A Risk Simulation Model to Assess Failure Costs in Geotechnical Construction Projects

A Case Study on Building Pit Construction

Master Thesis Project

Student

A. Mavridis

MSc Construction Management & Engineering

Supervision Committee

Dr. J. I. M. Halman (Chair)

Dr. S. H. Al-Jibouri (Supervisor)

Department of Construction Management & Engineering

Faculty of Engineering Technology (CTW)

University of Twente

Tuesday 30th October, 2012

UNIVERSITY OF TWENTE.

Abstract

Selection of a suitable method of procuring construction works is traditionally based on the intuition and past experience of managers overlooking the project. Their intuition is trusted to select the most cost effective means of construction with risk taken into account. Doubt is cast on the effectiveness of this approach, however, when numerous alternative construction sequences are possible.

The potential risk of failure and subsequent failure costs varies depending on the construction sequence selected, and the methods which comprise that sequence. In this research, a model is proposed which simulates the potential risk of failure for all possible building pit construction sequences. In doing so, a cost profile for every plausible construction sequence is generated, which incorporates the potential risk of failure and its impact on cost.

The model overcomes the limitations of traditional construction sequence selection by providing managers with enhanced risk-related information regarding the time, cost and quality of prospective projects.

Preface

This report is my final thesis project which forms part of the Master of Science programme in Construction Management and Engineering which I am undertaking at the University of Twente. It succeeds previous research undertaken within the Department of Construction Management and Engineering in the field of risk simulation and failure costs, culminating in an effort which offers my own coherent proposal.

Completion of the report would not be possible without the support of my supervision committee. I would like to thank my supervisor, Dr. Saad Al-Jibouri, for his excellent support and guidance over the past semester. His opinions on different angles to approach the project were greatly appreciated given its unorthodox and complex nature. I would also like to thank Dr. Joop Halman for suggesting this research topic to me and offering his support.

TABLE OF CONTENTS

1.0 INTRODUCTION

Ever present for construction contractors are the increasing demands and expectations of performance aspects set forth by the clients who fund the projects. The role of the Project Manager, on behalf of the contractor, is to satisfy these demands, relating to time, cost and quality, which are stipulated within the specifications at the design and development phase (Ramanathan et al., 2012).

The fragmented nature of the construction industry's supply chain provides insight into why satisfying these demands is such a complex task. Unlike the automotive industry wherein the development of a prototype design precedes the reproduction of millions of identical products, the construction industry is characterised by unique, one-off developments. As such, the procurement process is likely to involve a multitude of disciplines and parties whom have yet to collaborate. Because each party has its own time, cost, and quality objectives, a fragmented process is born wherein parties perform tasks without full appreciation of the context of the project as a whole. Ineffective coordination and cooperation of the parties involved can ultimately lead to miscommunication. Subsequent delayed or inaccurate transfer of information weakens the decision making ability of the various parties, ultimately increasing the likelihood of a failure to meet these requirements (Love and Irani, 2003).

In construction, the most common form of contracting is the traditional procurement method. This involves a tendering process for the selection of the most suitable contractor, and subcontractors for the various phases of the project, and is usually based on the lowest submitted bid. By using the lowest submitted bid as the primary criteria for selection of subcontractor packages, it is assumed that the cost of the project as a whole will be reduced (Bourn, 2001). Many contractors opt for this method given that the subletting of work packages can include the transfer of risks associated with them. Transferring of risk is important given the complexity of construction projects and their inherent uncertainties. These uncertainties can translate into risks which can ultimately lead to project failures, resulting in time and cost overruns (Imbeah and Guikema, 2009). Although the traditional procurement method is price-oriented, it only exacerbates the issue of process fragmentation and does not deal with the risk of project failures which can ultimately lead to failure to meet time, cost and quality objectives.

Because the industry is plagued by projects experiencing heavy delays and poor cost performance, Project Managers are increasingly inclined to focus on achieving time and cost objectives, in lieu of matters relating to quality (Ramanathan et al., 2012). This paradigm, however, fails to appreciate the significance of quality in achieving value in the longer term (Bourn, 2001). The interrelationship between time, cost, and quality ensures that failure to meet one of these objectives is likely to have an adverse effect on another. For example, a project completed with time delays is likely to incur cost overruns (Ramanathan et al., 2012). Similarly, a failure to meet quality objectives can result in rework, which in turn results in additional time and material costs. Subsequently, a stronger focus on quality may in fact be the key to enhancing project performance in relation to time and cost objectives. In this research, the concept of failure costs in building pit construction projects will be explored, and a risk-based approach to assessing them will be introduced.

DEFINING FAILURE COSTS

The reported magnitude of failure costs varies significantly. Some literature suggests that failure costs can account for in excess of 15% of the total contract value (Hegazy et al., 2011), while others suggest that as much 50% or more of the total project cost can be attributed to failure costs (Frimpong et al., 2003).

Existing literature has linked failure costs to terms such as quality failures, quality deviations, defects, rework, and non-conformance, and has defined them as the cost of "doing something at least one extra time due to non-conformance to requirements" (Hwang et al., 2009).

Hegazy et. al describe the importance of distinguishing between two types of failures – product and process failures, and understanding that product failures ultimately emanate as a result of process failures occurring (Hegazy et al., 2011). Love et al. describe these process failures as project pathogens, or latent conditions (Love et al., 2009). Project pathogens relate to flaws within the underlying mechanisms of an organisation, such as deviations from traditional practices throughout the construction process. These deviations can include compiling design documentation based on tentative information, or underestimating the time required for an engineering design. When these pathogens coincide with an *active failure* such as mistakes, lapses or slips, failures can occur.

In this study, failure costs will refer to any additional costs incurred as a result of process or product deficiencies. These process deficiencies will hereon be referred to as *failure sources,* given that they occur at process level, and are a prerequisite in the occurrence of a product deficiency. An example of a failure source may be *poor communication.*

The product deficiencies which occur at product, or activity level, emanate as a result of failure sources and will be distinguished as being of either local or global in nature. Hence, a failure source can give rise to the occurrence of a local or global failure. *Local failures* are those which occur at product, or activity level, and do not affect the likelihood other failures occurring within the construction process. The failure costs are therefore isolated. These local failures may include incorrect pile length, damage to a concrete pile, or a broken window. *Global failures* also occur at product, or activity level, but also affect the likelihood of other failures occurring. The failure therefore has a global effect, and the failure costs may not be isolated to the specific activity wherein the failure occurred. An example of a global failure in building pit construction may be foundation damage. As well as incurring failure costs specific to the damage, it is a global failure given that it also increases the likelihood of other failures occurring within the building pit construction process.

1.2 PROBLEM DEFINITION

It has been reported that up to 50-85% of failure costs in building construction are either directly or indirectly related to building pit failures; that is, failures associated with underground construction works (Oude Vrielink, 2011). It is imperative then that managers are equipped with decision support tools which assess the potential risk of these failures in order to minimise their impact.

At present, project managers "… lack appropriate decision support tools for simultaneously addressing project risks due to cost, schedule, and quality" (Imbeah and Guikema, 2009). Additionally, many tools which do exist simply reactively assess past, completed projects to determine the causes of failure costs, and do not offer advice for the risk assessment of current and future projects. Faith is often placed in the intuition and past experience of Project Managers in selecting the most appropriate method of carrying out construction projects. A tool is needed which can assist managers throughout this process, and effectively take into account the vast amount of failure risks involved with multiple methods of construction.

The purpose of this study is to propose a model which intends to overcome the issue of ill-informed construction-method selection, by effectively assessing the potential risk of failure and their associated costs. The following research question must therefore be answered:

- Can the potential risk of failure and failure costs be simulated to provide as a decision-support tool in geotechnical construction projects?

In order to answer this question, the following sub-questions must be answered:

- What failures exist in geotechnical construction projects?
- What are the causes of these failures?
- What are the potential risks, or probabilities, of these failures occurring?
- What are the cost implications of these failures occurring?

The research question and sub-questions will be used to guide this research in order to achieve the research objectives. The following section will now describe these aims and objectives in detail.

1.3 AIMS & OBJECTIVES

The aim of this study is to answer the research question of whether the potential risk of failure and failure costs can be simulated to enhance risk-based decision making in geotechnical construction projects. The following objectives have been outlined as necessary to achieve this aim:

- To identify the methods and activities involved in the building pit construction process.
- To determine the local and global failure risks inherent to these methods and activities, and what their impact is on the time and cost of the project.
- To determine the sources of local and global failure risks, and what factors influence their impact.
- To propose a model which simulates the potential risk of failure in building pit construction processes, for the purpose of assessing both the variation in risk and impact on cost.

2.0 LITERATURE REVIEW

Existing approaches to research in the field of failure costs vary significantly. The following literature review will examine the body of literature on the topic of failure costs in construction in order to determine their strengths and weaknesses, and any gaps in research which may exist. This will provide a theoretical framework for the study and assist in the development of a more well-rounded approach to assessing the risk of failure and failure costs.

TOTAL QUALITY MANAGEMENT

Total Quality Management (TQM) has been touted by some as a solution to managing failure costs in construction. In a study which examined the implementation of TQM practices across a spectrum of 1500 construction firms in the United States, it was concluded that significant economic benefits exist for firms that implement them (McIntyre and Kirschenman, 2000). These benefits include increased customer satisfaction, repeat customers, and reduced rework (Hoonakker, n.d.).

TQM is essentially a managerial philosophy developed for the manufacturing industry which looks to enhance product and process quality by fulfilling specified requirements (Juran and Gryna, 1988). Theoretically, by implementing TQM practices, product and process quality can be increased, reducing costs associated with failures.

One such practice introduced to the construction industry in recent years is the Prevention, Appraisal, and Failure (PAF) tool for measuring quality costs. The theory states that prevention costs are those associated with investigation, prevention and reduction of failures, appraisal costs are costs associated with evaluating conformity to specifications, and failure costs are those costs resulting from not meeting those specifications (Aoieong et al., 2002). Although this model presents a method of measuring quality costs, defining and measuring prevention costs is problematic. Quality practices are implemented throughout organisations over an extended period of time, and measuring the prevention costs for one project may not be possible. A more quantifiable and simplistic approach to measuring quality costs in construction is required.

A quality management system is essentially about continuous improvement. Quality control practices ensure that products and processes conform to requirements and quality improvement practices look to better these standards (Evans and Lindsay, 2005). Benchmarking models have been introduced which propose methods of formulating Key Performance Indicators (KPI) to be used as a tool for measuring project success (Luu et al., 2008). Process innovations such as database management software to reduce paperwork and improve organisational communication also falls within the realm of TQM (Rezaei et al., 2011). For some time, contractors have been looking to enhance their quality assurance systems in order to be eligible for tenders. A focus on quality, however, can have widespread benefit across an entire organisation.

> *"Only when a continuous improvement philosophy is used in conjunction with an effective QA (quality assurance) system will organisational performance improve significantly".*
>
> – (Love and Li, 2000)

Literature on TQM in construction provides no single solution to reducing failure costs. Instead, it provides recommendations on how to improve product, and process quality performance. TQM, therefore, should instead be implemented as a philosophical framework which forms the foundations of any quality-oriented construction firm seeking to reduce failure costs.

IDENTIFYING SOURCES OF FAILURE

To determine the causes of failures in construction, reactive approaches have been undertaken. A report entitled, 'Critical delays causing risk on time and cost – A critical review', examines the causes of time delays as identified in previously published literature (Ramanathan et al., 2012). Prospective project budgets are based on an estimated duration. Process and product deficiencies which extend this duration subsequently result in additional costs. An extensive list comprising 113 causes of failures was developed and assessed. In an attempt to correlate the data, indices including those which relate to the importance, frequency, severity of the causes were developed based on mathematical expressions. Ultimately, however, discrepancies in how the different authors ranked their lists of failure causes meant that converging them was simply impractical. Basing a model for the reduction of failure costs purely on data collected from differing sources is therefore not the appropriate methodology.

A literature review is an effective method of comprising a list of failure causes. In order to evaluate their importance and impact, however, internal data collection should be performed to ensure consistency and validity. A two-step method, incorporating a literature review for causes, and internal data collection for measuring severity, was used to effect in assessing the factors affecting delays in Indian construction projects (Doloi et al., 2012). Once the list of factors had been ascertained, industry professionals were distributed questionnaires which asked them to rank the factors based on the parameters of importance and impact severity using a Likert scale of 1 (very low) to 5 (very high).

Descriptive statistics using a relative importance index (RII) was used to correlate the input, in lieu of the more traditionally use of standard deviation, given that standard deviation does not take into account any relationship between the individual attributes. Additionally, factor analysis was used to determine the correlation between delays and their sources. An identified failure source, for example, was *lack of commitment* which had a high correlation with the cause of failure, *site accidents due to lack of safety measures*. The simplicity of the Likert scale and the use of statistics to correlate the data is the most practical means of determining failure causes. Additionally, identifying the underlying mechanisms of the failures is equally important in the development of a tool which aims to reduce them. The results of the study, entitled *'Analysing factors affecting delays in Indian construction projects',* can be used to better understand the causal relationship of failures in construction.

The failure source identification methodology described by Ramanathan et al. is simplistic, practical and can easily be applied across different fields of study (Ramanathan et al., 2012). Additionally, Doloi et al. demonstrated that the Likert scale is an effective means of assessing data regarding the severity of these failure sources (Doloi et al., 2012). Both approaches are reactive in the sense that they draw upon causal relations of past failure events. They fail, however, to provide a tool for proactively assessing future failure events. Also, they fail to consider the costs associated with them. Further research must therefore build upon these data collection methods, and implement them as part of a tool which examines the failure sources specific to construction processes and activities.

THE UNDERLYING MECHANISMS OF FAILURES

Understanding the underlying mechanisms of failures is important if the overall objective is to prevent their occurrence in the first place. An article on design errors in social infrastructure projects in Australia mapped these mechanisms in a conceptual systemic causal model based on a case study of two completed projects. Errors in documentation can contribute to "… a 5% increase in a project's contract value" (Love et al., 2011), and as such are specifically focused on in the paper.

> *"The ideal error prevention approach is to view errors as symptoms of underlying problems, and in so doing they become information sources that help explain how systems work".*
>
> – (Love, Lopez et al. 2011)

In mapping these causal relationships, the authors concluded that error prevention is a learning process, and that knowledge management is an integral part of that. While knowledge management may reduce the likelihood of process deficiencies, it does not provide as a proactive tool to evaluate the potential risk of failure of future events. Any tool which can perform this task, however, should incorporate knowledge management philosophy to ensure that it is continuously evolving and accurate in its assessment of failure costs. While this method provides important insight into the interdependencies between failure sources and events, its drawback is its focus on only the documentation phase of the construction process.

THE COST OF FAILURE

In their research, Hwang et al. have attempted to measure the impact of rework on construction cost performance by examining cost data obtained from over 1000 construction projects (Hwang et al., 2009). The authors introduced a Total

Field Rework Factor (TFRW), which basically expresses the cost of rework as a fraction of the overall project cost. By categorising the TFRW data according to industry groups, the nature of the project, the project size, and location, the major areas where rework is prevalent are illustrated. Additionally, by juxtaposing the TFRF against sources of failure, the relationship between failure sources and their associated costs are examined. The article provides retrospective insight into the sources and impacts of failures, however it does not examine the underlying reasons as to why failure events occur, and as such provides no effective means of proactively assessing failure risk and associated costs.

Some research indicates that Quality Management Information Systems (QM IS) are the solution to determining quality costs in construction. A report published by the Construction Industry Development Board (CIBD) in Singapore suggested that "… an effective QM IS would cost about 0.1-0.5% of total construction cost and produce a saving of at least 3% of total project cost" (Love and Irani, 2003). The Project Management Quality Cost System (PROMQACS) is one such model introduced in the research described by Love and Irani (Love and Irani, 2003). Through cooperation with a quality-oriented contracting organisation, the documentation of two completed projects was examined for input into the proposed model. Essentially, the model functioned as a register for every quality failure. For every failure event that occurred, the nature of the problem, the trade/s involved, the cause of the failure, its impact on time and cost, and the classification of the failure were determined. PROMQACS can then be used as a tool to evaluate performance and monitor progress of client change requirements, as well as a method of determining the cause of failure events. While this tool does not proactively assess the potential risk of future failure events, it does coincide with the aforementioned importance of knowledge management in establishing an evolving and accurate means of obtaining and managing data.

THE POTENTIAL RISK OF FAILURE

The studies of Hwang et al. (Hwang et al., 2009) and Love et al. (Love et al., 2011)draw a link between a failure event occurring and its subsequence impact on cost. While this data provides important insight into the effect of failure events, assessment of the risks which influence failures is required in order to proactively control costs of future projects.

> *"Due to the nature of the different activities involved, construction projects can be complicated and involve a number of uncertainties such as uncertainties about material delivery times and costs, task completion times and costs, and the quality of work completed by subcontractors. These uncertainties can lead to project risks and can be the cause of a construction project's failure to achieve predefined objectives".*
>
> - (Imbeah and Guikema, 2009)

RISK ANALYSIS METHODS

In an effort to assess the risks associated with construction projects, various risk-analysis methods have been developed. While these methods differ in nature – some are theoretical philosophies and frameworks, while others are practical technical tools – each centre on assessing one or more of the three criteria for project success; time, cost or quality. The following table describes these risk analysis methods, and identifies the benefits of their use, and any drawbacks which limit their effectiveness. It should be noted that this is not a complete list of risk analysis methods, but instead a list of the more prominently used methods in the construction industry.

Table 2.1: Risk Analysis Methods

<table>
<tr><th>METHOD</th><th>OVERVIEW</th></tr>
<tr><td>RISMAN Risk Management Method</td><td>In the Netherlands, the RISMAN risk management method has been widely adopted as a tool to analyse, quantify and manage risks associated with large infrastructure construction projects. The following diagram illustrates the six step process of the RISMAN method (Soares, 1997).

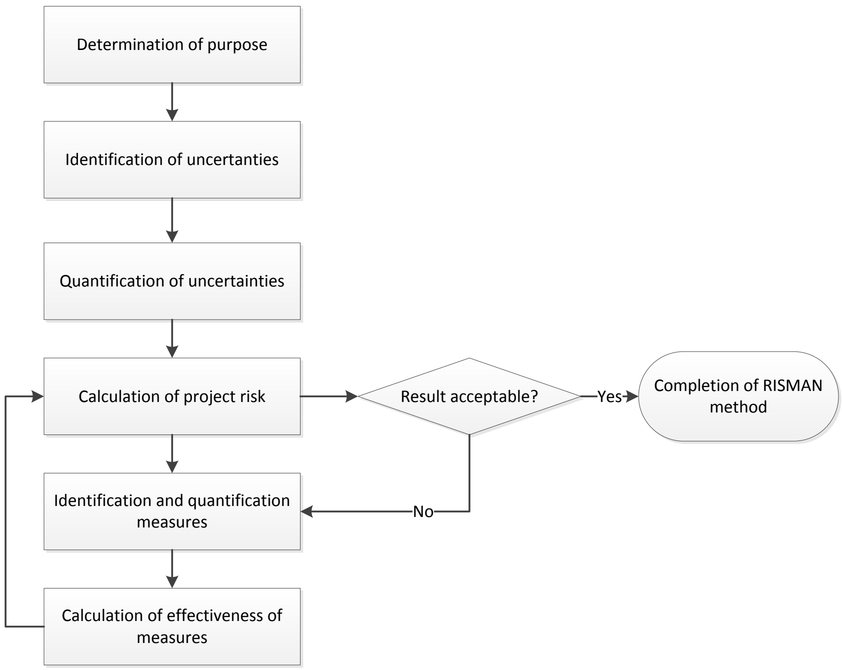

Figure 2.1: The RISMAN method (Soares, 1997).

Determination of purpose involves determining the focus, whether it be time, quality, or cost related. Secondly the uncertainties must be identified and grouped into three categories; normal (due to stochastic nature of reality), special (very low probability of occurrence but high impact), and plan uncertainties (uncertainties at initial stages of project). Uncertainties are then quantified and are used to calculate the level of project risk by means of Monte Carlo simulation. The Project Manager must then assess the risks if necessary given some of them may have changed over time, and new risks may have been identified. Once the results have been deemed</td></tr>
</table>

	acceptable, the process has been complete. The benefit of the RISMAN method is that it provides the Project Manager with a methodological and proactive decision support tool to help control risks. A pitfall of this method may be that it deals with risk from a broad perspective, and does not examine the causes of these risks or how risks interrelate with each other.
Computer Aided Simulation for Project Appraisal and Review (CASPAR)	Computer Aided Simulation for Project Appraisal and Review (CASPAR) is a project management tool designed to assist with the control of time, resources, cost and revenue throughout the entire duration of a project (Willmer, 1991). Two software programs, the CASPAR cost program and the CASPAR time program, can be used to map the sequence of activities of a construction process in a precedence network. Based on the estimated time, cost and resource attributes, the program can provide a single figure estimate of project cost. The time program can subsequently adjust this figure by manipulating the time allocation for each of the activities in the precedence network. Additionally, the CASPAR software allows for sensitivity analysis in order to predict the economic parameters by manipulating the risk variables. The program also uses Monte Carlo simulation to sample values for risk variables and values for the activity durations, providing an output of the earliest, latest and most likely project durations. This method is effective in analysing risks associated with time, and cost, however it does not address risks associated with quality. Additionally, it only calculates risk associated with one predefined sequence of activities.
Schedule Risk System	The Schedule Risk System is a risk analysis technique which "… models the effects of uncertainty on the project schedule" (Mulholland and Christian, 1999). The system consists of three steps; identifying schedule risks, evaluating their effects and the probability of occurrence, and modelling these risks using the

	Program Evaluation and Review (PERT) statistical technique to determine the project's schedule risk profile. What is interesting about this approach is its introduction of a knowledge management program called HyperCard. HyperCard essentially serves as a database of schedule risks which are stored and transferred in every project, to be used at the schedule risk identification stage. The downside of this technique, however, is that it focuses solely on time and can only be used to assess project schedule risk.
Judgmental Risk Analysis Process—JRAP	Judgemental Risk Analysis Process (JRAP) is a schedule risk analysis method. It has been defined as, "… a pessimistic risk analysis methodology or a hypothesis based on Monte Carlo simulation that is effective in uncertain conditions due to its capability of converting uncertainty to risk judgmentally in construction projects". (Oztas and Okmen, 2004). The first phase of JRAP is 'risk identification', wherein the risks which can affect time are brainstormed. Following this is the 'risk measurement' phase, where the probability of these risks occurring, and their estimated impact on the project schedule are evaluated and quantified. The method then uses Monte Carlo simulation to observe the variations in activity durations based on the input of the first two steps. The output of this method provides insight into the likely project duration, the most critical activities, and which risk elements have the greatest effect on project duration. This method, however, does not assess risks associated with cost and quality.
Estimating Project and Activity Duration Using Network	More realistically predicting a construction project's duration requires a methodology which considers the dependency between the activities. A risk management approach has been proposed which uses historical data to associate risk factors with the activities which form the construction schedule. Once the activity durations have been estimated, the risks can be

Analysis	analysed using probability distribution for project duration forecasts, as well as to determine the individual effects of risk factors on the project schedule (Dawood, 1998). This method essentially provides the same output as the JRAP method, and similarly has the same shortcoming of only analysing risk associated with time.
Data-Driven Analysis of Corporate Risk Using Historical Cost-Control	The article, 'Data-Driven Analysis of Corporate Risk Using Historical Cost-Control', makes a distinction between local and "corporate" approaches to dealing with risk (Minato and Ashley, 1998). The first, local method is one which is more traditionally adhered to, wherein the individual risks are analysed upon their own merit. The corporate approach, however, groups 'corporate risks' according to similarity, to ensure that organisations overlooking a portfolio of projects are not overwhelmed by the vast amount of risks which could affect each of their projects. The following equation expresses the total risk of a project according to the authors: Total risk = Dependent Risk + Independent Risk Independent risk involves risks which are unique to a project and will not affect other projects within the portfolio, while dependent, corporate risks are those which arise "…due to interactions of common risk factors among multiple projects" (Minato and Ashley, 1998). Regression statistics are then applied to historical cost data to assess the cost impact of these dependent risks. This methodology is unique and is an effective means of assessing cost performance. It does not, however, consider risks associated with time and quality. Additionally, because corporate risks will vary based on the organisational structure of different contractors, this approach would require extensive data analyses to be performed for every organisation

	looking to adopt it. Consequently, its ability to be universally adopted is questionable.
Estimating Using Risk Analysis—ERA	Estimating using Risk Analysis (ERA) has been propagated as an effective tool for calculating the financial implications of risk for the objective of determining project contingencies (Mak and Picken, 2000). The methodology behind this tool consists first of estimating the base cost of a construction project, with disregard to any possible risks. Then, the project team must identify a list of fixed and variable risks. Fixed risks are those which either occur with complete effect, or do not occur at all. Variable risks, however, are those which have varying degrees of impact on cost. The team must then calculate the average risk allowance and maximum risk allowance for each risk using predefined formulas. An average of these two outputs is then calculated to produce the average risk estimate, and the maximum likely estimate. Although this is an effective method for assessing risks associated with cost for the preparation of tender packages, its shortcoming is its disregard for both time and quality (Imbeah, 2007).
Failure Modes and Effects Analysis—FMEA	Failure Modes and Effects Analysis (FMEA) is a risk assessment tool adopted by the construction industry for the purpose of identifying all possible, potential project failures (Talon et al., 2008). Essentially, failures are assessed according to characteristics such as the cause of failure, and the consequence of its occurrence. Following this, a scale of 0-10 is used to subjectively evaluate "… the likelihood of occurrence of the phenomena, the level of significance related to the consequence of failure of the component and, the degree of detectability of failure" (Talon et al., 2008). This evaluation provides an organisation with insight into the nature of its failures, and can subsequently be used to prevent or minimise the effect of future failure events. Furthermore, FMEA takes into account the

	consequence of a failure in terms of its effect on all three major facets of project management; time, cost and quality, and therefor provides for a well-rounded risk assessment tool.
Program Evaluation and Review Technique—PERT	The Program Evaluation and Review Technique (PERT) is essentially a project management tool for assessing risk associated with time in projected schedules (Malcolm et al., 1959). For each activity that forms part of the construction process, three variables must be given; the optimistic, most likely, and pessimistic estimates of duration. Additionally, flow diagram must be formed which visually represents the dependencies and sequence of activities. Based on this input, the mean duration and variance of each activity can be calculated. PERT provides Project Managers with a means of assessing the risks associated with time, and the different ways in which delayed activity durations can affect the project schedule as a whole (Roman, 1962). While PERT provides an effective means of assessing the risk of activity delays, it does little to take into account risks associated with cost and quality.
Monte Carlo Process	Monte Carlo analysis is a stochastic simulation method which can determine the probability of a project's outcome by running a number of iterations; the accuracy of the output enhanced by the number of the iterations. The accuracy is also dependent on the subjective input that is required before the simulation can be performed. These inputs include quantification of probability occurrence and probability distribution of the risk factors (Akintoye and MacLoed, 1997). The advantage of Monte Carlo analysis is that it can be used to estimate the project cost based on a probable cost distribution, as well as the project duration based on the input of a probable time distribution. Because the accuracy of the output is based solely on the integrity of the input data, this risk analysis method is only suitable should a proficient data collection methodology be in place.

Advanced Programmatic Risk Analysis and Management Model (APRAM)	Imbeah and Guikema (2009) propose the Advanced Programmatic Risk Analysis and Management Model (APRAM) as a solution to managing risk in construction projects (Imbeah and Guikema, 2009). The model, developed for the aerospace industry, essentially comprises of the following steps; determining the total budget, identification of possible system configurations, determination of the residual budget (formulated by determining difference between total project estimate and cost of configuration), identification of technical failures and managerial problems, optimization and determination of technical reinforcement budget, optimization and determination of best response to managerial problems, and selection of the optimal alternative and allocation of residual budget that minimises overall failure risk. Identification of failure modes and assigning probabilities is to be performed "… based on expert elicitation of probabilities with the project management team using established elicitation methods" (Imbeah and Guikema, 2009). APRAM provides mathematical expressions for calculating the cost of failure, and offers solutions to lowering these costs through optimisation of the residual budget. A limitation of this method, however, is its dependency on the project team to subjectively determine the probability of failures. Additionally, because APRAM analyses risk on the scale of material type used, applying the methodology to large projects may prove overly complex and time consuming.

DISCUSSION

The risk analysis methods discussed all provide alternative means of assessing risk in construction. Their applicability and effectiveness depends entirely on the specific nature of the project and the types of risks that need to be analysed. Of the methods analysed, only two provide as a tool for measuring risks of all three project management constraints; time, cost and quality.

The first of these tools is the Failure Modes and Effects Analysis (FMEA) technique. When conducting an FMEA, the cause, effect, and probability of failures are analysed. Additionally, for each failure mode, preventative measures can be recommended in order to prevent their occurrence. This tool does not, however, take into the consideration of risk interrelationship; how one risk's probability may be influenced by project specific factors. The second tool which assesses time, cost and quality, is the Advanced Programmatic Risk Analysis and Management Model (APRAM). The strength of APRAM is its comprehensiveness in assessing the risks on a very small scale; beginning with the types of materials used. This attention to detail, however, is also its pitfall. Larger projects with a wider spectrum of components and materials will inherently involve an exponentially larger amount of risks; an amount which could perhaps be too many to individually assess for every new project. Additionally, relying on the subjective assessment of failure probabilities from the project team at hand for risks associated with material failure and such is not practical. A more valid approach to data collection would be seeking professional advice from those who are most familiar with the failures.

In assessing the risk of occupational hazards in the construction industry, Liu and Tsai (2012) establish that current approaches to risk assessment can broadly be categorised into the following groups; qualitative analysis (checklists, interviews), semi-quantitative analysis (matrix method, FMEA), and quantitative analysis (decision tree analysis, sensitivity analysis). Qualitative analysis is the most popular given the accessibility of the data. The subjective nature of this method, however, weakens the integrity of its output. While quantitative analysis provides the most objectively accurate output, obtaining objective data relating to the cause and effect relationships of risk failures is difficult (Liu and Tsai, 2012).

Consequently, the most practical means of assessing risk in construction is through the application of a semi-quantitative analysis. This involves formulating an approach which uses both qualitative and quantitative assessment methods. Similarly to FMEA, a qualitative means of data collection should be performed, using expert opinion about the sources of failure, the impact of these failures, and their underlying mechanisms.

In order to assess qualitative data through means of a quantitative assessment method, Mahant (2004) proposes the use of fuzzy logic.

> *"Fuzzy logic and fuzzy set operations enable characterization of vaguely defined (or fuzzy) sets of likelihood and consequence severity and the mathematics to combine them using expert knowledge, to determine risk".*
>
> - (Mahant, 2004).

The output of these fuzzy logic operations could then be used as input for a quantitative analysis, such as Monte Carlo simulation. Based on the assessment of the risk analysis methods identified (See Table 2.1), it is apparent that the construction industry lacks a semi-quantitative risk analysis method which can effectively and practically assess risks associated with time, cost and quality. Accordingly, the following methodology will explain a model which can perform this task with the objective of assessing failure cost and their risks in geotechnical construction projects.

3.0 RESEARCH METHODOLOGY

Based on the literature review, the following model has been developed which simulates the potential risk of failure associated with the building pit construction process, and generates cost profiles for multiple construction sequences, inclusive of risk and resultant failure costs. The model draws upon the concept that failure costs emanate from two sources; local failure risks and global failure risks (Hegazy et al., 2011). The model comprises of the following seven stages:

1. Define the activities and methods which are involved in the building pit construction process. The model could easily be applied to another construction process by instead defining the activities and methods specific to that process.
2. Define the parameters of the project and process. This involves all of the unique characteristics and risks inherent to project and the methods which comprise its process.
3. Based on the defined activities, methods, and parameters, generate all of the plausible sequences of construction.
4. Estimate the base costs for each construction sequence based on the production and cost unit rates.
5. In preparation for the Monte Carlo Simulation, assign the assumption input variables.
6. Perform Monte Carlo Simulation for each method within each construction sequence.
7. Analyse the output of the simulations.

The following diagram depicts the seven stages of the proposed model, followed by the research methodology. The research methodology is structured as such that it will systematically describe how the data was collected and applied at each of the seven stages of the model. The following chapter (See Section 4.0) demonstrates how the model can be applied in practice.

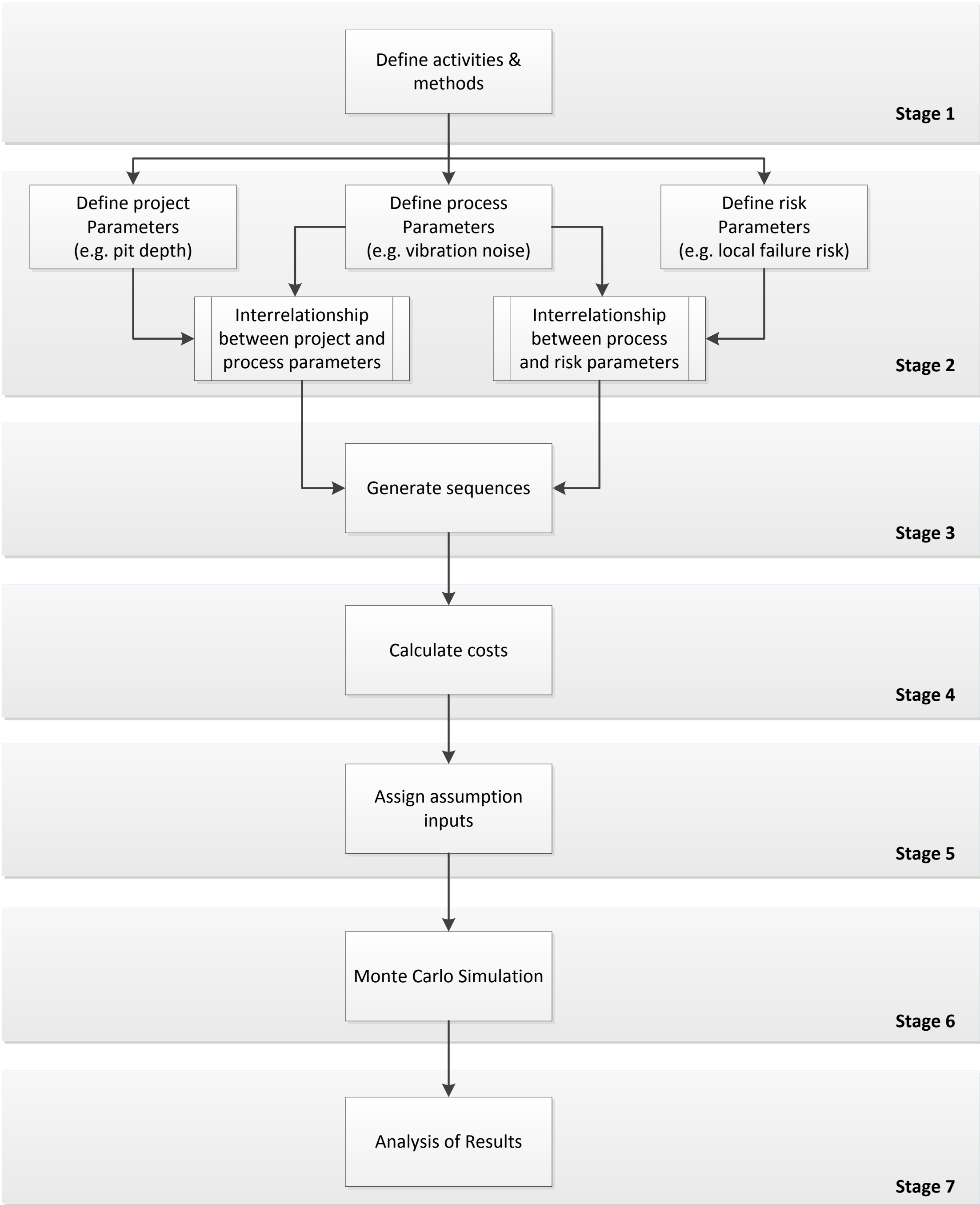

Figure 3.1: Seven stages of the model

3.1 STAGE 1: DEFINE ACTIVITIES & METHODS

A survey research was performed in order to obtain qualitative data for the development of the model. Six experts within the industry were approached for interviews and questionnaires relating to; the methods and activities inherent to the building pit construction process, the sources of failures, and the underlying mechanisms of failure sources.

In order to determine what risks are involved, first the nature of the building pit construction process had to be analysed. Based on the interviews, the following was concluded.

There are two main types of building pits; open and closed.

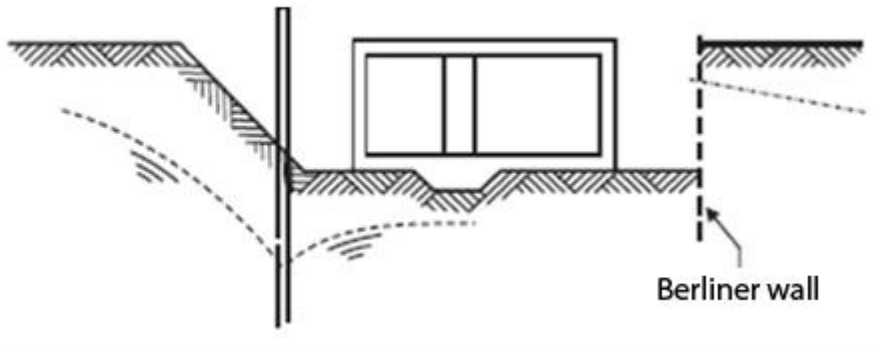

Figure 3.2: Open building pit (SBR, 2007)

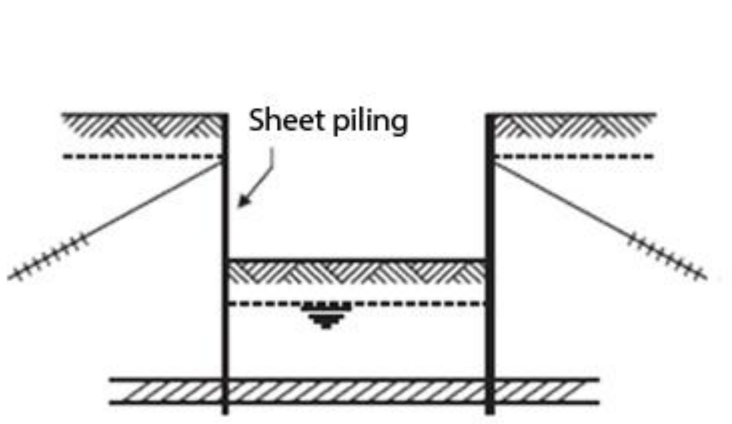

Figure 3.3: Closed building pit (SBR, 2007)

Open building pits are not water tight and are therefore affected by the surrounding water table. Closed building pits are water tight, and therefore are not affected by the water table of the surrounding environment. The proposed model is designed to assess risks associated with closed building pit construction, given that this is the most common form of building pit construction according to the experts.

Closed building pit construction comprises of the following activities and methods:

Table 3.1: Close building pit construction methods

ACTIVITY	POSSIBLE AVAILABLE METHOD
Wall construction	Berliner wall, driven Concrete retaining wall, driven Steel retaining wall (sheet piling), driven Combi-wall, driven Deep wall (diaphragm) Bored-pile wall
Excavation	Dry Excavation Wet Excavation
Pit bottom sealing (waterproofing)	Artificial sealing with concrete Artificial sealing with underwater concrete
Pit foundation	Concrete pre-fabricated piles Hollowed steel piles Linked concrete piles Hollow concrete pipes Tube segments piles MV-Piles
Securing of wall	Strut – steel pipe Anchor
Dewatering	Source pumping

The following tree-diagram illustrates the activities and methods involved in closed building pit construction projects.

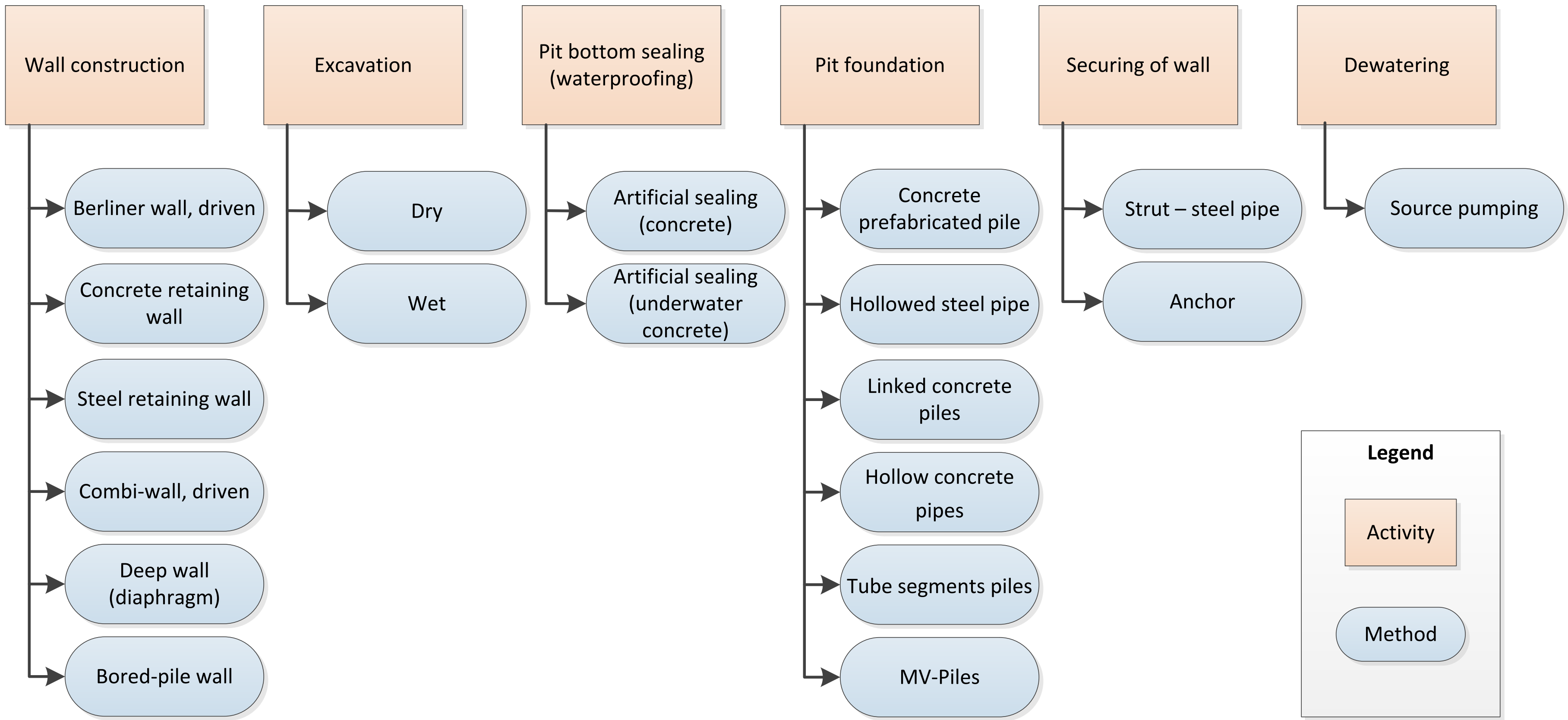

Figure 3.4: Close building pit methods and activities

3.2 STAGE 2: DEFINE PARAMETERS

The parameters essentially describe that nature of the project, the nature of the risks involved, and the limitations of the construction methods available. By defining these parameters, plausible sequences of construction and their inherent risks can be determined. The project, process, and risk-related parameters, as well as how they interrelate will now be described.

3.2.1 PROJECT PARAMETERS

Project parameters are essentially the characteristics unique to a particular construction project. Only when the project parameters are defined can suitable construction methods be selected. The reason for this is that certain construction methods are only suitable in certain scenarios. For example, a particular method of wall construction may not be suitable given that the project has a pit depth of over five metres.

The following parameters were decided upon based on discussion with experts.

Table 3.2: Project parameters

PROJECT PARAMETER
Pit wall parameter
Pit depth
Pit area
Wall maximum length
Acceptable vibration level
Acceptable noise level
Soil resistance; hard layer, medium layer, or soft layer
Soil classification; Sand, clay, or peat
Impermeable layer; present or not
Ground level reference
Ground water level
Surrounding environment
Construction type; permanent or temporal

Estimated building load
Site working space constraint; limited space or sufficient space

3.2.2 *PROCESS PARAMETERS*

Like the project parameters, process parameters that are unique to each construction activity must be defined. These include factors such as maximum length, maximum soil resistance, and maximum depth. Unlike project parameters, these are not unique to every project and can subsequently be used for multiple projects. In combination with the project parameters, process parameters dictate which sequences of construction methods and activities are possible based on the unique characteristics of every given project. The following table comprises a full list of the process parameters.

Table 3.3: Process parameters

ACTIVITY	PROCESS PARAMETER
Wall construction	Maximum wall length Maximum depth Vibration level Noise generation Suitable use: temporal, permanent or both Maximum soil resistance
Pit foundation	Maximum length Vibration level Noise generation Compression load range Tension load range
Securing of wall	Maximum length Compression load range Tension load range

Additionally, at this stage the production and cost unit rates of the construction methods also form part of the process parameters. This ensures that time, cost, and quality for each sequence can be estimated. A full list of production and cost unit rates has been composed (See Section 8.1). It should be noted that the cost rates for each of the activities should be updated to reflect current prices. Additional remarks which could potentially affect the cost of the activities were also stored in a table (See Section 8.2).

3.2.3 Interrelationship Between Project and Process Parameters

The interrelationships between project and process parameters are used to filter plausible methods of construction. For example, a process parameter for the 'Berliner wall' construction method is that the maximum retention depth is 6m. If the project has a parameter of a retention depth being greater than 6m, then the 'Berliner wall' construction method will be excluded from the next phase of the model, sequence generation.

3.2.4 Risk Parameters

The risk parameters of building pit construction essentially comprise of the sources of local and global failure risks, the underlying mechanisms of these failure sources, the local and global failure risks, as well as their impact on time and cost.

Sources of Failure

Industry experts were asked to state which they considered to be the most common sources of failure. This knowledge elicitation process was facilitated by a semi-structured interview protocol based on the following questions.

- How would you define failure costs in construction?
- Based on your experience in the Dutch construction industry, what are the main sources of failure costs in construction projects?
- Can you put these failure costs in order of their likelihood of occurrence?
- Can you differentiate between failure costs in terms of being product-related or process related?

The most important data collected was in relation to the most prominent failure sources. In combination with a literature review, the following 11 failure sources were identified as the most common:

Table 3.4: Failure sources

FAILURE SOURCES
Poor planning and coordination
Poor communication
Poor performance of external parties
Time pressure
Poor quality control
Equipment related problems
Uncontrollable external factors
Design related problems
Site and ground related problems
Motivation problems
Poor workmanship

UNDERLYING MECHANISMS OF FAILURE SOURCES

Understanding the underlying mechanisms of failure sources is important because it tells us how they relate to one another, which most definitely affects the potential risk of failure. For example, the occurrence of one failure source may increase the likelihood of another failure source occurring. Experts were first asked to rank each of these failure sources using a six point scale ranging from "never occurs" to "occurs in every project". Secondly, they were asked to assess the degree to which each failure source correlates with one another, using a 5 point scale ranging from "very low relationship" to "very high relationship".

Based on the findings, the following causal diagram could be developed:

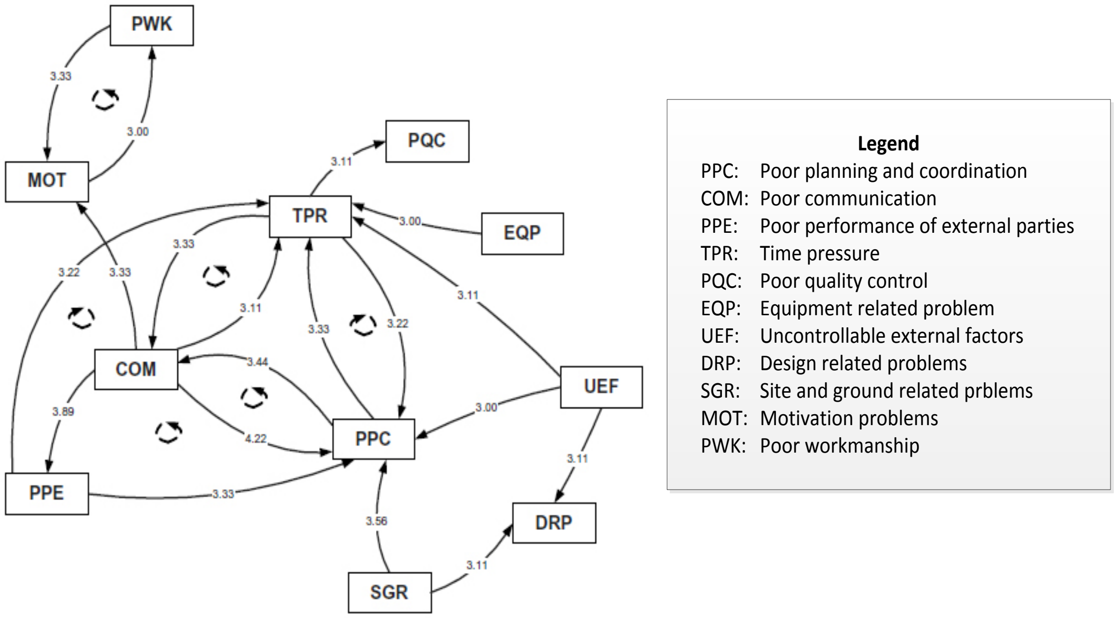

Figure 3.5: Underlying mechanisms of failure sources (Castillo et al., 2009)

Local Failures

Having identified the activities and methods, and sources of failure inherent to building pit construction, experts were asked to identify their local and global risks. Local risks are those which affect only the activity where the failure occurs, whereas global risks are those which, when having occurred, affect the process as a whole. The following table lists some of the local failure risks inherent to the different building pit construction activities. A full list of failure risks has also been composed (Refer to Appendix 8.3).

Table 3.5: Local failures

Local Failures
Sheet pile is not at the correct depth
Sheet pile is out of the lock
Damage to the sheet pile
Insufficient waterproofing of wall
Cement bentonite wall not cured
Pile wall not at the correct depth
Slot instability
Instability of pile wall section

Overconsumption concrete
Different element size
Abnormal strength element
Do not arrive at depth element

GLOBAL FAILURES

The following global failure risks were then identified:

Table 3.6: Global failures

GLOBAL FAILURES	SHORT DESCRIPTION
Damage to foundations due to excavation	If excavation is carried out after laying foundations, it is likely to damage the head of the foundation elements
Deformation of wall due to excavation	If excavation is dry it is likely to triggered a wall deformation because of horizontal load unbalance.
Deformation of the wall due to excavation and dewatering	If excavation is wet then during dewatering of pit it is likely to trigger a wall deformation because of horizontal load unbalance.
Settlement in the surroundings due to vibration during wall construction	If wall construction method generates vibration it is likely to trigger a settlement in the surroundings.
Settlement in the surroundings due to deformation of the wall	If deformation of the wall occurs, it is very likely to cause damage to the surroundings.

For both the local and global failure risks, experts were asked to give a percentage score (with 5% intervals) as to what they perceived the average probability of occurrence being.

METHOD SPECIFIC RISK

Experts were asked to state which methods were more prone to certain local or global failure risks. For example, the 'instability of pile wall section' local failure risk may have a higher chance of occurring should a certain type of construction method be used. Based on these results, the multiplying factors were assigned to construction methods to increase the probability of failure for certain failure events.

IMPACT ON TIME & COST

Additionally, experts were asked to rank the impact on both time and cost for each of the failure risks should they occur, using a Likert scale from one (very low impact) to two (very high impact).

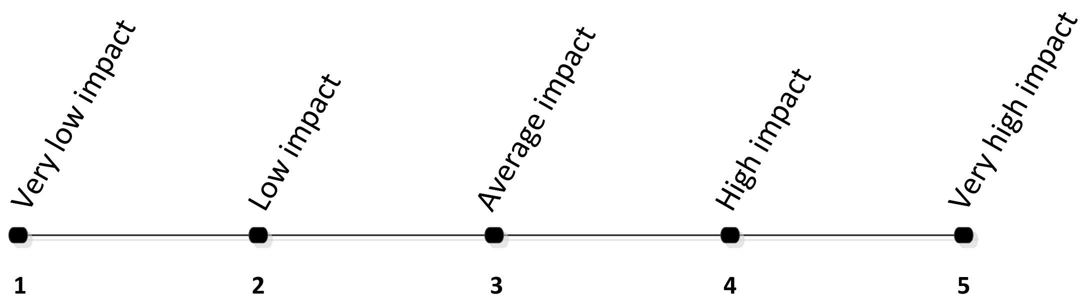

Figure 3.6: Likert scale assessing impact on time and cost

When collecting data related to the impact on cost, experts were shown the following cost-range matrix (See table 3.7). This ensured that realistic figures were given and that answers from the various respondents correlated. A more realistic approach, however, would be to ascertain estimates of the impact on cost from professional cost estimators. Given time limitations, however, this was not feasible. For the purpose of explaining the functioning of the proposed model, it was also not necessary.

Table 3.7: Cost range matrix for impact on cost.

Impact on cost	1	2	3	4	5
Cost range	1000	2000	25,000	100,000	250,000

3.2.5 Interrelationship Between Process and Risk Parameters

A correlation must then be drawn between the process and risk parameters. This involves drawing a link between the process dependencies of failure sources, as well as the failure sources and failure risks.

Process Dependencies of Failure Sources

Once the failure sources had been identified, experts were asked to draw a link between the occurrence of one failure source and its influence on another. Because failures are often linked to each other, incorporating these relationships into failure cost calculation will yield more realistic results. This information was stored in a matrix for future use.

Linking Failure Sources to Local and Global Failure Risks

Experts were then asked to list possible failure sources for each failure event which they considered to be the most likely causes of its occurrence. The following diagram depicts this relationship for the failure risk event of *damage to a sheet pile*, and its five most common sources of failure.

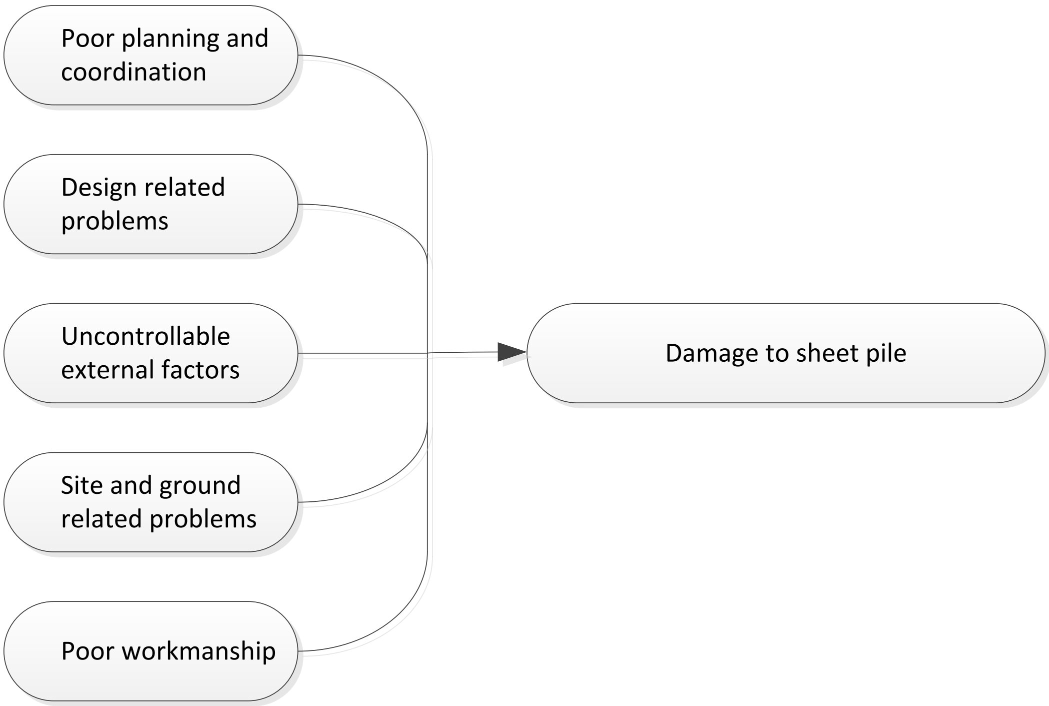

Figure 3.7: Linking failure sources to risks

3.2.6 *DATA ANALYSIS*

The following is a summary of the risk-related data that was obtained throughout the data collection process:

Table 3.8: Risk-related data

DATA	DATA COLLECTION METHOD
Local and global risk failure probability	For each of the risks, experts were asked to give a percentage score (with 5% intervals) as to what they perceive the average probability of occurrence being.
Impact on cost of failure events	Experts were asked to use a Likert scale ranging from 1 (very low) to 5 (very high) to assess the impact on cost for each of the failure events.
Impact on time of failure events	The same Likert scale was used for the assessment of impact on time for each of the failure events.
Failure sources	For each failure event, experts were asked to assign failure sources which they believe most heavily influence that event occurring. Once these three factors had been established, they were then asked to provide a subjective correlation value between the factor and the failure event.

The following section will now describe how some of this data was analysed to ensure applicability with the model.

KENDALL'S COEFFICIENT

Kendall's Coefficient of Concordance was used in order to determine the extent of agreement between the interviewees in relation to their assessment of failure sources. The coefficient provides a nonparametric measure of concordance and is calculated using the following formula:

$$W = \frac{12\sum_{i=1}^{n}(R_i^2) - 3m^2n(n+1)^2}{m^2n(n^2-1) - m\sum_{j=1}^{m}(T_j)},$$

Legend
m = number of groups
n = number of objects
R = overall rank given to variable
T = tied correlation value

Figure 3.8: Kendall's coefficient formula (Siegel and John Castellan, 1988).

The number of groups in this case is three, given general contractors, consultants, and clients were interviewed. The number of objects is 11, given 11 failure sources were identified. The overall rank given to the variable, the failure source, is a range from 1 to 12, ascending from most frequent occurrence to least.

The tied correctional value provides a correction for the effect of repeating, or tied, ranks within a data set, and can be calculated with the following formula:

$$T_j = \sum_{i=1}^{g_j}(t_i^3 - t_i),$$

Legend
t = number of tied ranks
g = number of groups

Figure 3.9: Tied correctional value (Siegel and John Castellan, 1988).

Based on this analysis, a more balanced perspective of the most common sources of failure could be depicted. This formed as a framework for determining the underlying mechanisms of failure sources (Refer to 3.2.2).

FUZZY LOGIC

Once the failure risks had been collected, it was important to grasp that these risks would be affected by the project parameters (Refer to 3.2.2) inherent to the individual project at hand. Estimating risk values for highly specific scenarios, however, is not practical and likely to yield inaccurate results.

Fuzzy logic methodology "…provides a way to characterize the imprecisely defined variables, define relationships between variables based on expert human knowledge and use them to compute results" (Mahant, 2004). By defining value sets, such as low (0-40%), medium (30-70%), and high probability (70-100%), multiple scenarios can be assessed and categorised into one of these groups.

For example, soil resistance has been classified into three groups; hard layer (1), medium layer (2), and soft layer (3). Using fuzzy logic methodology, the following framework could be formulated for the failure event of *damage to sheet pile*, and the construction method of *steel retaining wall (sheet piling).*

Table 3.9: Use of fuzzy logic

SCENARIO	IMPACT ON FAILURE RISK
IF soil resistance IS hard	3
IF soil resistance IS medium	2
IF soil resistance IS soft	1

What this logic states is that the risk of damage to sheet pile, as defined in the data collection stage, will be influenced by a factor of 1, 2 or 3, dependent on the nature of the soil. Fuzzy logic was used for multiple scenarios for a number of different construction methods and risks, and is important because it allows for more accurate predictions

3.3 STAGE 3: GENERATE SEQUENCES

In order to understand what risks are involved in a construction process, it is important to first determine its inherent sequence of activities. Discussion with experts led to a conclusion that only three sequences of activities were plausible. These sequences could be derived by posing the following two questions:

- Is there a natural impermeable layer below the pit which can be used to seal the pit bottom?
- What type of excavation method will be selected?

The following flow chart represents this derivation process;

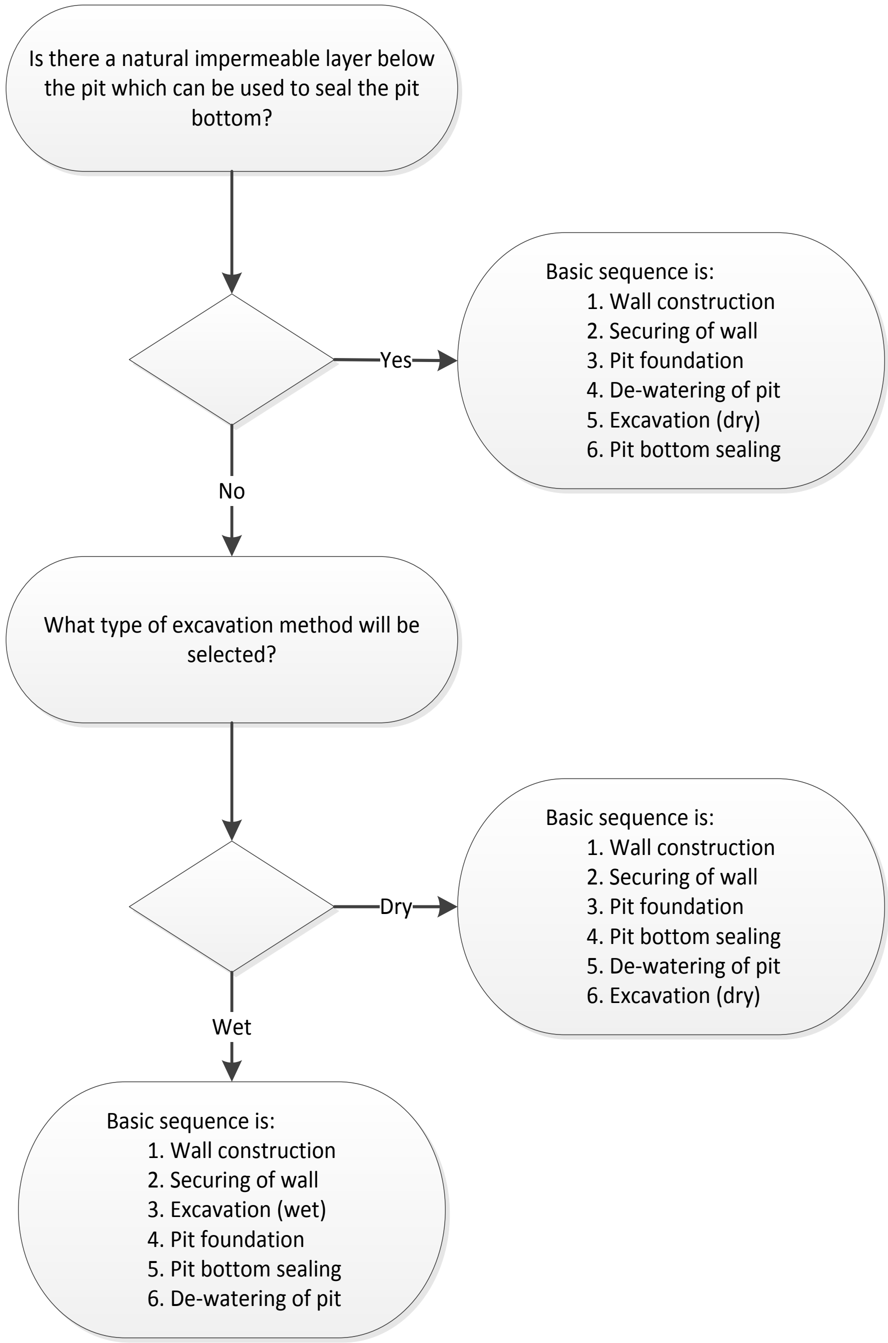

Figure 3.10 Sequence generation based on two closed-questions

The sequence generation phase is dependent upon data input from the 'interrelationship between project and process parameters' stage. Ultimately, there are three fundamental activity sequences of the building pit construction process (See Figure 3.10). The following table depicts these three scenarios.

Table 3.10: three potential closed building pit sequences

SEQUENCE 1	SEQUENCE 2	SEQUENCE 3
1. Wall construction	1. Wall construction	1. Wall construction
2. Securing of wall	2. Securing of wall	2. Securing of wall
3. Pit foundation	3. Pit foundation	3. Excavation (wet)
4. De-watering of pit	4. Pit bottom sealing	4. Pit foundation
5. Excavation (dry)	5. De-watering of pit	5. Pit bottom sealing
6. Pit bottom sealing	6. Excavation (dry)	6. De-watering of pit

The sequence of activities are to be manually selected by the Project Manager based on the conditions of the site, and whether dry or wet excavation is more suitable (See Figure 3.10). The following network diagram displays all possible sequences of methods possible for the construction of the building pit for sequence 1 of activities.

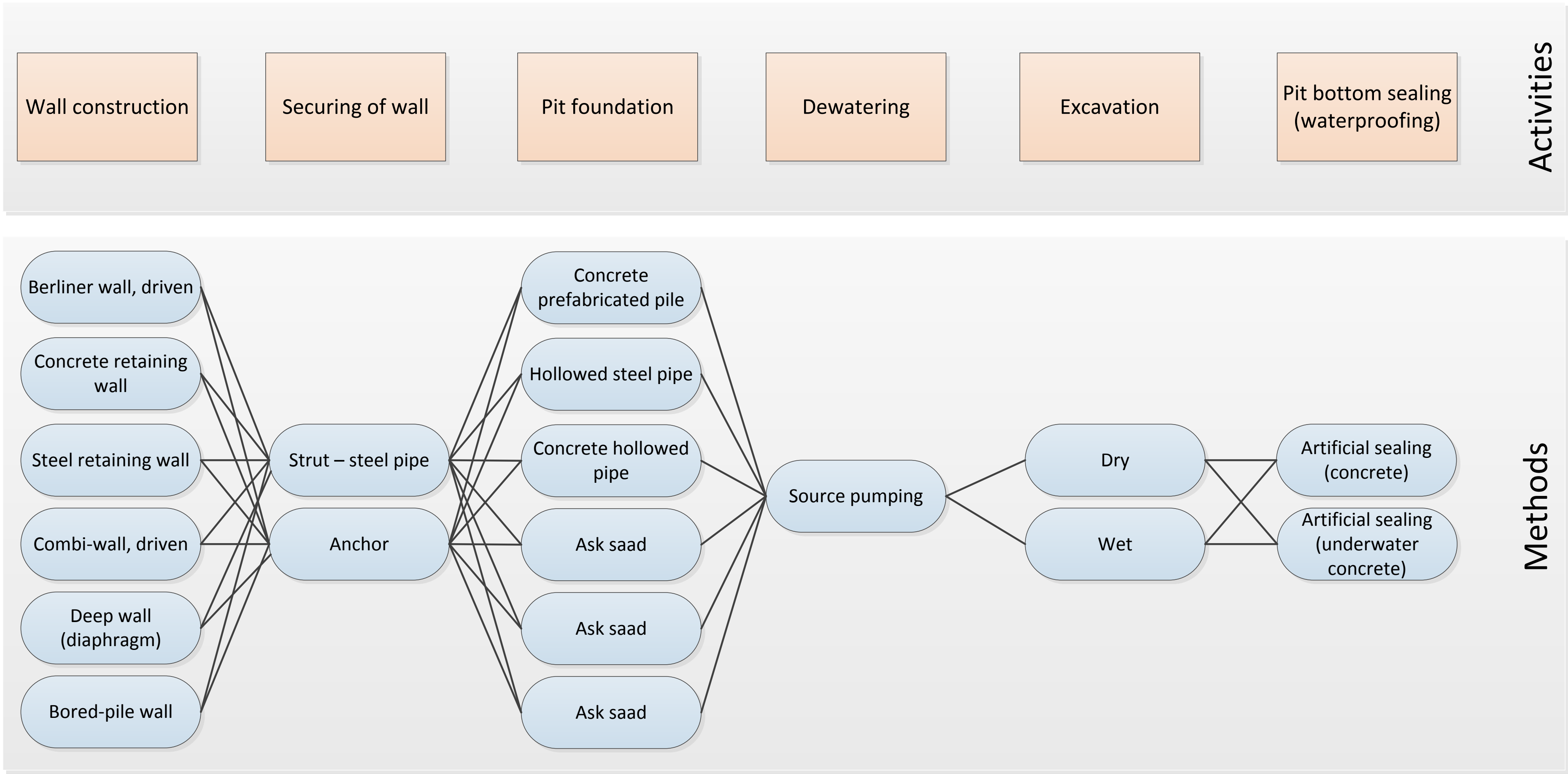

Figure 3.11: Network diagram of construction methods

The following figure indicates that there are 288 possible ways of carrying out the first sequence of construction activities and methods.

Method	Wall construction		Securing of wall		Pit foundation		Dewatering		Excavation		Pit bottom sealing (waterproofing)		
Number of activities	6	x	2	x	6	x	1	x	2	x	2	=	288

Figure 3.12: Number of activities possible for a given sequence of activities

There are two possible means of limiting this number. Firstly, the project manager can choose preferable methods of construction, thereby limiting the total number of methods exponentially. The total number of sequences will also be limited based on the interrelationship between process and project parameters. For example, certain construction methods will not be deemed suitable given the unique characteristics of the project. Based on these two factors, it can be expected that the total number of potential sequences will be a much more manageable sample.

3.4 STAGE 4: CALCULATE BASE COSTS

Having defined the activities and methods, and project and process parameters, the costs can be calculated for each of the generated construction sequences. The following formula illustrates how the total costs for a building pit construction process are calculated. This formula states that base cost of a particular activity has an inherent risk of failure. The cost of a construction activity is therefore the sum of its base cost as well the cost impact of local failure risks for that activity. The cost of constructing a building pit is subsequently the sum of this cost and the cost impact of global failure risks for the given sequence.

Cost (building pit construction) = ∑ (Estimated base cost + Local failure risk) activity *i* + ∑ Cost global risk

Figure 3.13: Cost of building pit construction formula

By substituting cost figures for projected activity time estimates, the duration of constructing a building pit can be represented by the following formula:

Time (building pit construction) = ∑ (Estimated duration + Local failure risk) activity *i* critical path + ∑ Time global risk

Figure 3.14: Duration of building pit construction formula

The following diagram depicts how each activity has local and global failure risks which affect the output of the proposed model:

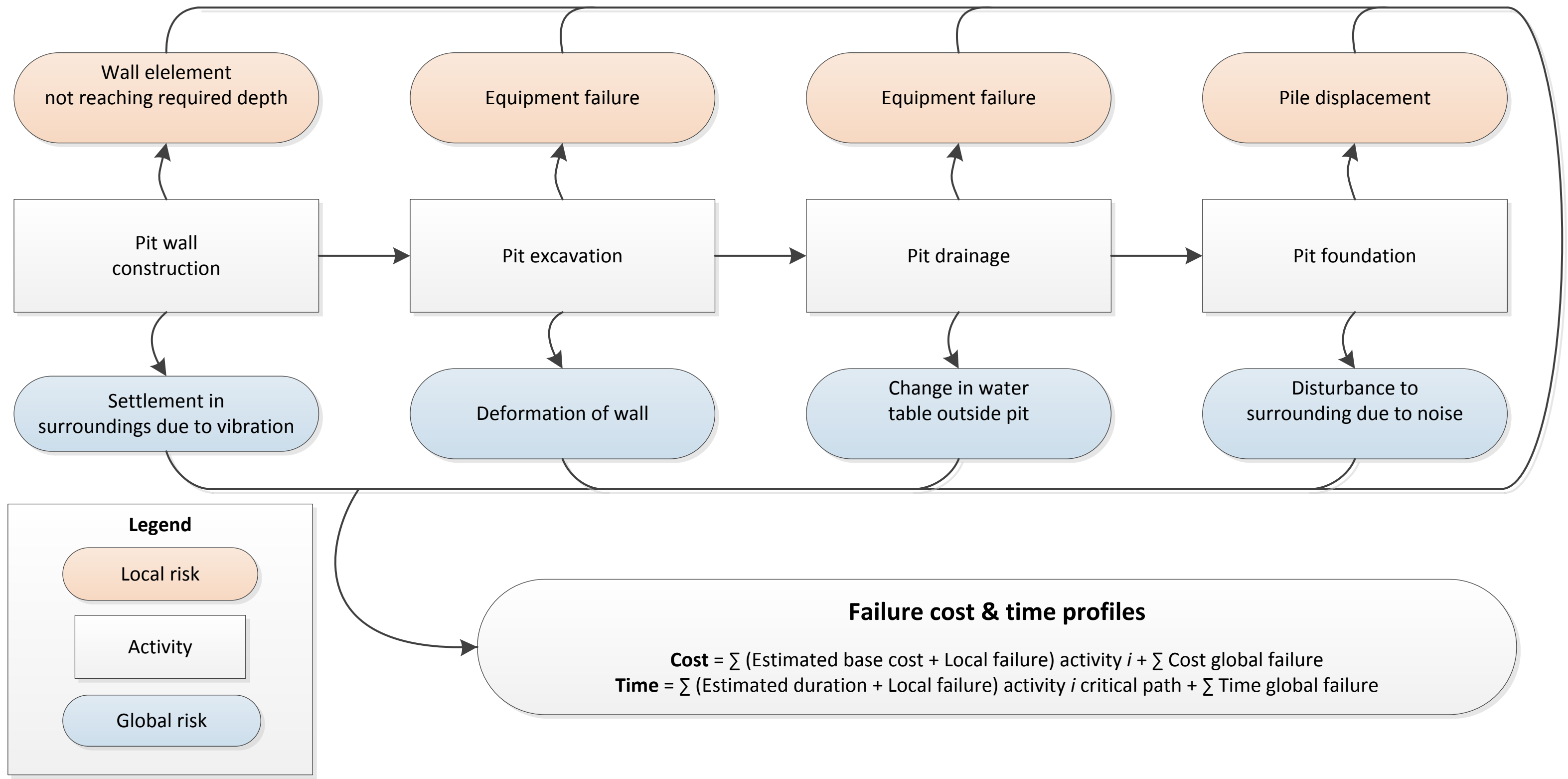

Figure 3.15: Local and global failure risks of a given construction sequence

The formula involves the calculation of base costs and failure costs. In this model, failure costs are determined in the following stage using Monte Carlo simulation. Therefore, at this stage only the base costs must be calculated.

The base costs are simply an estimation of the project costs, based on the methods comprising the construction sequence. The base costs are estimated traditionally incorporating material, labour and plan. See Section 8.1 for a list of production and unit cost rates used in this model. The following section will describe how assumption inputs are assigned to incorporate failure costs to determine the total cost of building pit construction.

3.5 STAGE 5: ASSIGN ASSUMPTION INPUT

In this model, Monte Carlo simulation is used to generate a cost profile for each of the identified construction sequences. As explained in the literature review, the Monte Carlo simulation method uses the quantification of probability occurrence and probability distribution of the risk factors to determine the probability of a project's outcome by running a series of iterations; the accuracy thereby increasing with the number of simulations (Akintoye and MacLoed, 1997).

To define a normal probability distribution, three inputs are required; a most likely value, and a lower (1st parameter) and higher (2nd parameter) value. These values define the variation range wherein the simulation will select a result. The following figure displays this graphically.

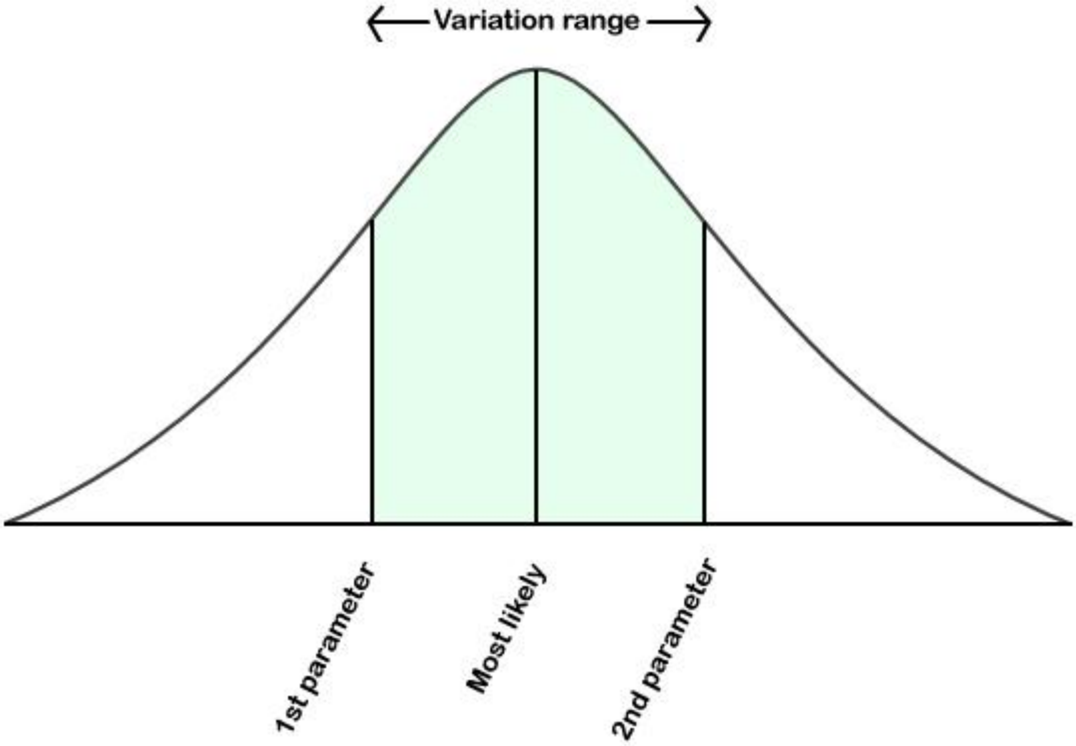

Figure 3.16: Normal distribution graph.

The following table describes how assumption inputs are assigned using data collected for this model.

Table 3.11: Assumption input for use in model

ASSUMPTION INPUT	DESCRIPTION
Most likely	The most likely value of the normal distribution is the estimated base cost of the construction method. This is can be calculated using given production and cost unit rates (See Section 8.1)
1st Parameter	Based on expert advice, the 1st parameter should be 0.9 times the base cost of the construction method.
2nd Parameter	Based on expert advice, the 2nd parameter should be 1.1 times the base cost of the construction method.

Because a construction method maybe susceptible to the risk of a failure occurring, this must be incorporated when defining assumptions. Should a failure event occur, it is the second parameter which will be affected. To adjust the value of input for the second parameter, we must incorporate a risk factor.

Risk of Failure

Risk can be defined as "the product of probability of the hazard and its potential impact", as illustrated in the following diagram (CEEP, n.d.).

Risk = Probability X Impact

Figure 3.17: Risk formula.

The impact on cost and probability of occurrence can then be used to determine the failure cost risk for each construction method. This risk factor can be added to the 2^{nd} parameter to increase the range, ensuring that the distribution is susceptible to the risk of failure costs. Table 3.7 demonstrates how the impact on cost for each failure is determined. The following section will explain how the probability of failure is calculated.

Probability of Failure

To determine the risk of a failure event, both the probability of its occurrence, as well as its impact on cost are required. The probability of a failure event occurring, however, is dependent on four factors; the failure risk, the failure sources, the method-specific risk, and process dependencies. This ensures that the probability of failure is adjusted based on the specificities of the project at hand. The following example scenario demonstrates how the impact on cost and probability of risk failures are used to incorporate risk as input for the Monte Carlo simulations.

Example Scenario

The following example will demonstrate how the inputs would be assigned based on the characteristics of a given construction method. The details of the method are as follows.

Table 3.12: Example scenario of Method & associated risks

Base cost	**Risk 1**	**Risk 2**
€10,000	**Impact on cost** €20,000	**Impact on cost** €2,000
	Probability 0.02	**Probability** 0.34
Risk =	€400	€680

For this example we can determine the following:

Base cost = €10,000

1st Parameter = €10,000 x 0.9 = €9,000

2nd Parameter = (€10,000 x 1.1) + Risk factor

Given we have two risk factors, it is important to select the largest risk factor to ensure that all failure cost risks are accounted for. In this example risk two has a higher failure cost risk. Therefore,

2nd Parameter = (€10,000 x 1.1) + €680

2nd Parameter = €11,680

Using these inputs the following normal distribution graph can be generated.

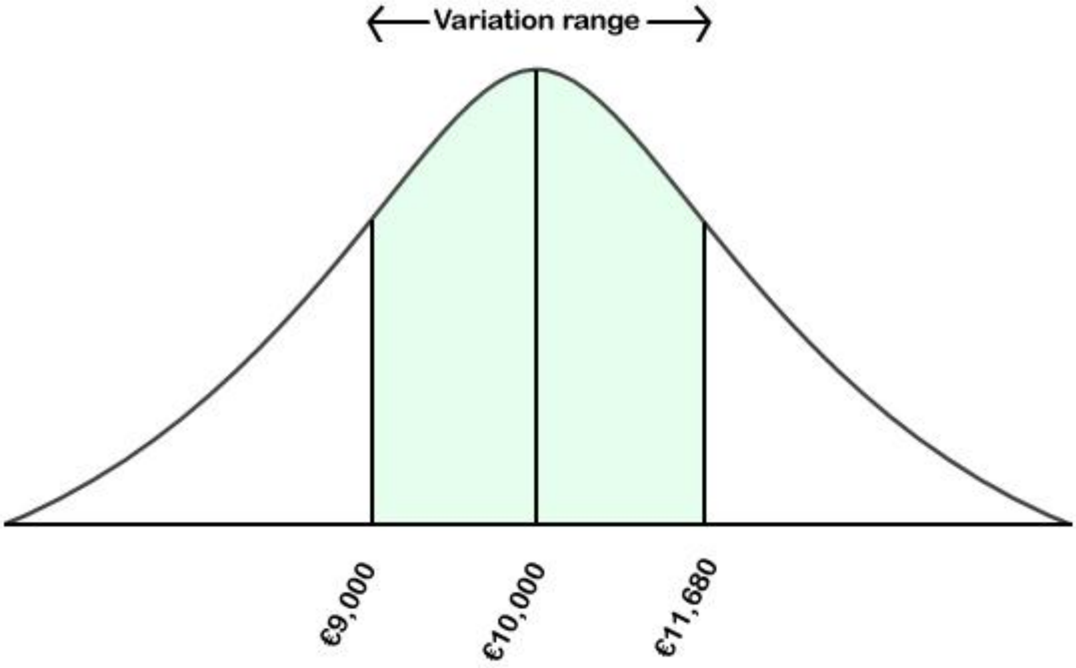

Figure 3.18: Normal probability distribution graph based on example.

When running the Monte Carlo simulation, a random result will be selected from within this range at each simulation. By running the simulation thousands of times, a realistic average will result. By adjusting the 2nd parameter range, it is ensured that the risk of failure and their costs are incorporated. The following section will explain the Monte Carlo simulation process in more detail.

3.6 STAGE 6: MONTE CARLO SIMULATION

In addition to the assumptions required to run the simulation, there following considerations about the functioning of the model should be taken into account before running the Monte Carlo simulations:

- The number of alternatives for a given construction process, as depicted in Figure 3.15, is high given the number of methods that can be used to execute a construction activity.
- A construction alternative is representative of a sequence of construction methods, with a maximum of one method for each activity that forms part of the sequence.

- The selection of one construction method will have an influence over which construction activities can succeed it.
- A number of risks will uniquely affect each construction alternative, given the difference in methods used.
- There are a total of ‘n’ construction methods that can be carried out to perform the construction process.

Figure 3.18 demonstrates how a Monte Carlo simulation can be performed for a specific construction method. A building pit construction process, however, is made up of many construction methods within a sequence. Additionally there are global failure risks which affect the entire process which must also be taken into account. The following diagram represents how a distribution exists for each of the methods within a sequence.

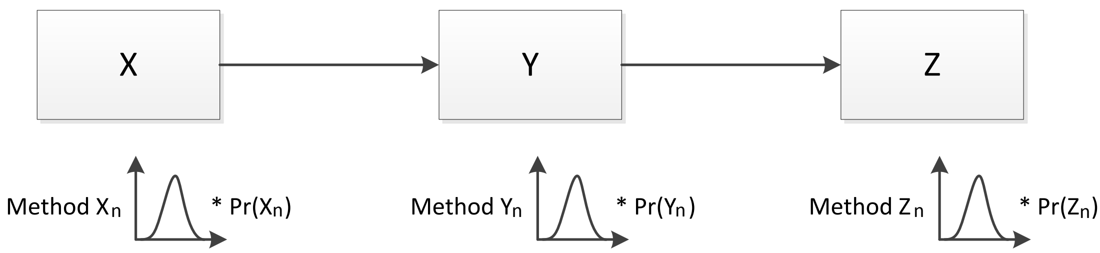

Figure 3.19: Local failure costs of three activity construction sequence

One Monte Carlo simulation involves a random selection from each of these ranges within the sequence, and adding them together. In addition to this, a probability distribution exists for the global failure costs, wherein a random selection is also made. By repeating this process multiple times, the mean average result can be generated for a given sequence, as well as minimum and maximum ranges wherein all of the results occurred. The following describes how this process can equally be applied to the concept of time.

APPLYING CONCEPT TO TIME VARIABLE

Given that the impact on time was also derived from experts for both local and global failure events, the same methodology used to estimate failure costs can be used to determine the impact on time from failure events. Using the impact on time as a variable, Monte Carlo simulation can be used to estimate the time of a construction sequence, incorporating the risk of failure. The impact on time of global failures will similarly be based on the process as a whole, and must be performed after the local failure time impacts have been assessed.

3.7 Stage 7: Analysis of Results

Upon completion of the simulations, analysis of the results is required. A graph is generated which displays a wealth of information, the most important however being the mean total cost, and the range width.

The mean total cost is the mean average of all of the simulations. Essentially, this indicated which construction sequence is most likely to be the cheapest, based on an estimation of the activity costs, and incorporating the risk of failure and its subsequent impact on cost.

The range width indicated the range of the results, from lowest total cost to the highest total cost for a given construction sequence. This is important because it provides insight into the risk involved in a project, and its susceptibility to higher costs.

The strength of this model is its ability to consider risk and its potential effect on the total cost. Analysis of the results requires apt judgement on behalf of the Project Manager in not only considering the mean total cost, but also considering the variation in risk as indicated by the range width.

4.0 MODEL OUTPUT

The following output is from a theoretical test case for a building pit construction project, using the proposed model. In this example, both sequence 1 (dry) and sequence 3 (wet) have theoretically been opted for as plausible solutions (See Figure 3.13). Additionally, the following construction methods have theoretically been considered as being feasible:

- Wall construction: Berliner wall, driven
- Pit foundation: Concrete prefabricated pile, Hollowed steel pile, Betonnen schalkelpaal, Steel pipes, and MV-piles

Based on this input, the following process networks can be devised:

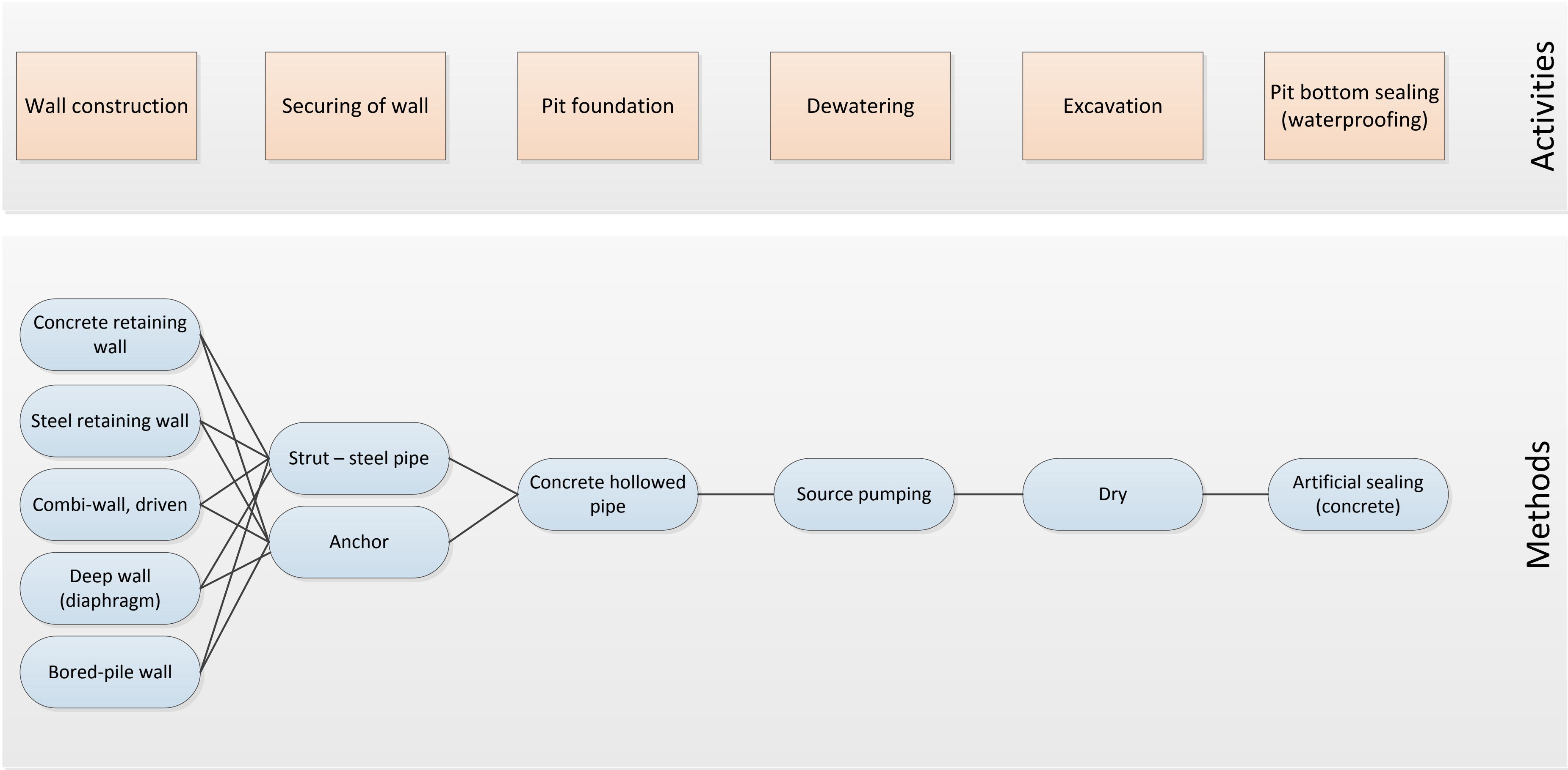

Figure 4.1: Process network featuring dry excavation (sequence one)

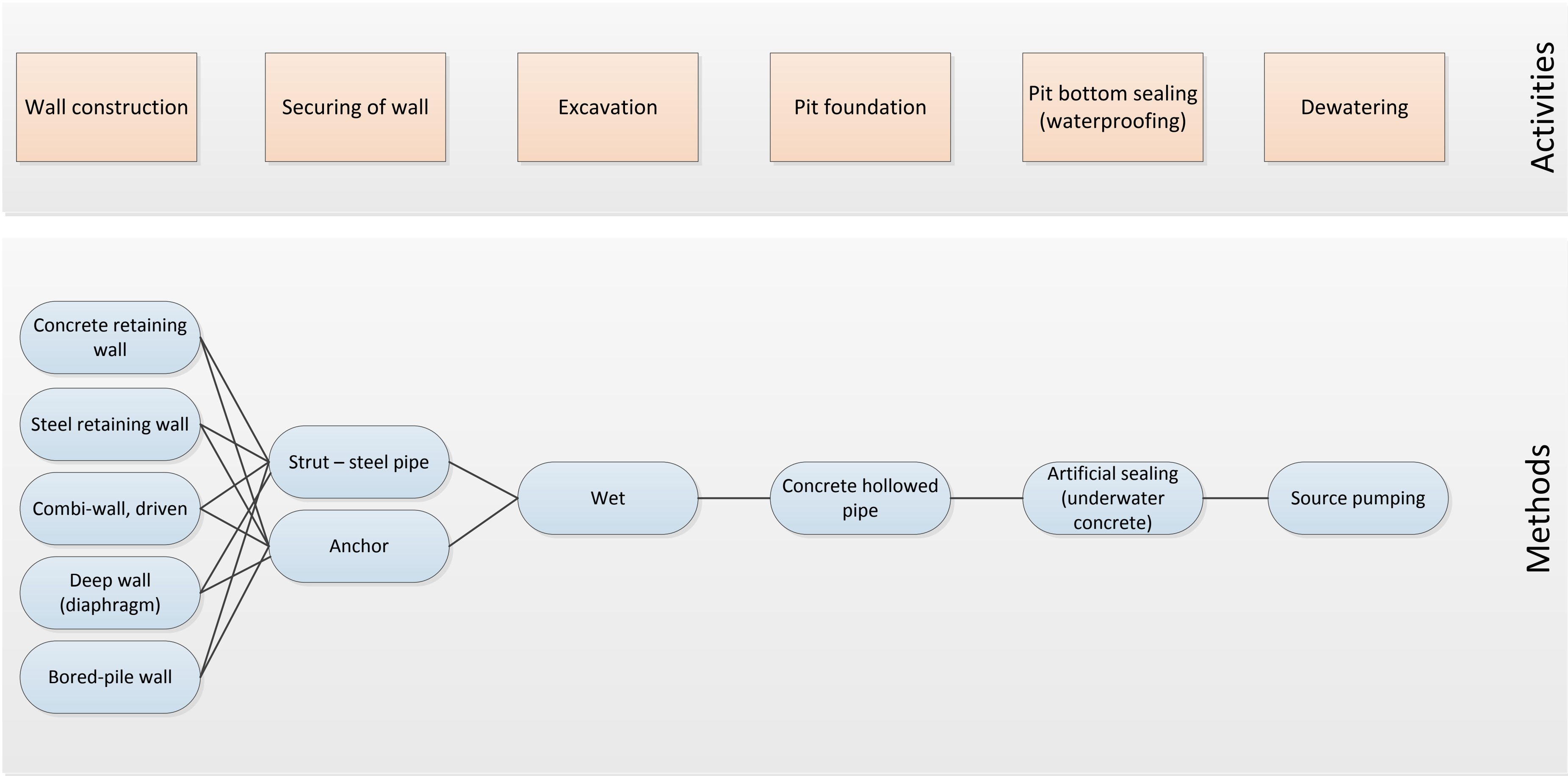

Figure 4.2: Process network featuring wet excavation (sequence three)

As can be seen from Figures 4.1 and 4.2, there are ten alternative sequences for both the dry and wet excavation methods, amounting to twenty alternative sequences. Having defined the project and process parameters, their relationships, and generated plausible sequences, Monte Carlo simulation can be performed. The following table displays the output of these results after 10,000 iterations, in order ascending of lowest mean cost risk profile.

Table 4.1: Output of Monte Carlo Simulation for all cost alternatives

STATISTICS	MEAN	STANDARD DEVIATION	MAXIMUM	RANGE WIDTH
Total Cost Alternative 7	128,753.19	175,629.27	1,355,620.03	1,355,620.03
Total Cost Alternative 8	133,079.39	178,859.43	1,400,379.53	1,400,379.53
Total Cost Alternative 2	136,586.26	172,396.10	1,191,880.05	1,191,880.05
Total Cost Alternative 1	138,211.68	177,033.01	1,202,329.91	1,202,329.91
Total Cost Alternative 9	139,899.47	185,102.28	1,415,317.45	1,415,317.45
Total Cost Alternative 10	141,257.09	183,285.02	1,427,459.34	1,427,459.34
Total Cost Alternative 3	142,694.99	174,806.49	1,177,203.27	1,177,203.27
Total Cost Alternative 5	143,244.29	177,727.40	1,355,313.32	1,355,313.32
Total Cost Alternative 4	146,628.98	176,277.58	1,185,061.26	1,185,061.26
Total Cost Alternative 6	148,385.63	180,036.59	1,347,484.08	1,347,484.08
Total Cost Alternative 17	149,703.91	194,875.28	1,849,634.29	1,849,634.29
Total Cost Alternative 18	153,479.04	196,160.11	1,581,046.84	1,581,046.84
Total Cost Alternative 11	157,109.84	193,487.34	1,480,550.56	1,480,550.56
Total Cost Alternative 19	161,983.91	202,537.94	1,480,720.59	1,480,720.59
Total Cost Alternative 20	162,772.09	200,452.22	1,424,500.26	1,424,500.26
Total Cost Alternative 12	163,922.94	196,744.49	1,519,715.30	1,519,715.30
Total Cost Alternative 13	165,311.85	194,144.30	1,506,523.59	1,506,523.59
Total Cost Alternative 15	165,705.03	192,497.92	1,416,119.33	1,416,119.33
Total Cost Alternative 16	167,374.39	192,582.85	1,316,253.82	1,316,253.82
Total Cost Alternative 14	170,905.01	200,389.21	1,583,981.29	1,583,981.29

The following distribution graph graphically represents the total cost for each of the 20 alternatives, as well as the range width wherein the result yielded.

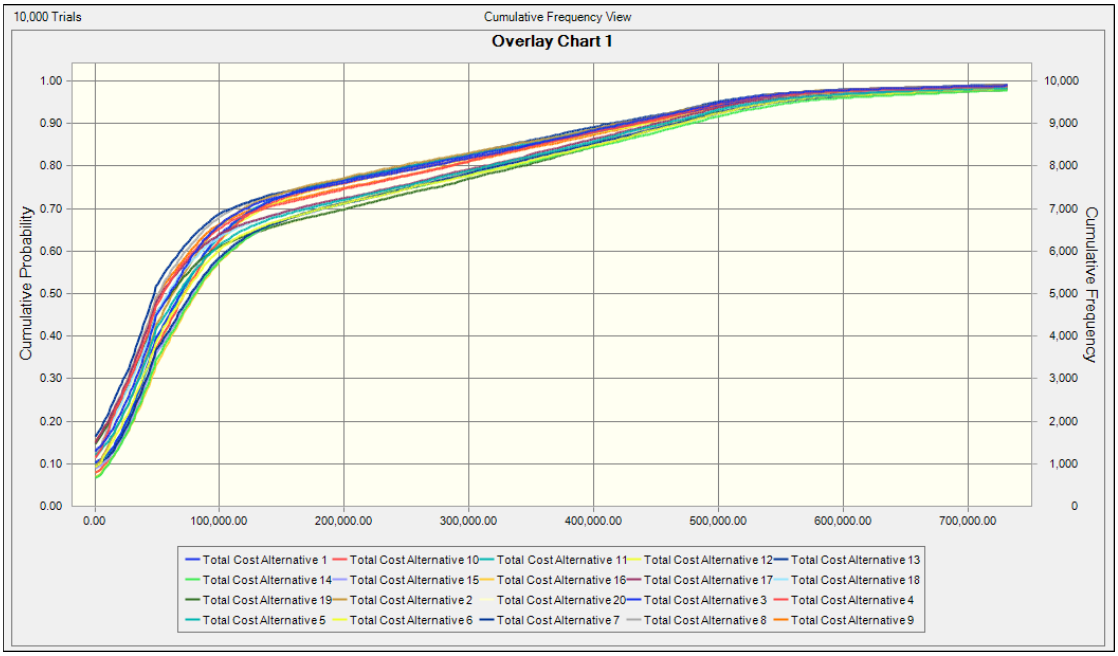

Figure 4.3: Distribution graph for all cost alternatives

Table 4.1 lists the alternative sequences in ascending order according to their mean total costs. The output shows us that Alternative 7 is estimated to have the lowest total cost. The range width however shows it to be more susceptible to risk that some of the other cost alternatives. Alternatives 1 and 2, for example, both yield similarly low cost estimates, yet have much smaller variations in risk. These two alternatives may therefore be considered as favourable options given both their low cost, and low susceptibility to risk.

5.0 DISCUSSION

The output of this model provides as a decision support tool for the selection of construction sequences in building pit construction. It does this by using Monte Carlo simulation to predict the mean total cost inclusive of failure risks. In comparing the results of the different sequences, it is apparent that there are huge variations in relation to the mean costs and risk variations.

There are significant differences when comparing the total mean costs of the different sequences. Also, some sequences display a low total mean cost, yet yield large variations in risk. Others, however, yield high total mean costs, yet represent safe options given their relative low amount of risk. Because these results vary so much, the most striking realisation is the impracticability in relying on Project Managers' intuition in selecting a construction sequence. Additionally, only twenty alternative sequences were tested in this study, yet some construction processes may comprise of hundreds of alternative sequences. Without a tool which can assess these costs and associated risks, it would be difficult to select a construction sequence with confidence that it is cost effective and low-risk, relative to the other potential sequences.

From a Project Manager's perspective, this model could represent a breakthrough in construction sequence selection in building pit construction projects. By assessing the costs and risk associated with failure of multiple construction methods and sequences, this model can take the guesswork out of construction sequence selection. Given the complexity and high risk involved with building pit construction projects, a tool which quantifies such risk, and promotes objective decision making to lower it is exactly what the industry is in need of.

It is not possible to confirm that this model is accurate given that time restriction meant that it could not be tested on real projects. Future studies must apply this model to past completed projects to test its validity. In order to do so, extensive cost and risk related data specific to that project would need to be obtained. If such proposal is deemed to be impractical, the model could be tested on a prospective project. The results of the model could then be compared to those of the project upon its completion.

6.0 CONCLUSIONS

All too often Project Managers base their selection of a construction sequence on past experience or intuition. If a project fail to meet its time, cost or quality objectives as a result of failures, the finger will often be pointed at the subcontractors overlooking those trades. Failure, however, is always a possibility. As such, construction sequence selection must be grounded in a proactive risk assessment approach which assessing the impact of failure.

The proposed risk simulation model provides an effective means assessing the risk related to time, cost and quality of building pit construction projects. The time and cost consequences of failures are determined based on expert advice, and used as input for Monte Carlo simulation which realistically predicts their occurrence. This method takes into consideration the failure events' probabilities and creates cost profiles inclusive of risk for every sequence conceivable. This approach ensures that every possible sequence is assessed according to comprehensive, quantitative risk analysis.

Drawbacks of this model, however, do exist. Firstly, the data collection process is extensive, and the risk data that is obtained is based on subjective opinion. This data may need to be adjusted over time after completing projects in order to represent more realistic probabilities. Also, cost ranges have been used to determine the impact on the cost of failures in this study. It is advisable, however, to use up to date cost data of failure impacts in order to generate applicable results. The comprehensiveness of the model may also be deemed as a drawback for some observants. As shown, closed building pit construction projects can yield hundreds of plausible alternative construction sequences. Running simulations for each of these sequences would require far too much time for any construction contractor to consider adopting the model. To counter this drawback, Microsoft Excel in combination with Microsoft Visual Basic have been used to provide a means of filtering and selecting suitable alternatives based on the project and process parameters. Although setting up and coding this framework requires forethought and time, it later functions as a program which instantly generates all possible sequences. Upon generating the sequences, Oracle Crystal Ball, an Excel add-on which performs probability distributions, can be automatically instructed to perform Monte Carlo simulations using Visual Basic. This study researches the fundamental principles of the model, however, the means of applying it and having it autonomously function is at the discretion of the user.

Use of the model is not specifically restricted to the building pit construction process. The model could be equally effective in assessing the risk in other systems which comprise of varying sequences of procurement and wherein failure costs can occur. The strength of this model is in its ability to assess an overwhelming spectrum of risk. Just because a Project Manager may have worked on several similar projects in the past, does not mean they can comprehend the risks associated with hundreds of alternative construction sequences. This model bridges that gap, and provides a means of simulating risk in order to assess failure costs of prospective projects.

The proposed model is promising given that it logically and systematically quantifies a large body of risk. It can simulate the potential risk of failure and resultant failure costs, ultimately providing as a decision-support tool for geotechnical construction projects. Given that the model has not been tested against real projects, however, the accuracy of its results cannot be vouched for. As such, future work on this model must test it against the risk-related data of real projects.

7.0 BIBLIOGRAPHY

AKINTOYE, A. S. & MACLOED, M. J. 1997. RISK ANALYSIS AND MANAGEMENT IN CONSTRUCTION. *INTERNATIONAL JOURNAL OF PROJECT MANAGEMENT,* 15, 31-38.

AOIEONG, R. T., TANG, S. L. & AHMED, S. M. 2002. A PROCESS APPROACH IN MEASURING QUALITY COSTS OF CONSTRUCTION PROJECTS: MODEL DEVELOPMENT. *CONSTRUCTION MANAGEMENT AND ECONOMICS,* 20, 179-192.

BOURN, J. 2001. MODERNISING CONSTRUCTION. 2000-2001 ED.: NATIONAL AUDIT OFFICE.

CASTILLO, J. E. A., AL-JIBOURI, S. H. & HALMAN, J. I. M. 2009. UNDERLYING MECHANISMS OF FAILURE COSTS IN CONSTRUCTION. UNIVERSITY OF TWENTE.

CEEP N.D. RISK ASSESSMENT TOOL FOR MEDICAL FACILITIES. CENTRE FOR EXCELLENCE IN EMERGENCY PREPAREDNESS.

DAWOOD, N. 1998. ESTIMATING PROJECT AND ACTIVITY DURATION: A RISK MANAGEMENT APPROACH USING NETWORK ANALYSIS. *CONSTRUCTION MANAGEMENT AND ECONOMICS,* 16, 41-48.

DOLOI, H., SAWHNEY, A., IYER, K. C. & RENTALA, S. 2012. ANALYSING FACTORS AFFECTING DELAYS IN INDIAN CONSTRUCTION PROJECTS. *INTERNATIONAL JOURNAL OF PROJECT MANAGEMENT,* 30, 479-489.

EVANS, J. R. & LINDSAY, W. M. 2005. *THE MANAGEMENT AND CONTROL OF QUALITY,* MASON, OH, SOUTH-WESTERN COLLEGE PUB.

FRIMPONG, Y., OLUWOYE, J. & CRAWFORD, L. 2003. CAUSES OF DELAY AND COST OVERRUNS IN CONSTRUCTION OF GROUNDWATER PROJECTS IN A DEVELOPING COUNTRIES; GHANA AS A CASE STUDY. *INTERNATIONAL JOURNAL OF PROJECT MANAGEMENT,* 21, 321-326.

HEGAZY, T., SAID, M. & KASSAB, M. 2011. INCORPORATING REWORK INTO CONSTRUCTION SCHEDULE ANALYSIS. *AUTOMATION IN CONSTRUCTION,* 20, 1051-1059.

HOONAKKER, P. N.D. QUALITY MANAGEMENT IN CONSTRUCTION INDUSTRY. CENTER FOR QUALITY AND PRODUCTIVITY IMPROVEMENT (CQPI): UNIVERSITY OF WISCONSIN-MADISON.

HWANG, B.-G., THOMAS, S. R., HAAS, C. T. & CALDAS, C. H. 2009. Measuring the Impact of Rework on Construction Cost Performance. *Journal of construction engineering and management*, 187-198.

IMBEAH, W. & GUIKEMA, S. 2009. Managing Construction Projects Using the Advanced Programmatic Risk Analysis and Management Model. *Journal of construction engineering and management*, 772-781.

IMBEAH, W. K. A. 2007. *Assessment of the effectiveness of the advanced programmatic risk analysis and management model (APRAM) as a decision suppport tool for construction projects.* Texas A&M University.

JURAN, J. M. & GRYNA, F. M. 1988. *Juran's Quality Control Handbook,* New York, McGraw-Hill

LIU, H.-T. & TSAI, Y.-L. 2012. A fuzzy risk assessment approach for occupational hazards in the construction industry. *Safety Science,* 50, 1067-1078.

LOVE, P. E. D., EDWARDS, D. J., IRANI, Z. & WALKER, D. H. T. 2009. Project Pathogens: The Anatomy of Omission Errors in Construction and Resource Engineering Project. *IEEE transactions on engineering management,* 56, 425-435.

LOVE, P. E. D. & IRANI, Z. 2003. A project management quality cost information system for the construction industry. *Information & Management,* 40, 649-661.

LOVE, P. E. D. & LI, H. 2000. Quantifying the causes and costs of rework in construction. *Construction Management and Economics,* 18, 479-490.

LOVE, P. E. D., LOPEZ, R., GOH, Y. M. & DAVIS, P. R. 2011. Systemic Modelling of Design Error Causation in Social Infrastructure Projects. *Procedia Engineering,* 14, 161-168.

LUU, V. T., KIM, S.-Y. & HUYNH, T.-A. 2008. Improving project management performance of large contractors using benchmarking approach. *International Journal of Project Management,* 26, 758-769.

MAHANT, N. 2004. RISK ASSESSMENT IS FUZZY BUSINESS – FUZZY LOGIC PROVIDES THE WAY TO ASSESS OFF-SITE RISK FROM INDUSTRIAL INSTALLATIONS. BRISBANE, AUSTRALIA: BECHTEL CORPORATION.

MAK, S. & PICKEN, D. 2000. USING RISK ANALYSIS TO DETERMINE CONSTRUCTION PROJECT CONTINGENCIES. *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT,* MARCH/APRIL, 130-136.

MALCOLM, D. G., ROSEBOOM, J. H., CLARK, C. E. & FAZAR, W. 1959. APPLICATION OF A TECHNIQUE FOR RESEARCH AND DEVELOPMENT PROGRAM EVALUATION. *RESEARCH AND DEVELOPMENT PROGRAM EVALUATION*, 646-669.

MCINTYRE, C. & KIRSCHENMAN, M. 2000. SURVEY OF TQM IN CONSTRUCTION INDUSTRY IN UPPER MIDWEST. *JOURNAL OF MANAGEMENT IN ENGINEERING,* 16, 67-70.

MINATO, T. & ASHLEY, D. B. 1998. DATA-DRIVEN ANALYSIS OF "CORPORATE RISK" USING HISTORICAL COST-CONTROL DATA. *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT,* JANUARY/FEBRUARY, 42-47.

MULHOLLAND, B. & CHRISTIAN, J. 1999. RISK ASSESSMENT IN CONSTRUCTION SCHEDULES. *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT,* JANUARY/FEBRUARY, 8-15.

OUDE VRIELINK, M. A. 2011. GEOTECHNISCH FALEN: OORZAKEN EN BEHEERSMAATREGELEN. ENSCHEDE: UNIVERSITY OF TWENTE.

OZTAS, A. & OKMEN, O. 2004. JUDGMENTAL RISK ANALYSIS PROCESS DEVELOPMENT IN CONSTRUCTION PROJECTS. *BUILDING AND ENVIRONMENT,* 40, 1244-1254.

RAMANATHAN, C., NARAYANAN, S. P. & IDRUS, A. J. 2012. CONSTRUCTION DELAYS CAUSING RISKS ON TIME AND COST - A CRITICAL REVIEW. *AUSTRALASIAN JOURNAL OF CONSTRUCTION ECONOMICS AND BUILDING,* 12, 35-57.

REZAEI, A. R., ÇELIK, T. & BAALOUSHA, Y. 2011. PERFORMANCE MEASUREMENT IN A QUALITY MANAGEMENT SYSTEM. *SCIENTIA IRANICA, TRANSACTIONS E: INDUSTRIAL ENGINEERING,* 18, 742-752.

ROMAN, D. 1962. THE PERT SYSTEM: AN APPRAISAL OF PROGRAM EVALUATION REVIEW TECHNIQUE. *THE JOURNAL OF THE ACADEMY OF MANAGEMENT,* 5, 57-65.

SBR 2007. *HANDBOEK FUNDERINGSHERSTEL*.

SIEGEL, S. & JOHN CASTELLAN, N. 1988. *NONPARAMETRIC STATISTICS FOR THE BEHAVIORAL SCIENCES,* NEW YORK, MCGRAW-HIL.

SOARES, C. G. 1997. *ADVANCES IN SAFETY AND RELIABILITY : PROCEEDINGS OF THE ESREL '97 INTERNATIONAL CONFERENCE ON SAFETY AND RELIABILITY*, OXFORD.

TALON, A., BOISSIER, D., HANS, J., LACASSE, M. A. & CHORIER, J. FMECA AND MANAGEMENT OF BUILDING COMPONENTS. INTERNATIONAL CONFERENCE ON DURABILITY OF BUILDING MATERIALS AND COMPONENTS, MAY 11, 2008 2008 ISTANBUL, TURKEY. NATIONAL RESEARCH COUNCIL CANADA.

WILLMER, G. 1991. TIME AND COST RISK ANALYSIS. *COMPUTERS & STRUCTURES,* 41, 1149-1155.

8.0 Appendices

8.1 Appendix 1: Production and Cost Unit Rates

Table 8.1: Production and Cost Unit Rates

Activity	Method	Prod. (hours)	Cost (€)
Wall construction	Berliner wall, driven	42.5/m	1014/m
	Concrete retaining wall, driven	62.5/m	1014/m
	Steel retaining wall (sheet	87.5/m	676/m
	piling), driven	87.5/m	1555/m
	Combi-wall, driven	25/m	4056/m
	Deep wall (diaphragm)	62.5/m	3042/m
	Bored-pile wall		
Excavation	Dry Excavation	50	0.02/m^3
	Wet Excavation	50	0.042/m^3
Pit bottom sealing (waterproofing)	Artificial sealing with concrete	10	0.3/m^2
	Artificial sealing with underwater concrete	-	-
Pit foundation	Concrete pre-fabricated piles	12/m	1.15/m
	Hollowed steel piles	10/m	1.05/m
	Linked concrete piles	11/m	0.85/m
	Hollow concrete pipes	12/m	0.8/m
	Tube segments piles	9/m	0.7/m
	MV-Piles	10/m	1.5/m
Securing of wall	Strut – steel pipe	25/m^2	.25/m^2
	Anchor	-	-
Dewatering	Source pumping	-	-

8.2 APPENDIX 2: EXPERT REMARKS ON ACTIVITIES

Table 8.2: Expert Remarks on Activities

ACTIVITY	REMARK
Wall construction	Based on installation costs, Sheet-wall installation costs represent a quarter of the installation costs of Diaphragm walls; "The difference in costs between Sheet piling and diaphragm wall affects the decision to accept certain risks. For example the ratio in costs maybe 1EUR of sheet wall cost over 4EUR of diaphragm wall. So if the risk of using sheet pile is around 10 to 20%, it is still cheaper to use sheet pile against DW" Based on production rate, Sheet-walls are installed faster than Diaphragm wall. Sheet wall production rate is between 300m2 and 400m2 per day, whereas Diaphragm wall production rate ranges between 80m2 to 100m2 per day; Wall construction based on driven methods are associated with high risk for damaging the surroundings; Bored pile walls are not suitable for depth of more than 6m because of its high probability for not being sealed. This happens when the bored piles being constructed deviate from the vertical axis during construction and this may lead to failures such as filtration of water and ground; Concrete and steel retaining walls are more suitable for soft soil; Diaphragm walls are suitable in hard soil, but can be used in soft soil in case vibration is not tolerable.
Securing of wall	The use of anchors is preferred against the use of struts, unless there is a legal/technical objections for using anchors, e.g. buildings near-by;
Pit foundation	When foundation piles need to be installed inside the pit you can either install them before a dry excavation or after a wet

	excavation. This is important in order to avoid damaging the pile heads. Nevertheless steel piles are less sensitive to be damage by the excavation equipment. "When tension anchors are needed these should be installed after the excavation has been carried out. Otherwise the anchors may be damage while excavating." Sheet piles should not be pressed when soil resistance reaches 20mPa or more.
Excavation	Wet excavation is more expensive than dry excavation Dry excavation costs around 4EUR/m3 and wet excavation about 12EUR/m3
Dewatering	Cost wise "spannings" pumping is more expensive than "bron" pumping. The cost ratio between these two types of pumping is usually 3 to 1; "Spannings" pumping permit usually take between 6 to 12 months, which means that this activity is likely to lead to time delay in case the permit is not granted on time. The type of drainage needed will depend in the type of excavation and in the maintenance of the vertical load level.

8.3 APPENDIX 3: LOCAL FAILURE RISKS

Table 8.3: Local Failure Risks

LOCAL RISK
Sheet pile is not at the correct depth
Sheet pile is out of the lock
Damage to the sheet pile
Insufficient waterproofing wall
Cement bentonite wall not cured enough
Did not arrive at the correct depth pile wall
Slot instability
Instability pile wall section
Overconsumption of concrete
Different element size
Abnormal strength of element
Do not arrive at depth element
Do not arrive at depth anchoring
Succumb stamp / anchor / purlin
Different size / strength / stiffness anchor
Tearing or perforation
Thickness floor is too small
Diameter / height shielded insufficient
Flooding caused by drainage failure
Insufficient overlap of elements
Injection material is washed away
Did not arrive at depth pile
Different quality pile
Different pile capacity
Bases is not compacted
Drainage failure due to wear, clogging, vandalism, etc.
Instability (collapse) wall

Leakage / excavation through holes in wall
Leakage / excavation through holes in floor
By collapsing wall collapse stamp / anchor / purlin
Uplifting pit floor / floor increase
Succumb foundation element
Ground deformation and adjoining recreation ground by drilling or by injection (only sheet piling)
Ground deformation and adjoining properties by compaction / relaxation by ground vibration / drilling of the wall / foundation element
Ground deformation and adjoining properties by surface relaxation by jet grouting next foundation
Deformation under load and adjoining properties by influencing neighbouring foundations by drilling in anchors
Deformation and adjoining land by large deformation / failure of wall / strut / anchor / purlin
Deformation and adjoining land by excavation or leakage through holes in wall
Ground deformation and adjoining properties due to leakage / uplifting by excavation pit floor or heaving