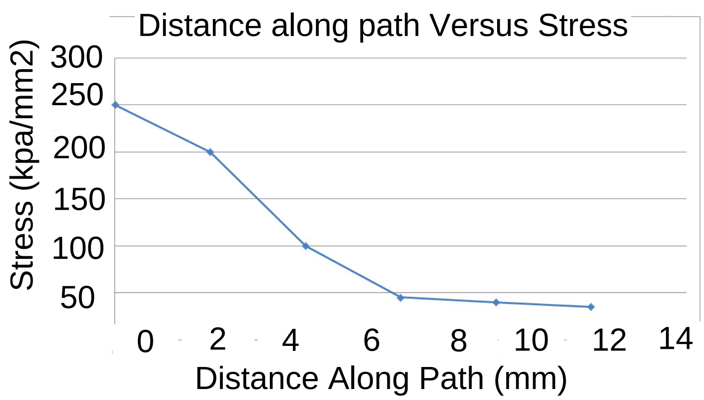
Figure 4.13: Fatigue Results in Trench Section

The results as seen in Figure 4.13, show that sloped excavation is safe however when the same soil sample was treated to similar FEM parameters found considerable soil deformation and fatigue were detected. The simulation correlates the finding of the research to be in parallel with realistic conditions. However the simulation is considered only to be a proof of concept since the soils have been considered to be homogenous in nature.

In order to understand the flow of stresses through the trench a path was selected starting at node 2 and running toward the bottom of the trench ending at node 91. The results of the stress plot and path selected to measure stress is shown below.



((a)) Node Path Selected



((b)) Stress Plotted

Figure 4.14: Nodes Path Selected and Results of Stress Plotting

The results of the stress plot were nothing short of expected; the maximum stress is observed at the top of trench wall and decreases gradually toward bottom of the trench. Such simulations help construction safety managers and excavation crews to analyze the method of excavation and the degree of safety that can be achieved with confidence. Such confidence in building, construction, and excavation practices will help remove the risk and much of the contingency preloaded in the bidding policies for most construction companies helping them compete in the industry at a healthier level.

4.2.1 Sensitivity Analysis

As a part of the thesis, a sensitivity analysis was not conducted but it is mportant to note that the strategy to perform the trench excavation FEM simulations would have some impact on the type of results which can be achieved. Use of Plaxis has specialised geotech based modules in the FEM software program, and this would not rely on use of Young's Modulus and Poisson's Ratio for the soil modelling purposes. Since the simulations were assumed to be modeled as continuum problems in Abaaqus CAE, the research was completed in the method described in Chapter 3. The Sue of boundary conditions and type of elements would all be different when considering different FEM software packages and modelling assumptions.

Chapter 5

Guidelines to Build The FEM Model

Due to the lack of availability of procedures to build the models in such programs a guideline is built in the present section.This chapter discusses a guideline to build a trench model in ABAQUS. It is aimed to build readily available modules that would contain most forms of trenches that are constructed, and which is compatible with most commercially available software programs. This will help trench excavation companies to implement FEM based safety protocol on a regular basis. E-learning will be an apporpriate program to educate the construction proffesionals of the proposed safety program with FEM.

The modules reduce the effort needed to build individual FEM trench models for each project. However since construction work and site locations are unique there might be instances where such modules would not be able to represent real conditions and the required FEM model needs to be built individually.

It is focused on a commonly occurring hazardous condition in trench excavations, which is the appearance of wall cracks and have laid out a guideline to model such instances. Themodel is meant to be considered as only a framework for building more complex realistic models that can present real world parameters accurately.

The process to create the trench is followed similar to the 3D edge crack for solids in tutorial 3D Static Edge Crack (Pais, 2010). The procedure to build a 3D static Edge crack in trench is laid down in the following parts:

1. Creating an un-cracked domain (trench)
2. Creating the crack domain
3. Creating the boundary conditions
4. Solving the system of equations

5.1 Creating the Un-cracked Domain

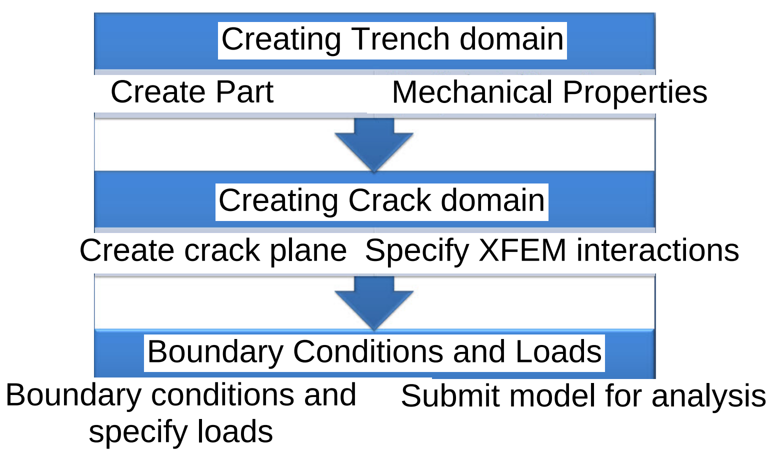


Figure 5.1: Outline of ABAQUS Model Building

The procedure to create the simulation for 3 D static edge Trench is shown in Figure 5.1

Design Steps:

a. Use ABAQUS/CAE 6.9 or later.

b. Create a new model as named TrenchCrack. Do not include spaces in naming configurations in ABAQUS as it runs into errors.

c. Now Select parts and enter the name as Trench, Modeling Space to be used is 3D, type is deformable, base feature is solid and approximate size is 2. The size is kept small to make the simulation run faster, as bigger models will take a longer time to run and will also need a lot of system resources.

d. Using the drawing tool draw a trench section as shown in Figure 5.2, The left side of the image with menu options of the image is only for visual reference only, small text is not meant to be readable.

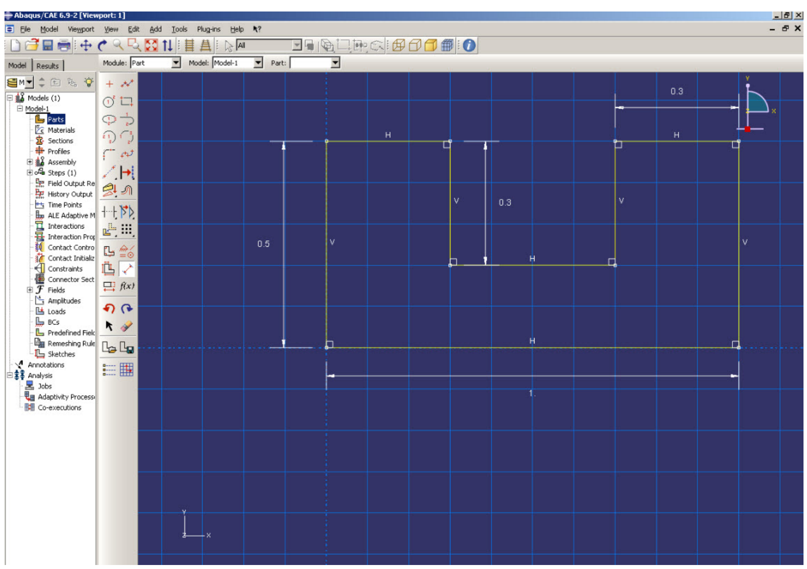
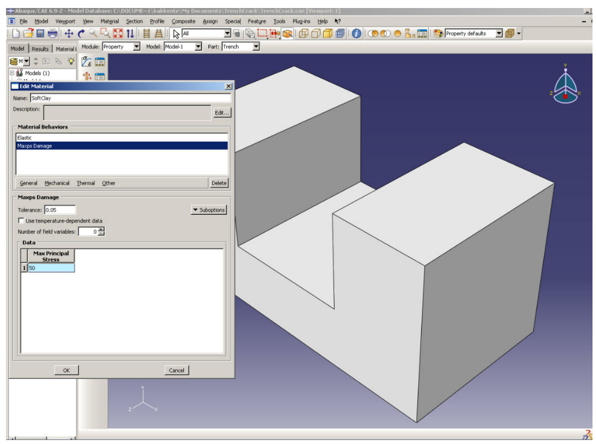


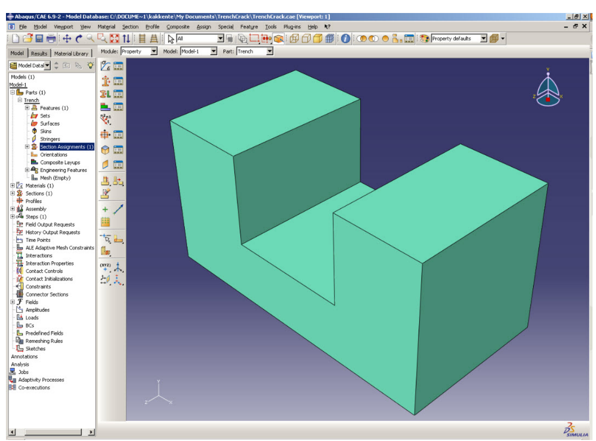
Figure 5.2: Geometry of Trench

e. Complete the drawing and enter depth 5 which is the third dimension of the trench to be extruded.

f. For Materials and enter name as SoftClay. Provide Mechanical, Elasticity. Enter Young's modulus as 15MPa and Poisson's ratio as 0.25. Enter Mechanical, then damage for traction separation laws, then Maxps Damage. Enter a value of 5 MPa. From the Sub-options menu choose Damage Evolution. Now enter Displacement at Failure as 1 and exit out of the options. Figure 5.3(a) shows the current stage in the process.The left side of the image with menu options of the image is only for visual reference only, small text is not meant to be readable.



((a)) Maxps and Mechancical Properties

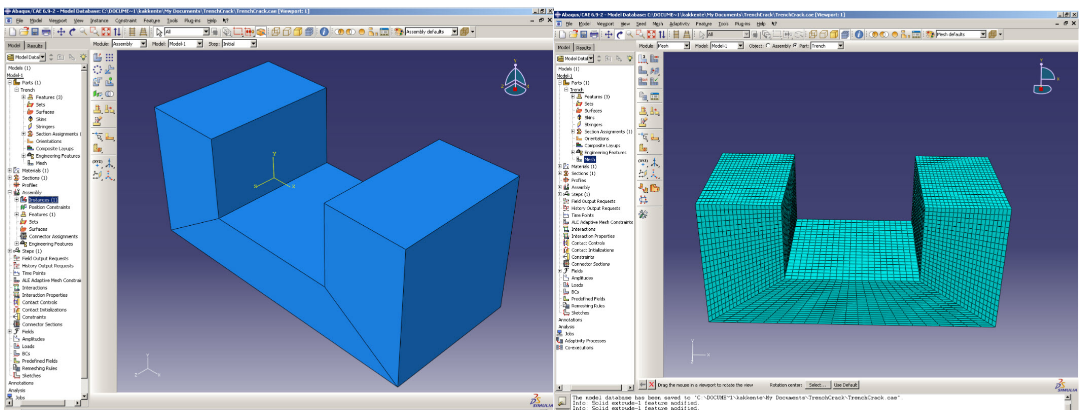


((b)) Section Assignments

Figure 5.3: Trench Extrude and Meshing Results

g. In sections, enter the name of section as Main. Accept default settings. Select SoftClay as material and check the box by Plane stress/strain thickness and enter 1 as thickness. In the parts menu expand the TrenchCrack and double click on section assignments. Select the domain and exit by accepting default settings. The resulting Figure in 5.3(b) should represent the 3D trench at currently.

h. To avoid complications in the meshing sequence partition is needed in the trench at the joints of the base and the walls as shown in the Figure 5.4(a). The left side of the image with menu options of the image is only for visual reference only, small text is not meant to be readable.



((a)) Partitioned Trench Domain ((b)) Meshed Domain

Figure 5.4: Trench Extrude and Meshing Results

i. Expand the parts and expanding the TrenchCrack exposes the Mesh menu. Select mesh and from the menu bar select controls choose Hex, structured. From the menu bar select mesh and the part. The meshes are developed in the part as shown Figure 5.4(b). The left side of the image with menu options of the image is only for visual reference only, small text is not meant to be readable.

5.2 Creating The Cracked Domain

a. To create the crack, make a new part. For Parts enter name as Crack, select modeling space as 3D planar and type is deformable, base feature is shell, type is extrusion and approximate size is 2.

b. Draw a line from coordinates (8,5) to (8,3) and click done and extrude for the same depth as the trench which is 0.5m. This generates a 3D plane along the depth of the trench on the right wall.

c. Expand the assembly menu and double click on instances. Select crack and accept default settings. The Figure 5.5 depicts the current stage of the assembly process. The left side of the image with menu options of the image is only for visual reference only, small text is not meant to be readable.

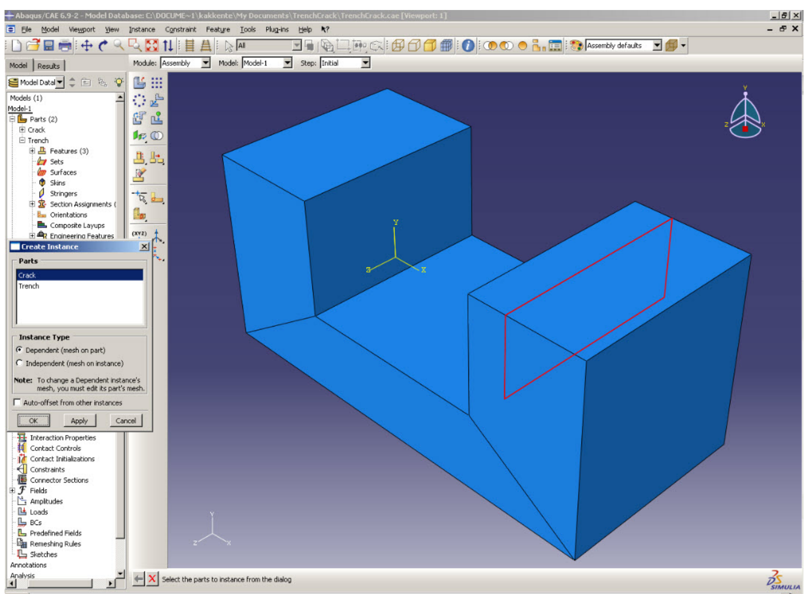


Figure 5.5: Cranck Instance

d. The next step in the simulation is perhaps the most important step. It is necessary to specify the behavior of the crack with the domain of the trench. From the menu bar select special, crack and select create. Name the interaction as EdgeCrack. Select type as XFEM. Select the uncracked domain as the Crack Domain. As shown in the Figure 5.6 on the menu which appears, specify the crack location by clicking on the line signifying the crack and exit the options. The left side of the image with menu options of the image is only for visual reference only, small text is not meant to be readable.

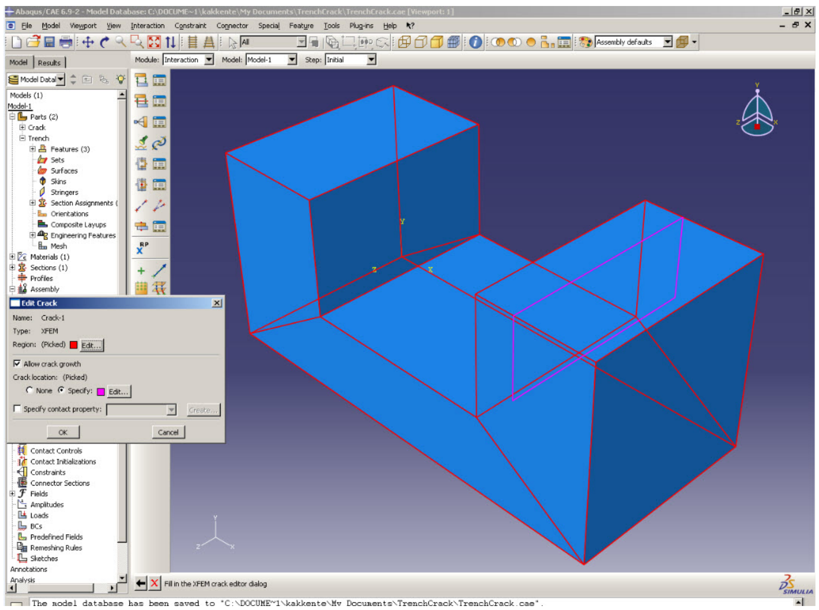


Figure 5.6: Crack Interaction

e. For Interactions and name the module as Growth. Select initial step and types for selected step as XFEM crack growth. XFEM Crack should have EdgeCrack and exit the options.

5.3 Creating the Boundary Conditions and Loads

The following steps helps in adding the necessary boundary conditions in ABAQUS:

1. Enter name as Loads and accept default settings.

2. From menu bar and enter the name as TopLoads and select the mechanical from the categories, type is pressure. Select the top surface of the domain as shown in the Figure 5.7 and enter magnitude of 0.025MPa and exit by accepting default settings. The left side of the image with menu options of the image is only for visual reference only, small text is not meant to be readable.

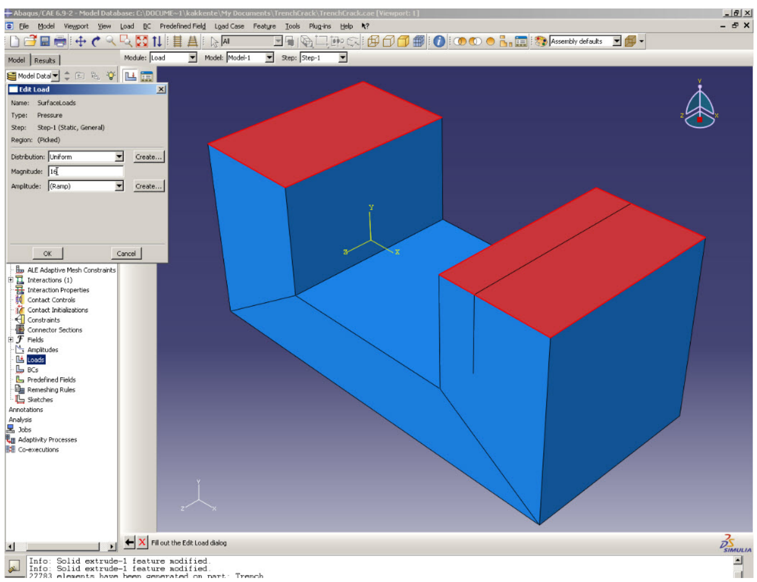
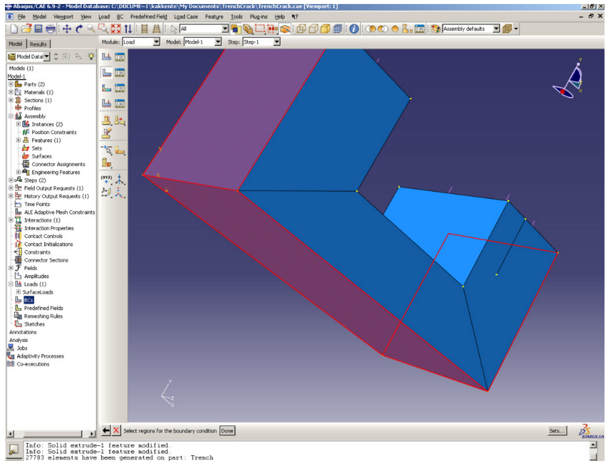


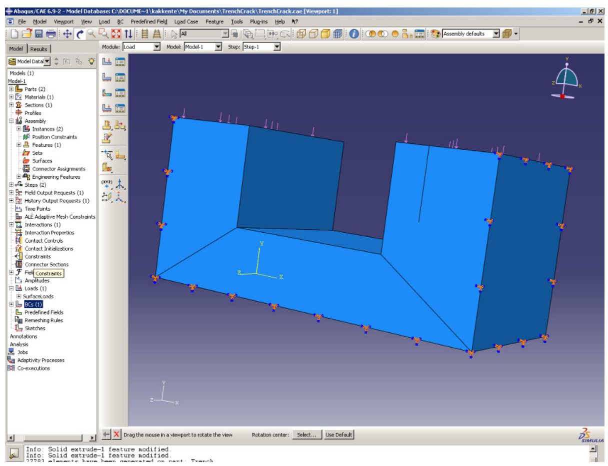
Figure 5.7: Loading Condtions

3. To create boundary conditions choose the outer walls of the trench (side1, side2, side 3) to be fixed by 6 degrees of freedom using symmetry/ antisymmetry/ encastre for the trench load step. The type of boundary conditions chosen is encastre. The Figure 5.8(a) shows how the boundaries domains are selected and the resulting boundary

conditions as applied as shown in Figure 5.8(b). The left side of the image with menu options of the image is only for visual reference only, small text is not meant to be readable.



((a)) Selected Boundaries



((b)) Assigned Bounadries

Figure 5.8: Boundary Conddtions

4. To create the required outputs we first expand field output requests, choose F-Output-1. Expand the failure/fracture options and check the box next to PHILSM, level set value phi. This will allow to view the level set function defining the crack.

5.4 Solving the System of Equations

1. From jobs menu on the right hand side menu bar, enter the name as EdgeCrack1. Exit by accepting default settings.

2. EdgeCrack1 allows to submit for analysis.

3. Check the results of the analysis. Figure 5.9 represents the results of the simulation. The left side of the image with menu options of the image is only for visual reference only, small text is not meant to be readable.

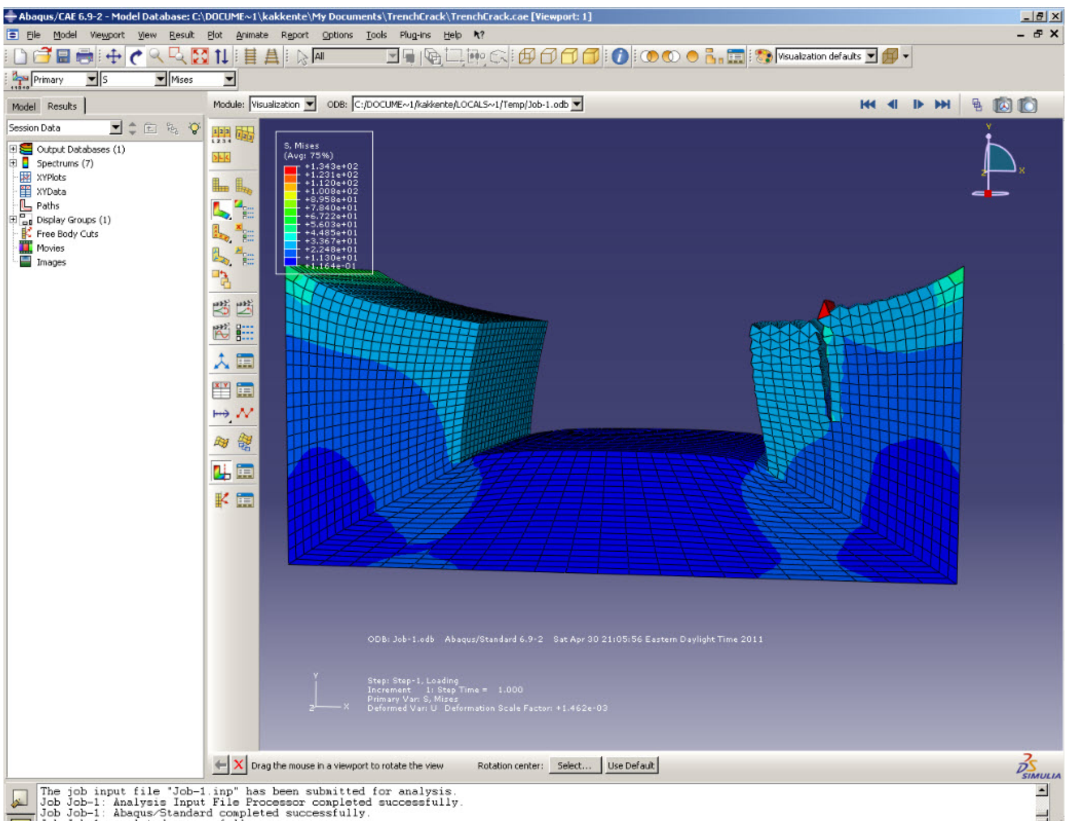


Figure 5.9: Results of Crack Growth in Trench

5.5 E-Leanring

The literature review established that E-learning is an effective tool which can be adopted for training purposes of the trench excavation crew memebers and safety managers and various construction population. It is ideal owing to the diversity of the people from different backgrounds. To make the guidelines laid out in the thesis available as an E-learning tool, further work will need to be carried out to place animated videos of step-by-step process of designing trench excavation simualtions.

Chapter 6

Systems Dynamics Model: To Help Predict Company Behavior Towards New Safety Protocol

Chapter 6 details the methodology approached to build a systems dynamics (SD) model using the Vensim PLE research software. The goal of using systems dynamics as a part of the thesis is to establish the outcome of using FEM as a safety program for construction companies focused in trench excavation. The simulation aims to help management level decision for adoption of the FEM safety protocol by highlighting the difference between the current protocols and predicting a future trend if the FEM safety program is implemented. The data collection, methodology and analysis of results of the model are discussed in the chapter 6. The model is presented as a proof of concept to show that systems dynamics would be ideal to test the impact of adopting the FEM based safety program in the construction industry.

6.1 Model Development

The systems dynamics model adopted is a modification of the simulator program developed by Owaba and Adebayi, (2006). The simulator program developed by Owaba and Adebayi, (2006) served to predict the performance of a manufacturing safety program. The Table 6.1 represents the findings by CONN-OSHA for the reported incidents related to trench excavations between the years 2003-2005 (Rocheleau, 2007).

Table 6.1: U.S Excavation and trenching injuries and fatalities (Rocheleau, 2007)

Year	Fatal	Non-Fatal	Totals
2003	48	310	358
2004	41	100	141
2005	44	120	164

In order to build the model some of the assumptions made were:

Time lag (T) needed for the learning curve and delay in adoption rate of the new safety program (SP) is neglected because the data used for the model was for short period of time of three years. The number of accidents prior to the new SP is the average of the sum of fatal and non fatal injuries from Table 6.1. The total man hours (q) worked assumes a 10 crew team working for 3 years. An average estimated value of $10,000 per year is assumed to be invested by the company on implementation of safety programs. The difference between pre-safety accident level and prevented accident at any instant of time step (t) defines the potential accident varaible (GL). The accident proneness factor (f) was estimated from total man hours of work force, average number of accidents before SP as 0.01156. From common practice in the industry an average propotion of 0.8 of acutal budget was estimated to be implemented for annual SP.

6.2 Model Equations

Some of the equations used to develop the safety simulator program are shown below. The parameter sued in the equations are explained in the Table 6.2. The Figure 6.1 and 6.2 represent the flow of the systems of equations. For Figure 6.2, the text within the image is for visual reference with respect to the working of equations.

$$GL = Xp - Yt \tag{6.1}$$

$$\lambda = \frac{1}{Xp} \tag{6.2}$$

$$F = qf - Yt \tag{6.3}$$

$$\alpha t = (GL - X) * \rho 1 * h \tag{6.4}$$

$$\rho 2 = 1 - \rho 1 \tag{6.5}$$

$$\gamma t = \frac{R - Yt}{\rho 2} \tag{6.6}$$

Table 6.2: Equation variables and the description

Symbol	Description
Pk	Proportion of planned budget actually expended on training
Bk	Actual budget expended on training
μ	SP activities effectiveness factor
R	Prevention goal
γ	Prevention rate
Yt	Number of accidents prevented
Xt	number of accidents caused
αt	Accident causing rate
F	Hazardous condition
Xp	Potential Accidents
q	Total man hours of work
f	accident proneness factor
$\rho 1$	Probability of accidents
λ	Probability of accident caused parameter
h	Accident causing factor
GL	Potential accidents
BT	Total budget actually expended on the program

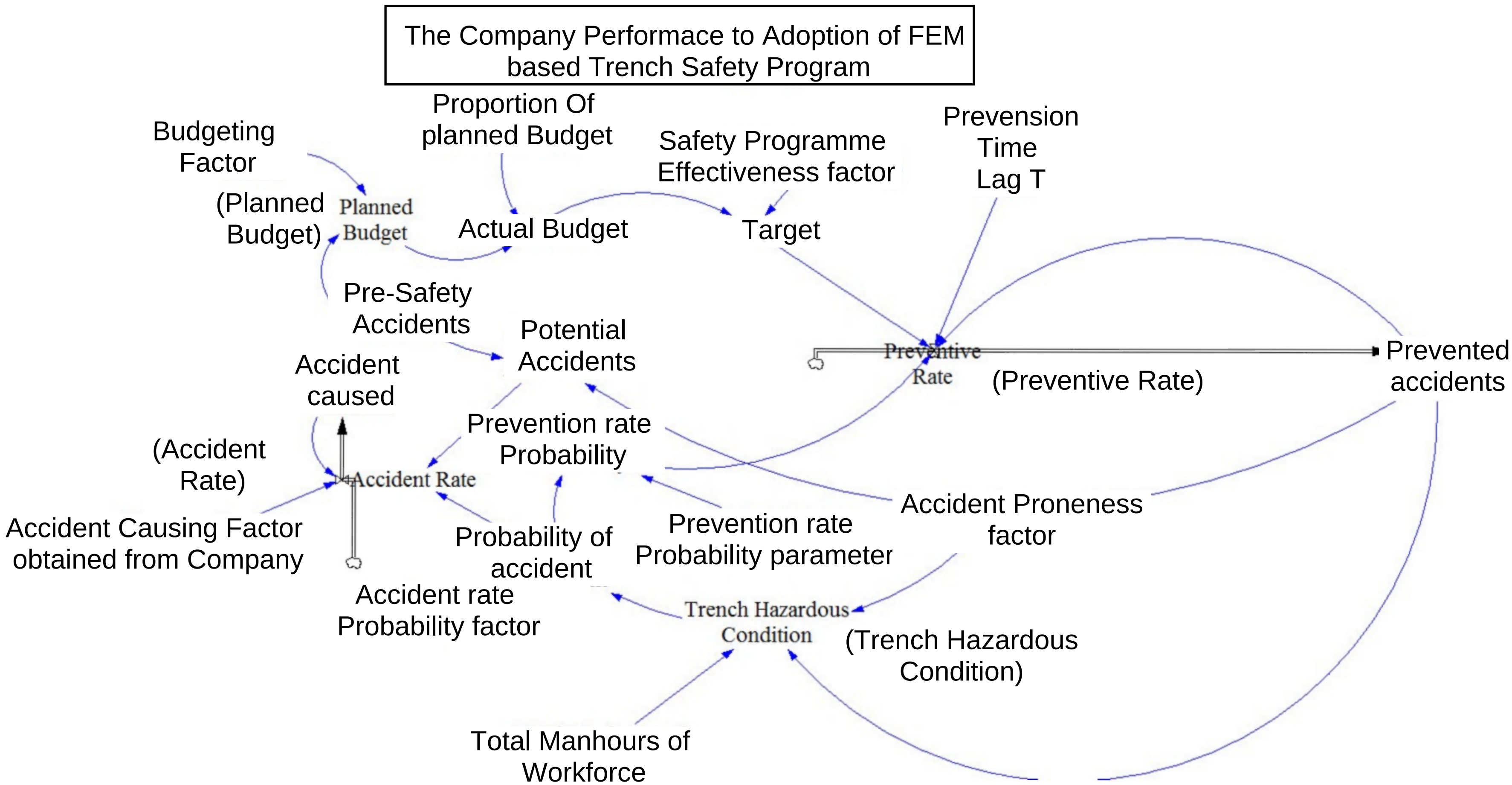


Figure 6.1: Trench Safety Program Simulator

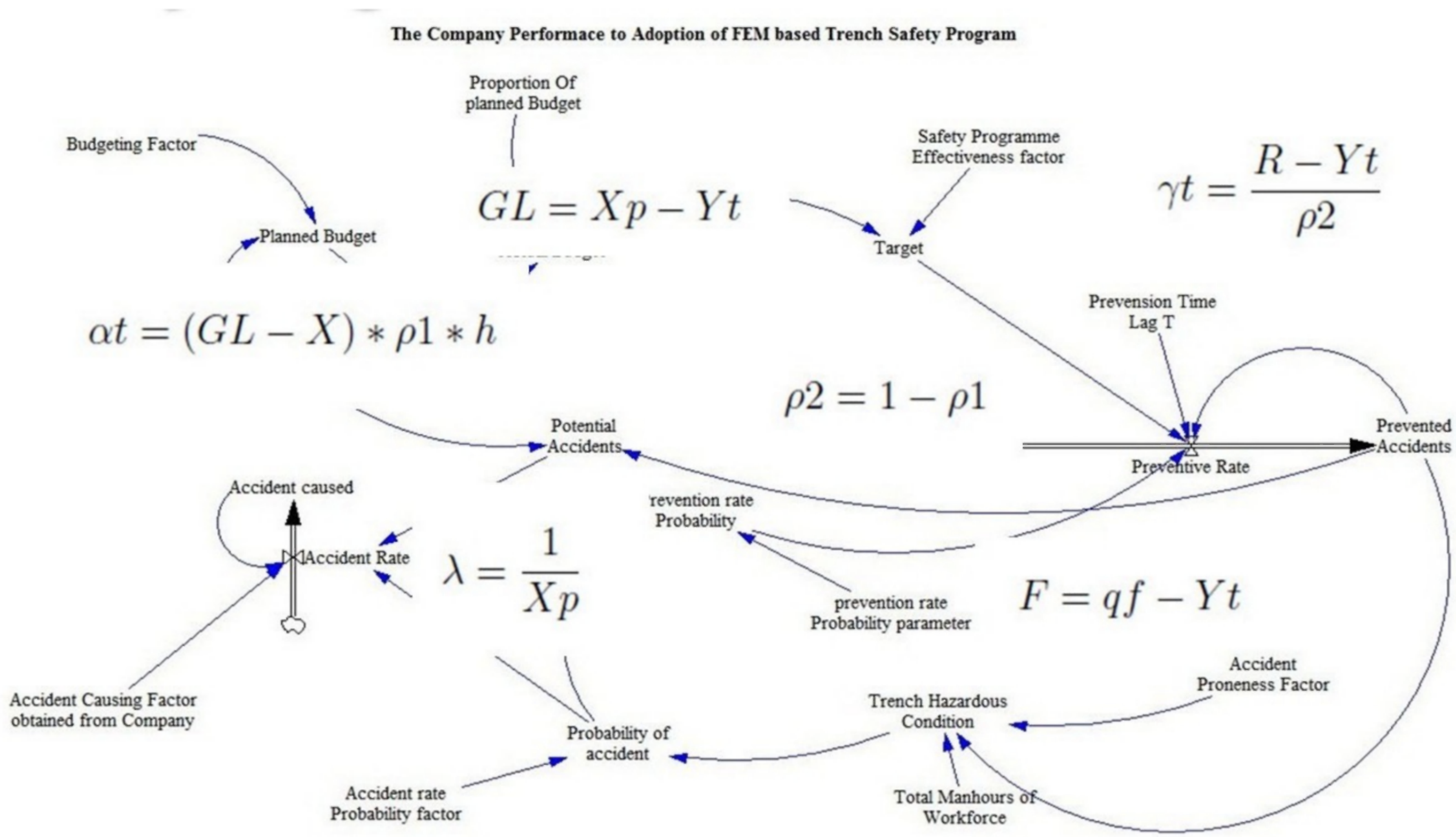


Figure 6.2: Trench Safety Program Simulator. This figure is not meant to be readable, but is for visual reference only.

6.3 Analysis of The Results of FEM Simulation Model

The results of the data are compared by plotting the trends of accidents prevented versus the accidents caused during the implementation of the new safety program. Figure 6.3 shows the results of the analysis.

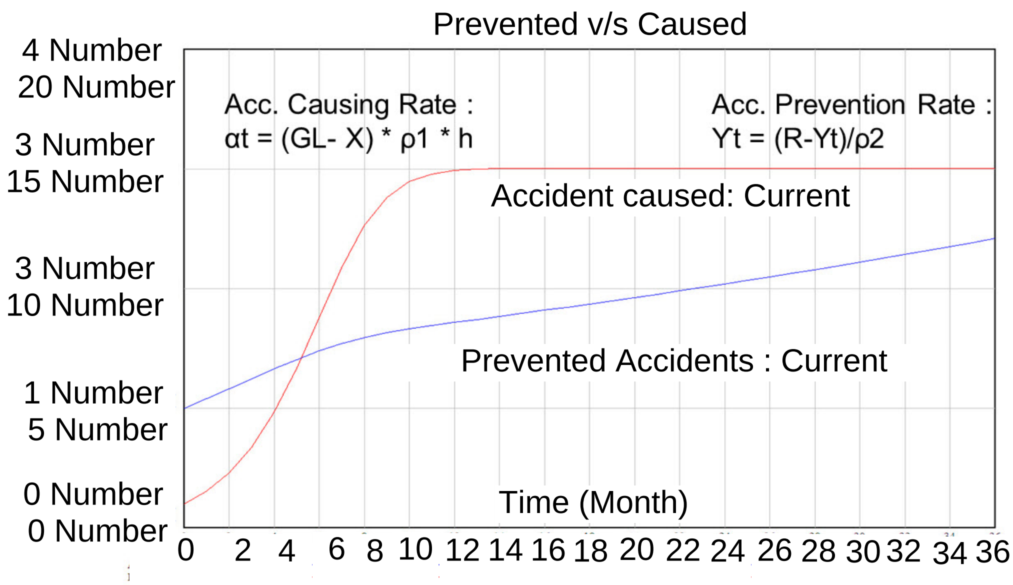


Figure 6.3: Prevented Accidents versus Accidents Caused

The simulation was run for 36 months of simulation time. This time limitation was imposed to keep the results in check with reality because of the limited amount of data used for the simulation. The data acquired as a part of literature review showed the number of injuries and fatalities occurred between the years 2003 through 2005. The national average of incidents in the recent year as reported by BLS (2010), states a number of 20 incidents per year on an average as the incident rates for trench excavation. The results as seen in Figure 6.2 shows us a trend of accidents caused versus the prevented accidents in numbers. The accident caused, as initialized to 1 for realistic purposes, increased to maximum of 2.45 at the end of 36 months, while the curve showing the number accidents prevented, initialized at 0, rose to 15 and stayed constant at the end of 36 months. While such numbers do not reflect realistic accident caused and prevented numbers within the construction industry, they however represent the expected prevention rates and decline in accidents that could occur by using a new and realistic safety protocol. The trench hazardous conditions as simulated by the program show a great improvement by implementing the new safety protocols given in Figure 6.3.

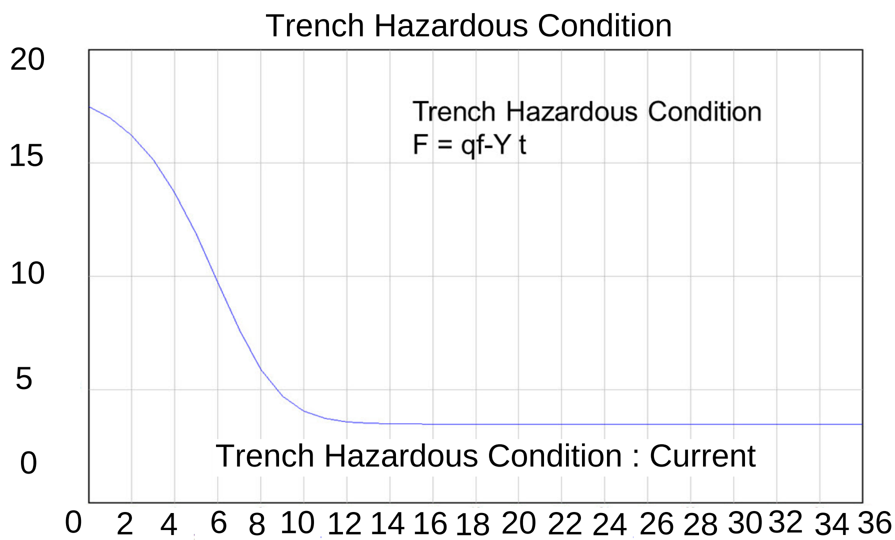


Figure 6.4: Trench hazard Condition

6.4 Limitations of Safety Program Simulator

An effective use of systems dynamics is given to explore the impacts of using a new safety program for a construction company. This model was developed to understand the impact of safety in a single company. The model does not include the dynamics of cost versus market competition trends etc. This is one of the major concerns for construction companies as in the market competition this is one of the major causes for lack of funding imported to safety programs. Due to lack of data for many parameters such as the total man hours worked for 36 months within a company and average estimate of the crew size of 5 people was assumed to work full time for the time period of simulation. The budget for safety program was estimated from interviews with several trenching companies. These companies were reluctant to be interviewed formally for the present research purposes.

Chapter 7

Conclusions

Chapter 7 gives the conclusion regarding the goals and objectives of thesis. The summary of results and significance of the various FEM simulations and the importance of simulation in construction are also identified in the present chapter. Recommendations, limitations of research are also summarized in the chapter.

As given in Chapter 2 involving the comprehensive literature review, the need for a new and predictive method to improve safety in trench excavation projects is stated. The element of unpredictability leads to increased costs of construction and to avoid losses in profits most small sized excavation contractors tend to avoid the required safety measures and have led to highest incident rates in construction industry. Although an established OSHA protocol for trench safety is enough to reduce the incident rates, it is found that the protocol does not address the adverse affects of the protocol for the trenching, and there continues to occur a significant number of injuries and fatalities today. Every time such accidents occur, it puts the construction companies in grave risks of bankruptcy.

The literature review identifies the strength of FEM to predict the behavior of soils of all types. The various aspects needed to successfully model the trench and its associated environment were identified as the type of soil, the mechanical properties of the soil, the moisture content and how they affect the mechanical properties, surcharge pressures, loads imposed on trenches by machinery placed close to trench walls, boundary conditions of the trench and the geometrical shape of the trench itself.

Three different trenches were modeled as discussed in the Research Methodology section of the thesis. Trench with homogenous soil study was modeled to show the response of trench to loads close to the edge of trench walls. The trend of soil cave in as observed in the results of the simulation coincided well with the expectations of the researcher. The model was however not suited visualize the cave-in aspect of trenches, and hence the second simulation aimed at resolving that issue. The 3Dedge crack simulation built to show the cave-in occurrence in trenches was a successful demonstration of a trench consisting of a homogenous soft clay material failing due to over loaded trench walls due to surcharge or soil placement close to trench walls. Finite element analysis performed with ABAQUS of a scenario involving two layers of soils was lastly presented in Chapter 3. The simulation introduced a new level of complexity to previous models.

In order to model a realistic trench with multiple types of soil and all of its complexity a much more comprehensive soil study needs to be performed. The use of ABAQUS CAE FEM program yields promising results as discussed in the Chapter 4. Chapter 5 enlists the a guideline to build a 3-D edge crack formation in a homogenous trench.

A New safety program is proposed in order to incorporate FEM into existing process of trench excavation; the steps are shown below:

a. Bore log data collection

b. Investigate the surroundings of the trench to be dug

c. Identify the major factors which could cause instability of the trench walls such as: Vibration due to existing rail road; Unpredictable weather conditions, etc.

d. Model these parameters in FEM and identify the requirements for a safe trench excavation

e. If cave-in is predicted use trench box. If not required avoid excessive costs Proceed with excavation

SD model was adopted in the present thesis to predict the impact of adopting a new safety program. For making decision, to make a major change in safety protocol in major and minor companies, it usually takes time and evidence of the working nature of the protocol. To establish further confidence in the use of the FEM based protocol a systems dynamics approach was chosen as a suitable option to address such concerns and thereby reducing the time involved in proving the effectiveness of finite element based safety protocol. The SD model captured the current safety program and its effectiveness and also took into account the reliability of FEM predictions to influence a high accident prevention variable in the model.

The model was suitable to the present thesis because it captured a number of soft variables and also introduced noise levels into the model to yield as close to realistic results as possible. The results of the SD model simulation proved to be very helpful in understanding how the new protocol would affect a trench excavation company should they choose to adopt the safety program. The simulation yielded results for a run of 36 months where only 3 accidents were caused in the entire span and 16 were prevented. The costs of required budget for the safety program was also given due importance and the results as observed were from a very modest planned budget for the safety programs. The increase in budgeting factor does not yield any significant difference in the results. This observation is important to be noted for companies looking to invest very little and expecting a change in safety and build more confidence within the company and all its workers.

The following conclusions are drawn from the work described in the Thesis:

1. The implementation of FEM to simulate trench excavation problems can be done quickly with relatively higher confidence.

2. Finite element analysis and instrumentation that helps in monitoring the excavations will be an ideal tool to improve construction safety standards.

3. More detailed soil study prior to excavation and continuous monitoring of soil conditions are highly important in finite element simulations.

4. Systems dynamics models help in predicting behavior for change in company protocol over a length of time yielding realistic trends.

5. Adopting a FEM based safety protocol would set a higher standard of technology in construction and help make the industry safer significantly also improving chances for small sized construction companies to last longer in the industry.

Recommendations for further research in trench excavation finite element simulations are as follows:

1. A more comprehensive real life trench should be dug and simulated using FEM.

2. The bore log details of the soils to be encountered should be accurately investigated.

3. The use of digital sensors to measure the soil stress conditions in real time should be implemented to validate the FEM model and its accuracy.

4. The future research can focus on modeling impact thermal factors and vibrations which could cause significant damage to trench stability over time.

5. Dynamic loading can be accurately modeled assuming moving equipment adjacent to trench walls.

BIBLIOGRAPHY

BIBLIOGRAPHY

Abdelhamid T. S. and Everett J. G., (2000). Identifying Root Causes of Construction Accidents, J. Constr. Engrg. and Mgmt. 126, 52.

ANSYS (2011) CivilFEM geotechnical solution http://www.civilfem.com/solutions/geotechnical. Web. 11/11/2010.

Adhikary D. P., and Guo H. (2009). An Efficient Approach To Numerical Simulation Of Coal Mine-Related Geotechnical Issues, 2009; Retrieved from Proceedings of The International Workshop on Numerical Modeling for Underground Mine Excavation Design No. 2009-141, Pg 6-11.

Bathe, K.,(1967). "The finite element method Publisher", Journal of the University of Cape Town Engineering Society. 57-61.

Bentler, J. D., (1998). "Finite Element Analysis of Deep Excavations". Virginia Polytechnic Institute and State University, U.S.

Brassinga, H. E., and Van Tol, A.F., (1991). "Deformation of a highrise building adjacent to a strutted diaphragm wall", Proceedings of the Tenth European Conference on Soil Mechanics and Foundation Engineering, 10(2), 787-790.

Bureau of Labor Statistics, Career Guide to Industries (2010) Retrieved from United States department of Labor, http://www.bls.gov/oco/cg/cgs003.htm , Web. 05.07.2010

Burns, J.R. (1975). Toward a Mathematical Rigorous Methodology for Simulation of Social Processes, 1975 Summer Computer Simulation Conference, July, pp. 1139-4.

Carlos A.,and Abraham D. M., (2004). Fatalities in Trenching Operations-Analysis Using Models of Accident Causation, 10.1061/(ASCE)0733-9364130:2 (273).

Choudhry, R.M., Fang, D. and Mohamed, S. (2007). The nature of safety culture:

a survey of the state-of-the-art, Journal of Safety Science, Vol. 45 No. 10, pp. 993-1012.

CivilFEM (2011). Geotechnical Module capabilities; CivilFEM INTRO Technical Overview.

Dassault Systemes, (2009). ABAQUS CAE 6.7 Users Manual.

Davis, A., and O'Donnell J. (1997). Modelling Complex Problems System Dynamics and Performance Measurement; Financial Management 75.5 18,18-20. ABI/INFORM Complete.

Dhondt G., (2010). "CalculiX CrunchiX USER'S MANUAL version 2.0", http://web.mit.edu/calculix_v2.0/CalculiX/ccx_2.0/doc/ccx/ , Web. 09.07.2011.

EFQM (2000). Introducing Excellence, EFQM, Brussels.

Eurostat, (2010). Construction Site Safety, Retrieved from Wikipedia, May 28th 2010 http://en.wikipedia.org/wiki/Construction_site_safety.

Finno, R. J., (1992). "Deep cuts and ground movements in Chicago clay", Excavation and Support for the Urban Infrastructure, ASCE Geotechnical Special Publication 33, 119-143.

Forrester, J.W. (1973). Principles of Systems, Wright Allen Press Inc., Cambridge, MA, U.S.

GIT, (2010). Georgia Institute of Technology, Environmental Health and Safety Excavation and Trenching Procedure, Pg2-4.

Landscape management,(2009). Athletic Turf Content, Trenching Part 1: Don't dig your own grave, 21 Jan, 2009, http://www.landscapemanagement.net/athletic-turf-content/news/trenching-part-i-dont-dig-your-own-grave-7937.

LaBaw, S. M., (2009) "Earth Pressure Determination in Trench Rescue Shoring Systems." University of Maryland, College Park. Maryland, U.S.

Lee, F. H., Yong, K.W., Quan, K.C.N., and Chee, K.T., (1998). "Effect of corners in strutted excavations: field monitoring and case histories," Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 124(4); 339-349.

Meguid M.A., Saada O., Nunes M.A., Mattar J., (2008) Tunneling and Underground Space Technology Physical modeling of tunnels in soft ground: A review, 23, Pg.185-198.

Nivar, R.M., (2009). Development of Universal Design Guidelines for E-Learning and E-Training. University of Puerto Rico, Mayaguez (Puerto Rico),. United States – Puerto Rico.

Shawna, M., (2006). Trench Lacked Proper Safety Precautions: The Collapse Trapped Two Workers Tuesday. neither was Seriously Injured. United States, Washington: McClatchy - Tribune Information Services.

NIOSH (2010), Trench Safety Awareness, Trench protective systems and use, DHHS (NIOSH) Publication No.2006-133D http://www.cdc.gov/niosh/docs/2006-133D/flash/index.html.

Norman, D., (2004). Emotional Design: Why We Love (or Hate) Everyday Things, Basic Books,NY, U.S.

Ongsuksun, B., (2009). Three-dimensional analysis of displacements resulting from tunneling in soft ground, University of Colorado at Boulder, 223 pages; AAT 3387516.

Owaba, C., Adebiyi, D.,A.,(2006). The Development of Manufacturing Safety Programme Simulator. Journal of Modeling in Management 1.3 270-90.

Pais, M., (2010). 3D Static Edge Crack; Abaqus XFEM tutorials, https://sites.google.com/site/matthewjpais/3dedgecrack. Web 02.02.2011.

Peck,R.B., (1969). Deep Exccavations and Tunneling in Soft Ground, Proceedings of Seventh International Conference on soil Mechanics and Foundation Engineering, State of the art volume, 7(3), 225-290.

Prentiss, D., (2004). Managing Trench Safety; Water Environment & Technology; Nov 2004; 16, 11; ProQuest Research Library; pg. 33.

Rene E., De, R., Fritzsche, B., and Salas, E.,(2004). Optimizing e-Learning: Research-Based Guidelines for Learner-Controlled Training. Human resource management 43.(2-3) 147-62.

Robert, L.H., (1990) "Engineering and design settlement analysis", Department of The Army, U.S. Army Corps of Engineers Washington, DC, Engineers Manual, EM1110-1-1904.

Rocheleau, R., (2007). CONN -OSHA quarterly Volume No. 49, http://www.ctdol.state.ct.us/osha/qtly-spring07.htm., Web 05.07.2011.

Rotstein, G., (2004). Workers often Ignore Trench Safety Rules, Experts Say. United States, Washington: McClatchy - Tribune Information Services.

Sherif, M., and Chinda, T., (2011). System Dynamics Modelling of Construction Safety Culture. Engineering, Construction and Architectural Management 18.3 : 266-81.

Sims D., Burke C. H., Metcalf D., and Salas E.,(2008).Research- Based Guidelines for Designing Blended Learning, Ergonomics in Design, Vol. 16, 1, pp. 23- 29.

Syrmakezis, C. A. Asteris, P. G. Antonopoulos, A. K. Mavrouli O. A. 2006 Stress-Failure Analysis of Masonry Structures under Earthquake Loading Fracture and Failure of Natural Building Stones, 157-166.

Swan CC,and Seo Y.K.,(1999). Limit State Analysis of earthen slopes using dual continuum/ FEM approaches; International J Num Analy Meth in Geo, 23-12; 1359-1371.

Tamano, T., Fukui, S., Kadota, S., and Ueshitta, K. (1991). Mechanical behavior of bottom ground heave due to excavation, Proceedings of the Seventh International Conference on Computer Methods and Advances in Geomechanics, 7(1), 199-204.

Tee, H. C., (2005). Dynamic Response of Plates and Buried Structures. West Virginia University, West Virginia,U.S.

US Fed News Service (2011), Michigan Occupational Safety and Health Administration Cites Maco Concrete for Willful, Serious Violations in Fatal Trench Collapse (2006),.ProQuest Research Library. http://search.proquest.com/docview/471001466?accountid=12598 Web. 3 Nov. 2011.

Vishnu, C.S, (2009). Stability Analysis Of Spread Footings on Weak Massive & Layered Floor Strata Weak Massive & Layered Floor Strata Using Finite Element Modeling (FEM) ANSYS, http://www.scribd.com/doc/19441924/Ansys-Geotechnical-GeologyFinite-Element-Modeling, Web. 11/20/2010.

Xi ZX (2008). Flow through Granular Dam Filters and Modeling of Particle Migration; International ANSYS Conference Proceedings, Pg 1/4.

Xiadong L., Rodrigo S., and Altschaeffl A., (1998). Cone Penetration Test to Assess the Mechanical Properties of Subgrade Soils,September Joint Transportation Research Program; Project No: C-36-45N; File No: 6-18-13; Pg 18/147

Xiujuan, Y, Shanpo, J., and Xiangzhen Y., (2008). International ANSYS Conference Proceedings, Finite Elements Analysis on Weak Foundation of Oil Storage Tank; Pg 1-14

Zienkiewicz O. C. and Taylor, R. L. 1967 The Finite Element Method, Basic Formulation and Linear Problems, p. 153

Zemke, R., (2001). Systems Thinking. Training 38.2 40,40-46. ProQuest. Web. 30 Oct. 2011