Dura Vermeer Infra
Landelijke Projecten BV

Measures for structural safety – Modelling the human error influence on temporary falsework during the design and construction phase.

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By

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Abstract

Within the Netherlands, the building industry is startled every couple of years by an impactful structure collapse. Even though over the years, a large amount of structural failure investigation reports and studies have provided abundant lessons, regulations, and good practices, structural failures still occur occasionally. The question arises why the existing control measures and regulations have not led to safer building industry, with fewer (or none) structural failures.

A potential answer lies in the occurrence of human errors that always can take place. Unsafe situations, that are the result of human errors can take place unnoticed, due to the lack of overview of the constructed structure in the design and construction process. Moreover, methods to model human error and its consequences, such as the Human Reliability Assessment (HRA), are not commonly applied in the construction industry.

The objective of this research is to study the applicability of the HRA model in the building industry. This is done by evaluating the effectiveness of control measures dealing with human errors for the design and construction phase using a case study. The main research question that is addressed in this work is:

What are effective control measures to apply in practice in structural design and construction, when considering human errors?

The research question is addressed in two ways:

- First, a literature study is conducted to examine the current recommended and applied control measures. Moreover, it assesses how effective these control measures take into account human error.
- Secondly, a model for HRA is introduced to investigate the effect of control measures for a case study. The model is applied to a case study, a foundation pile element from the project Theemswegtracé. A simulation model is used to obtain the results of the design and construction phase to inquire about the effectiveness of the control measures in reducing the number of structural failures.

Literature study

In the literature study the focus is on three topics: Recommended control measures (from reports), the practically applied control measures, and the theoretical effectiveness of these control measures for human errors.

First, the reports regarding the recommended control measures for structural safety are studied. Critical factors regarding structural safety can be found on three levels: the micro-, meso- and macro level [1][2], respectively professional, organisational, and industry levels. Recommended control measures are classified in the same levels, and are often described differently and therefore numerous. The leading guidelines available are Governance Code Veiligheid Bouw and Kennisplatform Constructieve Veiligheid.

Secondly, practically applied control measures are studied at Dura Vermeer, the company involved in this research. On micro level, these control measures were found to be: training individuals and Last-Minute Risk Analysis. On meso level the company works with a checklist, structural safety documents, toolboxes and gate reviews. On macro level, the company is involved with several national structural safety initiatives.

Lastly, it is studied which practical control measures can effectively be taken into account when dealing with the negative effects of human errors. For control measures to be effective when considering human error, they should focus on limiting or detecting possible negative outcomes. The type of errors used in this research is errors of commission, where a

task is performed incorrectly. The type of control measures that are investigated in this study is self-checking, internal review, third-party checking and construction checking.

HRA model and Case Study

In part two, the HRA model is introduced to find out the effect of human error in a case study. The model is based on that developed by De Haan [6][7] and consists of four process steps: 1) The qualitative HRA analysis, 2) Human Error Quantification, 3) Simulation Model, and, 4) Structural Reliability Analysis.

In the first step, the qualitative HRA analysis resulted in the demarcation of the case context, the task analysis and the error magnitude table. The control measures that are taken from the literature study are explained in this step as well. The applied control measures are self-checking, third-part check, and construction checking.

In the second step of the HRA model, the quantification of the human error probability is performed with basic task types adopted from the studies of Hollnagel, De Haan, and Kim. The human error probability states the likelihood of error. The second part of the quantification is to set the error magnitude, the variable representing the severity of the error.

The error magnitude table serves as input for the simulation model, which is step three of the HRA model. All parameters from the error magnitude table are modelled as a micro-task, which is the name of one task simulation in the model. The outcome of the design and construction phase is obtained after the simulation of a complete micro-task series, which is a sequence of micro-tasks. This step also includes the modelling of the control measures, as they affect the outcome of micro-tasks and micro-tasks series.

The last step (4), is the structural reliability analysis. With this analysis, it is determined if the results from the simulation lead to structural failure. The effectiveness of control measures is deduced from the reduction of the failure probability.

Conclusion

Taking into account the literature study and the case study overall it can be concluded that self-checking is an effective control measure to implement in the design phase. The effectiveness is relative and is subjected to the assumptions and context of the case study. Self-checking shows a relative increase between 10-30% of the correct result.

For third-party checking with 5 times random check without self-checking, this increase is between 0.5-1.1% of success probability. With self-checking, the success probability shows no increase and a possible slight decrease in the success probability. The implementation of third-party check is possibly not a reflection of practice. Another possibility is that with self-checking not many errors are left to correct for the third-party check.

Construction checking is an effective control measure in addition to the self-check as it is capable to link the construction phase results with the results for the design phase. Analysing the structural reliability of the simulation results is an effective measure to control structural safety.

All control measures show a smaller spread of output parameter values in the simulation results. It can be concluded that the control measures are working accordingly to the human error theory.

Overall, this research has provided a framework to determine the effectiveness of control measures when dealing with human errors. It is possible to perform sensitivity analysis on project tasks, to find out when control measures are most effective. Therefore, this research brings the practical application of HRA models in the building industry a step further.

Acknowledgements

During my work at a construction site, I noticed the impact of early design choices and corrections in design in the construction phase. In the design phase, some buckling elements were added and as a result, the construction phase became significantly more difficult.
Why was this not added to the design in the first place, and how can one predict or eliminate changes with such an impact in the process?

This trail of thought brought me to HRA methods, and consequently to a finished thesis report. One of which I thoroughly enjoy handing in. The process took some time, and just like most civil engineering projects, it had some delays. However, the HRA methods, modelling of human error and reflection on structural safety made me even more aware of the human impact.

I would like to thank the members of my committee: dr. ir. K.C. Terwel, prof. dr. ir. P.H.A.J.M. van Gelder, ing. J Schilder and ms. X. Ren. This thesis is the result of discussing the problem described above with dr. ir. Terwel, and I would like to thank you for your visions shared throughout the process. Prof. dr. ir. Van Gelder, thank you for the shared knowledge on the human aspect of HRA methods. Mr Schilder and Dura Vermeer, thank you very much for the support throughout the completion of this thesis. I hope it will prove of benefit for future projects or initiatives. Ms. Ren, thank you for all the coffee, the chats and discussions about this topic and everything around it. I am sure your PhD work is worth reading for our successors. Furthermore, I want to thank my family and in particular my parents for all your support. You are the best. And a big thank you to Marre, it's done.

Koen van de Loo

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Introduction

Research context

In the last decade, several big collapses in the building industry made the news and attracted widespread attention to structural safety. After a collapse of a parking garage under construction in Eindhoven in 2017, the Dutch Safety Board concluded in research that, within the project, the collective attention to structural safety was insufficient. [5] For them, it was clear that the main cause of collapses was the same over the years and they released a letter to the Dutch building industry, stating that changes are required. Their recommendations are 1. Less voluntary Construction Safety Governance Code. 2. Ensure overview. 3. Ensure professional critique. [6]

Problem statement

More studies on structural failure find similar conclusions as to the Dutch Safety Board and mention human error as the main cause that led to incidents. Frühwald and Thelandersson stated that over 90% of structural failures are caused by gross human errors [7].

More research is needed to treat the human error issue and transfer the building industry to a safer industry. For the Dutch construction industry, this research gap is investigated by Terwel, de Haan, and more. Terwel investigated the most important Human and Organisational Factors (HOFs) relating to structural safety. De Haan proposed a Human Reliability Assessment (HRA) method to analyse the effect of human error on structural reliability in the design phase. It is still unclear though how human error led to structural failures and, where and how in the design and construction phase, control can be the most effective.

Definitions

To create clarity the most important terms are stated here. **Human error** is a departure from acceptable or desired practice on part of an individual that can result in unacceptable or undesired results [8]. **Structural safety** is the absence of unacceptable risk associated with failure of (part of) a structure [8]. **Structural failure** is an inadequate performance of a structure that creates or might create an unsafe situation [8]. A **safe structure** can withstand the loads acting upon it adequately, during its lifetime. Subsequently, an **unsafe situation** is a moment in time, in this thesis caused by structural failure, that can harm the (safety) goals.

Problem definition

The tricky part of safety is its invisibility, unlike unsafety. As mentioned, human error plays a key role in safety management. With the help of different types of models, insight into how human error affects structural reliability is provided. The problem of this thesis is split into two parts, the practical problem statement and the scientific problem statement. Those are in order summed up below.

Within the building industry, unsafe situations as a result of human error take place unnoticed, due to of lack of overview in the design and construction process.

Methods to model human error probability and its consequences are not yet validated on existing case studies and therefore practical applicability is unsure. Also, the methods are incomplete as the construction phase is missing.

Objective

George Box's well-known expression *all models are wrong, and some are useful* is also valid in this research. Therefore, it is useful to keep in mind that a theoretical model is used for one practical case study. The outcome of the model will not be an exact reflection of the degree of structural safety but merely a method for validating the effectiveness of (control) measures used in specific steps in the design and construction phase. Summarising this the objective of this research will become:

The objective of this research is to find the applicability of the HRA model in the building industry doing so by evaluating the effectiveness of control measures considering human errors for the design and construction phase of a foundation pile element.

Scope of the research

The focus of this research is on the human error effects on structural reliability and how control measures can affect this outcome.

As the objective of this research is quite broad, further demarcation is necessary to specify this research. Several restrictions are applied and are stated point for point. First of all, the applied HRA model is developed by De Haan [6][7]. His model is based on the Cognitive reliability and error analysis method (CREAM) by Hollnagel [10] and the human error simulation model proposed by Stewart & Melchers [11].

To improve the applicability of the model, tasks in the construction phase are included in this thesis. As a consequence, re-evaluation of the model and simulation is necessary to adjust the model usability for construction tasks. The practical applicability of the model for both design and construction is tested using a case study.

The case study is one foundation pile element, part of the total falsework of the Theemswegtracé project, Rotterdam. It is extremely difficult to produce a task analysis that covers the actual variables of designing and constructing the specific element, as this is more of an iterative process where a lot of steps are co-dependent. Therefore, the task analysis of the foundation pile is a simplified representation of steps taken in consecutive order.

Outside the scope is quantifying the probability and the consequence of human errors. These inputs are looked up from existing studies, and not researched in this work. The probabilities of human error are determined with a large margin and are not a precise reflection of reality.

Research question

With the problem definition, research objective, and research scope determined, the research question can be subsequently defined. The research question is the common thread in the report.

What are effective control measures to apply in practice for structural design and construction, when considering human errors?

The main question can be answered with the help of multiple sub-questions. Each question represents a chapter in this report and after all chapters, the sub-questions will be answered. An overview of all questions is shown below.

Sub-questions		
Literature	1)	What is the current state of structural safety in the Netherlands?
	2)	What is the safety culture of Dura Vermeer towards structural safety?
	3)	In what way does Dura Vermeer implement the safety culture in practice?
	4)	How can control measures work effectively to limit the consequences of human error?
Case	5)	What does the design and construction process of the case study look like?
	6)	How do control measures influence the outcome of the HRA model?
	7)	How effective are the control measures in limiting the structural failure probability?

Table 1 Sub-question used to answer the research question

End deliverable

This report provides an HRA model that is capable of analysing the human error effects on structural reliability in the design and construction phase of an infrastructural element. For this, a model is developed and tested with a case study on practical applicability. Mainly, variables of different quality control are evaluated for their effectiveness. Even though all kinds of measures and variables can be simulated with this model to test the relative effectiveness, this study focuses on the structural safety-related control measures. The term **Effectiveness** is determined by how much a measure can decrease the structural failure probability. It is a relative concept reflected via comparing the results when applying different measure variables.

Structure of the report

This thesis is divided into a literature study and a case study. Each chapter will elaborate on an aspect of the scope and will answer a sub-question. Each chapter will reach a conclusion, which will be summarised at the end of this report. Figure 1 is a visual representation of the structure of this report.

Literature study

In the first part, the research problem and research gap are identified with a literature study. It introduces structural safety, current obstacles, and existing measures relating to structural safety and provides an overview of recent structural failures in the Netherlands (chapter 1). How national viewing and regulation are translated into the safety attitude of Dura Vermeer is given in chapter 2. Elaborating how this safety attitude is translated to practice is also part of this chapter. This includes measures related to structural safety applied in the project of Dura Vermeer. The last chapter of part 1, chapter 3, discusses ways of modelling structural safety found in literature and elaborates on the usage of an HRA model and how this method can be of benefit for this research.

Case study

The main research can be found in this part of the thesis. In chapter 4 the implementation of the HRA model for the specific research scope of this thesis is explained. The content of chapter 5 consists of project context and qualitative analysis of the case study. The outcome of this chapter is a task analysis of the case study. Assigning the corresponding Human Error Probability (HEP) and Error Magnitude (EM) to each micro-task step and relevant parameters is done in chapter 6. Chapter 7 presents the results of the simulation for the micro-tasks and task sequences. In this chapter, the simulation process is explained via a schematic representation. Also, ways of modelling the control measures are discussed in this chapter. With the simulation model, chapter 8 shows the outcome of the structural reliability analysis.

Lastly, the whole research is concluded and future research is discussed in chapter 9.

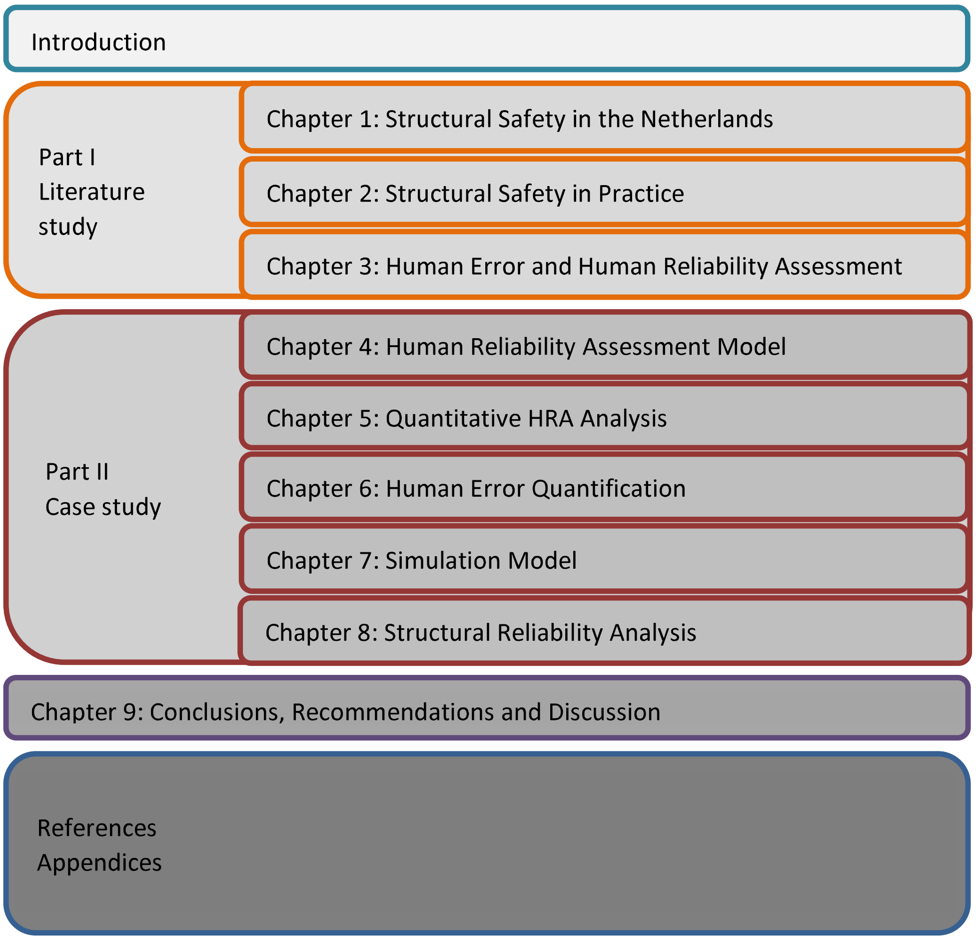

Figure 1 Structure of the report

PART I

Literature study

Over the last three decades, structural safety has been a well-studied subject in literature. But every couple of years an accident, collapse or other failures leave the society and industry appalled. Why is it that difficult to bridge the gap from theory to practice? And how are recommendations implemented in projects?

This part contains three chapters. In the first chapter structural safety is addressed and the research gap is elaborated. The second chapter examines how safety is guaranteed in practice. The third chapter connects the recommendations to a research model.

1. Structural Safety in the Netherlands

The first step in the literature review is to explore the issue of structural safety in the Netherlands. This chapter includes a short introduction to structural safety and shows the current status of the problem. Furthermore, some recognised causes for structural failures are summed up with their respective measures for prevention. Next, a brief introduction of the publicly available tools KPCV and GCVB is shown (Kennisplatform Constructieve Veiligheid and Governance Code Veiligheid Bouw), on which mainly the available control measures are explored.

The chapter concludes with an answer to the following question:

What is the current state of structural safety in the Netherlands?

Structural safety

Frijters asks if safety can be measured within the construction industry [12]. The answer: Yes, in line with the general belief within the industry. However, further thoughts on this simple answer raise quite some more questions. Frijters concluded that when (un)safe conditions of apparently normal situations are quantified, improvements can be made before incidents happen. This conclusion consists of two key elements. One is that incidents can be prevented. The second one is even more interesting: safe and unsafe situations need to be quantified to detect flaws. Though this article focuses on safety in the workplace, which focuses on occupational safety instead of structural safety, some of the ideas and conclusions are worth noting.

A couple of years later, Karel Terwel got his doctorate in Human and Organisational Factors (HOFs) influencing structural safety. For human and organisational subdivisions, Terwel followed the guideline of Van Duin [1] and categorised the factors into micro, meso, and macro levels. The micro level concerns the professional and personal influence of actors. This level describes errors due to mistakes or lack of skills as a cause of failures. If another person would not have made this mistake, it is categorised on the micro level.
The meso level describes all factors from the managerial level within the company. This broad division contains the most influencing factors. If another project team, better coordination, communication, or different quality control would have prevented the failure, this type is on the meso level.
Lastly is the macro level. This level acts in the building industry and is often neglected in recommendations from failure reports due to the stiff nature of this industry.

Available data structural incidents

In the Netherlands, structural safety is often part of the safety policy. Now and then, structural safety is put to the fore on the national agenda. This often happens after an incident with a significant impact on the safety experience of civilians. Consequently, an investigation starts that forms a plan to improve structural safety. Those investigations are done, though, only for more significant incidents. A clear overview of the extent of the problem is missing. Terwel [13] tried to fill in this knowledge gap. Data from three different sources are analysed to observe the magnitude of the problem. It was possible to spot trends and address the causes and origins of the failure with the data. That study concluded that human errors cause around 90% of failures. For approximately 35%, the cause is in the design phase. Approximately 30% of the causes occur during the construction phase, and for over 10% of the cases, it is a combination of design and construction errors. The data are gattered with ABC registration, Dutch arbitration awards, and newspaper articles for the building industry called Cobouw. The numbers concluded from each database, however, are not consistent with each other. The newspapers provide a significantly vast number of cases that are missing in the other databases. It raises the question if the industry has a whole picture of the degree of the problem, especially when it comes to unsafe situations that did not lead to incidents of significance.

Research by Develi [14] supports this hypothesis, which states that enough accurate data on structural failure incidents is missing in the construction industry. For this conclusion, he analysed the same data source as Terwel; however, the ABC registration project had failed at the time of his research. Cobouw restructured its database, after which not enough data was available. His research only focuses on failure databases, so it misses insights into errors. As errors do not always result in incidents, much data is unnoticed or not on record. Errors often result in unsafe situations, which can have different outcomes. For instance, 1) the unsafe situation can be noticed and anticipated, 2) it is not noticed but does not have consequences, 3) it is noticed but not acted on, or lastly, 4) it is not noticed, and as a result, an incident occurred. Databases often lack insight into unsafe or safe situations and mainly report incidents. Detailed analysis is therefore not possible.

Guideline Failing Structures

In 2004 a collaboration of VROM inspectie, Bouwend Nederland, NIingenieurs en CUR Bouw & Infra took the initiative for the project 'Leren van Instortingen' ('Learning from Collabses'). After a series of collapses, this raised serious doubts about to what extent the industry guarantees structural safety. The CUR Bouw & Infra Falende Constructies (Failing Structures), 2010 [15], results from their collaboration. This report addresses the direct and indirect causes of multiple failures in different case studies. The goal is to reduce failure costs and increase structural safety by providing insights into lessons learned.

The fifteen case studies are well-known cases that received national attention in the media. The cases differ in structure, type of failure, and project size. The researchers divided the causes into the levels previously explained, namely the micro, mesa, and macro levels of Van Duin [1].

A table with all structural causes, broken down to every level, came forward from these case studies. The causes then undergo closer examination in the report. On the micro level, errors were made in the design, the (detail)engineering, and the construction phase. Project teams undertook no measures to detect the errors in time. Knowledge to prevent the errors is almost always available; however not known or not used by the persons involved. On the meso level, in the (project-) organisation, there is a lack of clear task division, coordination, effective communication and integration between design and construction. Furthermore, the case studies showed that errors occurred in more than one task, on more than one level. As the Swiss Cheese Model demonstrated, removing one of these causes could have prevented the failure. The findings of the cases are subjected to expert judgment. The experts came up with additional indirect causes. To select a few: 1) Lack of structural coherence. 2) No direction role for the engineer. 3) Insufficient attention in design for robustness, secondary support, and the consequences of warnings for construction. 4) Too little attention to stiffness ratios between structural elements.

It concludes that the (project) organisations have insufficient awareness of, and take insufficient measures to, prevent or correct errors in the design, construction and maintenance phase. Suggestions for risk management are internal review (four-eyes principle) or external review (strange eyes). Furthermore, it concludes that communication is vital. This communication is about the principles, preconditions, alternative designs and choices, risks, and control measures. An important recommendation is, again, to share best practices. The knowledge platform KPCV has included this research output in its realised tool.

Guideline Learning from Geotechnical Failing

Similar to the report Failing Structures, the CUR Bouw & Infra came in 2010 with a report with geotechnical case studies [16]. Again, the goal is to learn from mistakes and make lessons learned available within the industry. The reports are composed simultaneously.

In the report, multiple ways are used to answer the research question. This question is as follows: "Which structural failure causes play a role in damage to soil and geotechnical (soil-bound) structures?" Cross-case analysis, expert judgment and literature review research methods are used to identify around seventeen causes. For the micro level, the following six causes are concluded: 1) Faulty geotechnical analysis and design choices. 2) incomplete analysis and design. 3) Insufficient robustness in design. 4) Construction deviates from starting principles, preconditions and assumptions. 5) No monitoring. 6) geotechnical uncertainties are insufficiently recognised and acknowledged.
On the meso level, another six causes are concluded: 1) Insufficient review of the design and control during construction. 2) Insufficient attention to the effect of the structure on the surroundings. 3) Insufficient coordination between sub-systems. 4) insufficiently assertive, wanting to know what they do not know yet. 5) Insufficient overview of costs of failure and benefits of avoiding failure. 6) Insufficiently communicating objectives to limit failures.
Also, some causes are concluded on the macro level. These causes are less relevant as it is outside the scope of this research.

Not only the report provides insights into structural failure causes but also proposes measures to limit incidents. These measures are, like the causes, divided into sub-level micro, meso and macro. Again, the macro level is left out in this discussion. On a micro level, it recommends having a design team with relevant experience and expertise. This relevant experience and expertise also hold for the teams performing second opinions and the construction. Other recommendations include implementing control moments in design based on straightforward calculating models, as well as ensuring clear communication between construction and design. In case of deviations in design, always give feedback to designers. Use risk analysis in the design and transfer the results to the construction phase. In the design phase, provide a project-specific plan for monitoring and how to act on deviations.
On the meso level, relevant recommendations are: organising effective design review and control during construction; coordinating the sub-systems within the project, including phase transitions; dividing knowledge into groups of what is known, what to find out and what is uncertain; implementing geotechnical risk management in project risk management.

Both reports show many similarities in the identified causes for failures. Again, the most important causes are related to the micro and meso levels. However, there are some differences between the two studies. Three different points are addressed: 1) information about material properties, loads etc., is less than complete for soil and geotechnical structures and contains more uncertainties than building structures. 2) For soil and geotechnical structures, the construction phase is often critical; errors mainly occur during construction. This is, to a lesser extent, the case for building structures. 3) For building structures, focusing on the lowest costs does not lead to risky choices, as failures could have been prevented without high additional costs. While this is not the case for geotechnical structure projects.

Kennisplatform Constructieve Veiligheid (KPCV) & Governance Code Veiligheid Bouw (GCVB)

The knowledge platform KPCV is the follow-up of the "compendium aanpak constructieve veiligheid" and is a collaboration between clients, engineering firms, construction companies, and knowledge institutions. Their website, intended as a design tool within a project, is publicly available for all to use as a reference or guideline in any project. KPCV provides assurance actions for every phase and subject within a project. For instance, the action *second opinion* is part of the design phase. The website describes the subject for this phase and the relevant matters. For second opinions, it describes who can provide the second opinion, how it relates to the Eurocode, and what correlates to the subject. As a result, it provides more information relating to the subject. The information is quite general, although it can link to follow-up actions and information. The tool is formulated in the form of a flowchart. The assurance actions are ordered throughout the project phases. Once the current phase is determined, all corresponding assurance actions can be found in the tool. Therefore, relevant actions can be taken.

The governance code is a different website aiming at improving structural reliability. On this website, best practices and news are shared as guidelines and recommendations. Their database shows that structural safety is still snowed under by occupational health and safety management. The remarks related to structural safety are superficial and are not applicable in practice.

Control measures from the Eurocode

The norm NEN-EN-1990 [17] provides three control methods and the condition when they are obligated. These three methods are two different kinds of *Normal supervision* and one *External supervision*. Normal supervision is further distinguished into *Self-checking* and *Internal review*. External supervision in practice is often referred to as *Third-party checking*. These checking are defined by the code as the following:

Self-checking
Checking is performed by the person who has prepared the design.

Internal review
Checking by different personnel than those originally responsible and following the procedure of the organization.

Third-party check
Checking is performed by an organization different from that which has prepared the design.

All three types of control measures are very common and applied in every company in some way. The next chapter, chapter 2 explains how these control measures are used in practice by Dura Vermeer.

Conclusion

According to an analysis of data from databases, fatalities due to structural failures do not exceed the limit of the safety philosophy of the Eurocode [18]. However, the quantity of total failure is unclear, as the industry lacks one complete database [13][14]. Recent incidents with fortunately no fatalities, like Eindhoven airport or AZ AFAS stadium, forced the Dutch Safety Board to call for action [6]. For them, it was clear that the main cause of collapses was the same over the years, and they released a letter to the Dutch building industry stating that changes are required. Their recommendations are; 1. Less voluntary Construction Safety Governance Code. 2. Ensure overview. 3. Ensure professional critique. [19]

The cited guidelines from CUR Bouw & Infra support these three basal conclusions [17][18]. The guidelines provide more detailed insights into different failure cases. Incidents between soil structures and building structures differ in multiple aspects. Three conclusions provided by the guidelines are:

- Information about material properties, loads etc., is less than complete for soil and geotechnical structures and contains more uncertainties than building structures.
- For soil and geotechnical structures, the construction phase is often critical; errors mainly occur during construction. This is, to a lesser extent, the case for building structures.
- For building structures, focusing on the lowest costs does not lead to risky choices, as failures could have been prevented without high additional costs.

The guidelines also state that the most important causes are related to the micro and meso level and macro level to a lesser extent. Both levels are helpful for the risk analysis setup or for implementing them in control measures. The most critical causes for failures in soil structures are [16]:

- Faulty geotechnical analysis and design choices.
- Incomplete analysis and design.
- Insufficient robustness in design.
- Construction deviates from starting principles, preconditions and assumptions.
- No monitoring.
- Geotechnical uncertainties are insufficiently recognised and acknowledged.

Lastly, the Eurocode distinguish three types of control measures: 1) self-checking, 2) internal review, and 3) third-party check.

Answer sub-question chapter:
According to analysis, it is concluded that structural safety on micro, meso and macro level fall short. In the literature, it is stated clearly what the causes for structural failures are. However, the industry struggles to apply measures to reduce the number of incidents. There is a gap between what has been researched and what has been implemented in practice. Multiple tools have been developed and task groups were formed to deal with this gap. The most prominent groups active are currently KPCV and GCVB. Both show that ensuring structural safety is a continuous process.
Moreover, both platforms are focussed on training personnel and informing the industry on the level of structural safety. Mainly KPCV offers references for each step per project phase. The structure handled by KPCV, see Figure 2, is presented in the task analysis in Chapter 5 of this thesis.

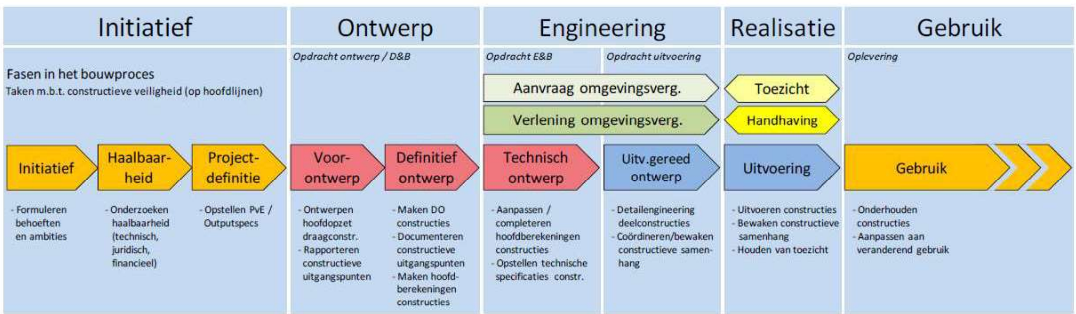

Figure 2 standard project process, offered by KPCV. The steps involved are initiative, design, engineering, construction, and maintenance.

2. Structural Safety in Practice

National attention on structural safety flows through to practice. This chapter is the link between the national state of structural safety and measures applied in the practice. The focus of this chapter is to determine how, and when control measures are used in projects. This is done by first stating the state of structural safety within Dura Vermeer and secondly by summing their measures applied to control structural safety. The needed information is derived from public and internal documents, interviews and project documents. The chapter ends with conclusions and relevance to the research, as the aim is to find out how relevant control measures are implemented. The following sub-questions are answered in this chapter:

What is the safety culture of Dura Vermeer towards structural safety?

In what way does Dura Vermeer implement the safety culture in practice?

Safety attitude

The attitude of Dura Vermeer towards structural safety is found in various safety brochures [20]. Structural safety is part of their safety program, together with creating a safety culture, a safe and sound construction site, and safety in the vicinity of the construction site. The company's ambition is threefold: 1) to have no incidents or damage as a result of structural failure. 2) To have a clear role for the constructor(s) within projects. 3) Access to instruments to secure structural safety.

To help achieve these goals, safety is secured from the first moment of the project, the tender phase. The integral safety is ensured and controlled in phase transitions, and the structural safety is assured through a self-develop tool, an online document. In practice, this means more specific: there is access to struts, to the scaffolding protocol, protocol dismantling existing elevators, structural safety is part of inspections, securing knowledge about wide slab floor problems, and imbedding demarcation list tasks and responsibilities structural safety.

Lessons learned from the past

Grolsch Veste

On the 7th of July, 2011, a roofing structure of a football stadium collapsed, resulting in two fatalities and nine casualties, of which some were severely injured. This accident, of which Dura Vermeer was part of the construction combination, was investigated by the Dutch Safety Board [21][22]. The Dutch Safety Board focussed its investigation on the structure itself and the building process. The results are a list of direct causes and underlying causes.

The investigation provided three direct causes that led to the collapse of the structure. The first one was that parts were missing. This resulted in insufficient stability of the structure and was not compensated with temporary bracings. Secondly, the unfinished roofing structure was overloaded. Thirdly, and lastly, the steel roof structure did not fit properly due to deviations in the concrete supporting structure. The structure was mounted with force, and as a result, the structure's resistance decreased.

As for the organisation of the construction process, the board came up with ten different points that "*could create a situation in which the risk of the roof collapsing was not controlled*". The points all relate to steps in the construction phase and are divided into the following steps or moments in the construction process: 1. Using an unstable steel structure. 2. Actions become larger than resistance: failure of the structure. 3. Ignoring signals of the reduced load-bearing structure. 4. Concrete structure with dimensional deviations. Summarised, it concluded that in all four steps, the level of control was substandard to none. Furthermore, parties came up short in acting on their responsibilities professionally and in allocating the responsibilities.

The last paragraph of the conclusion is reserved to state underlying causes. Those causes are summed up in five statements and are roughly alike. Although they were assigned in the contract, there was no allocation of risks to a person. The same holds for allocating responsibilities towards ensuring structural safety, constructability of the design, and ensuring compliment of agreements. Lastly, due to a delay in the construction of the roofing structure, the order of planning was let go. Without considering the consequences for structural safety, the planning changed from linear to parallel.

The investigation provided numerous recommendations. Those recommendations are towards the client, the main contractor, and the industry. It is advised first to map future work and circumstances on which parties can perform the planned work realistically for the client. Secondly, ensure or enforce safety agreements. As for the industry, in the form of the branch organisation Bouwend Nederland, take the initiative to create more precise guidelines of roles and responsibilities, and make ideas for improvement explicit, also from non-members.

The main contractor's recommendation was to respond to the investigation with a letter pointing out the weak spots in the collaboration and how they influenced the safety. Also, give meaning to the responsibilities of the main contractor. The parties responded to the investigation with a letter promising to reflect on the weak spots. In the reflection, many points repeat or align with previous suggestions [22]. Some notable corrections mentioned in the letter are:

- The incomplete phase transition from the design to the implementation phase results in a thorough risk inventory and high-quality management document.
- Insufficient demonstrable assurance of craftsmanship, knowledge and skills within all parties involved.
- Lack of a second opinion as part of expert judgment.
- Inadequate structure in monitoring the pre-identified critical parts through sequential hold points in the planning.

The letter further contains positions of the companies concerning improving safety.

Theatre Emmen

In 2015, a sudden collapse of hollow-core slabs occurred during a construction project in Emmen, which resulted in one casualty. The sudden collapse occurred because the temporary support structure could not withstand acting forces.

The investigation report into the Emmen incident shows how the Swiss cheese model works in practice [23]. The extended investigation is an investigation to track down underlying technical and organisational causes before the collapse and learn from mistakes made.

The indirect causes of the sudden collapse were similar to the Grolsch Veste. In the investigation came forward that on three levels, mistakes were made. Those levels are organisational, communication, and professionally.

Organisationally, mistakes have been made by all involved parties. First of all, the contract management has been insufficient. Contracts are not present, have not been signed and returned, or contain relevant exceptions from the contractor. It is also concluded that the contents of the contracts have not been converted into actions by the parties involved. Second, responsibilities have not been filled in or acted on. The lead engineer failed to act as responsible as it was unclear this was part of his assignment. The main contractor failed to point out this responsibility. Also, the main contractor failed to communicate the purpose and expected forces acting on the structures as part of the instruction to the scaffolding company. This party, in his turn, did not make inquiries about the lack of information, drawings, and calculations.

Safety survey

The outcome of a safety survey, including the structural safety presentation from 2014 [24], were three notable responses from respondents. Those statements are:

1) Sometimes, I doubt the safety of (support) structures on my project.
2) I have sufficient knowledge to estimate the safety of (temporary) (support) structures.
3) In the past five years, I have experienced that last-minute adjustments were necessary.

The following conclusions for every question were drawn:

1) Almost half of the project organisation has doubts to a greater or lesser extent about the safety of (support) structures or their project.
2) Less than 20% of the project organisation indicates that they have sufficient knowledge to make a statement about the security/safety of (support) construction on their project. The alleged knowledge increases with the number of years of experience in construction.
3) Almost half of the project organisation has experienced a last-minute adjustment. A late level of education combined with little experience seems to influence the recognition of dangerous situations negatively.

The implementation of the lessons from the survey is construction orientated. The purpose of control measures was to be more aware of unsafe situations during and after constructing structural elements. Thirty questions long checklist enables the control and verification of structural reliability. This list is part of (re-) gaining awareness about structural (un-)reliable situations. The goal is to recreate the gut feeling of construction workers.

From theory to practice

SaVe

Dura Vermeer developed an internal toolbox method to register (un)safe situations, incidents, and improvement ideas called SaVe (Samen Veilig – Together Save). This database is publicly accessible as a website and includes all kinds of toolboxes used or still in use in practice. An example of such a toolbox is that of *the removal of temporary support structures* [25]. This toolbox is a guideline, designed as a discussion tool during the construction phase. It directs the user to make sure specific information is present and known by all parties. It provides also a summary of involved risks, measures, and support for discussion. A toolbox is generic and the focus of a toolbox as a control measure is on stimulating awareness of the design and construction method.

Including in this database are some mentions of structural incidents, though most of the notifications, 95-98%, on the website are about working conditions and related safety hazards. Reports that relate to structural safety are about temporary structures and describe an incident. No records of near misses or (un)safe situations are found in the database.

One of those reports that describe an incident with a temporary structure is about a failure of the jack structure during the lowering of a viaduct [26]. The report follows a pre-set recording tool and starts with a description of the *cause*, followed by the *Effects*, *Cause analysis*, *Own insight*, *Acting actively*, and finally, *Learning together*. The jack structure is shot out under the final bridge structure during construction activities. While lowering the bridge parts, the jack is loaded both vertical and horizontal. As a result of the shot out, the bridge part fell on the bearing columns, causing damage to the pier and concrete structure. Some parts fell on the emergency lane of the highway underneath the viaduct. From external research, numerous shortcomings are found, divided into two main conclusions. The first one is that structural safety is insufficient guaranteed. The other conclusion is that the construction deviated from the intended method. The reflection in paragraph *Own insights* aligns with the conclusion from external research, though less extensive. The lessons drawn from the incident are summed up in Act actively and Learning together. The lessons are copied and summed up below. The lessons are similar to the observations and lessons from the Dutch safety board, treated in chapter 2. It concludes that difficulties in the construction industry hold for more minor incidents within projects as well as within companies and nationwide.

Lessons learned from the SaVe incident:

Act actively:

- Work out falsework in drawings and calculations with an internal review.
- Appoint how the structure is checked during construction and include it in the assembly document.
- Make sure certain structural parts can be checked in the design or the construction phase.
- Appoint responsibilities for checking and reviewing plans. Agree on the depth and status of these checks.
- Take unexpected design situations into account and make the structure sufficiently resilient.

Learning together:

- Do not deviate from intended work methods or sequence. Stick to the plan.
- In the event of deviations in a process, check the consequences of this and call in a specialist if necessary.
- Supervise the implementation and compliance with the process from the (assembly) plans drawn up.
- For temporary structures, always have the work plans, calculations, and drawings checked by a specialist.

Check-list

Dura Vermeer Bouw, the division focused on public and residency buildings, composed a check-up list obligatory for each project. This check-up list has as starting points the following documents: the compendium structural safety [27], code of conduct structural safety [28], and guidelines for supports and formwork [29]. The check-up list/ document is checked within each phase transition if it is up to date, contains solely green boxes, and is filled in. This check is performed by company management as part of the internal review. If satisfactory, the project receives the green light to proceed with the design.

The list is a response to the incidents in the past to ensure structural safety. The working principle of the list is that it is an active document, a tool for the project team to verify and control structural safety. It is also a tool to prove structural safety to supervisors and/ or reviewers. As a communication tool, the list is an opening for a more thorough discussion about the depth and reliability of structures, structural principles, construction order, and more. As a controlling tool, the document defines the assignment of responsibilities. Furthermore, the progress and fulfilment of the task are registered.

The list is a collection of five tabs: Cover sheet, initiative, design, work planning, and realization. For the cover sheet, several standardised pieces of information are necessary as input. Every project is sorted in the project classification. Once classified, the tool suggests what items are relevant and necessary to process.

Conclusions

Safety attitude

The safety attitude of Dura Vermeer towards structural safety is summarised in the safety program document [20]. In the safety program, safety is divided into four sub-sections. These sub-sections are 1) safety culture. 2) safety and health on site. 3) structural safety. 4) safe environment construction. For structural safety, the official attitude is in their words: *To guarantee and monitor structural safety during the design, construction and maintenance phase of all projects.* [20]

The company's ambition is to have no safety-related incidents in Dura Vermeer's projects. In jargon, they strive to have no absenteeism for any employee due to safety incidents: an IF-rate (Injury Frequency - rate) of zero. Dura Vermeer is proactive in its policy, which has been implemented in different ways to accomplish this ambition.

Implementation

First of all, within the company, it is highly encouraged to report safe or unsafe situations to the internal report tool SaVe. SaVe does not only provide an overview of the current safety standard; it also includes toolboxes to apply lessons learned. Many reports are publicly available. However, not every record is visible or accessible, even for employees. Another downside is that not all incidents are mentioned in the SaVe database, especially within division Infra. Several reasons can be the cause for this. For example, if the situation is not spotted or unknown by employees of Dura Vermeer. What has also very commonly happened is that incidents are not reported to the tool. For the latter one, the company put in lots of effort to promote the tool to be used for reporting safe or unsafe situations. This is done with safety paper [30], [31], workshops and training (like To See, To Act, To Learn). However, searching through the database, it is concluded that a lack of structural safety reports exists. The database consists of only severe incidents, not unsafe situations or best practices. This conclusion of the implementation of a safety attitude is in line with what is seen in the industry, nationwide.

Dura Vermeer Bouw & Vastgoed provides training to (re-)gain "gut feeling" in structural safety. This is not the case within Dura Vermeer Infra. The training directly responds to internal investigation about the awareness of structural safety on site. This awareness among carpenters turned out to be seriously below par. At least under Dura Vermeer Infra, the hypothesis is that this gut feeling is more present within the infra-projects. It is supposed to be part of the 'DNA' of all Infra-colleagues. It is unclear if the training helps prevent or monitor unsafe situations. Also, the 'DNA hypothesis' is yet to be investigated. Training the gut feeling is a form of self-checking, and stimulates a critical attitude towards design and construction outcomes. An example of how this training is put into practice is with a check called "LMRA" (Last-Minute Risk Analysis), in which the construction worker makes a quick risk assessment of the situation. This self-check is on the micro level.

On the organisational level, Dura Vermeer Bouw & Vastgoed implemented another control measure: the checklist. This document assures allocation of pre-set responsibilities and the progress status. This document guides phase transitions in the project. Within Infra, it has been decided not to apply this document. This is because of several reasons: the nature of the project is unique, and often Dura Vermeer is not the main contractor but forms an alliance with other contractors. Working with compendium structural safety is the norm as a substitute for the checklist. For some projects, a structural safety document is drawn. Such a document describes the project, goals, allocation of tasks and roles, and a conflict ladder if the requirements concerning structural safety are not met. The main differences between the different documents are that a checklist is a tool with a fixed focus, that only changes depending on the type of project. The structural safety document is more dependent on the discretion of the author. Both ways of measure are focussing on the allocation of risks and include how to deal with design adjustments and construction deviations.

Within the organisation, it is obligatory to have the design checked with every phase transition by several reviewers. This moment is called the gate review.

Finally, on the macro level, the company is actively involved in numerous respected initiatives, like the KPCV (see chapter 1). Also, several guidelines and protocols are drafted by Dura Vermeer, such as disassembly protocol elevators.

Notes

The control measures applied in Dura Vermeer are generic and not specified on moments in time, structural elements or project roles. This is for instance visible in the Toolbox, SaVe, and the checklist. For this reason, the possible control measures are not made specifically for the company. This could be possible if the implemented practical control measures are more specific. Research within a different company could result in a different implementation of control measures and change the way of modelling the case study and safety measures.

3. Human Error and Human Reliability Assessment

For decades, the challenge within safety engineering is to reflect reality within models. Over the years, many HRA methods have been developed to deal with human contributions to accidents and failures. These HRA methods take different approaches to human errors and their impact on systems.

The two previous chapters described the research problem. Chapter 1 describes the efforts made and lessons learned concerning structural safety in the Netherlands, from multiple perspectives. This is then further specified with a company case in chapter 2, in which the applied safety measures are summed up. The literature study is up to now only focused on structural safety and control measures that have been recommended or applied to improve structural safety. Also, common causes of failures are mentioned in the chapters, of which human error is recognised as the most significant. This chapter clarifies the term human error and the relation between human error and structural safety. Types of control measures and how they work are explained in the first subsection. In the second subsection, the used HRA method is explained from a theoretical point of view. With this, the impact, benefits and shortcomings of the implemented HRA method are stated. In the conclusion the following sub-question is answered:

How can control measures work effectively to limit the consequences of human error?

Human Error

Human error is credited as the major cause of structural failures and is an inevitable part of the building process [32]. In the research of Frühwald [7], it is stated that over 90% of structural failures are accredited to gross human errors. Several definitions of human error are provided over the years [33]. The term human error can be misleading for any reader or researcher. Hollnagel's view on the term 'error', written on his website in a disclaimer from 2012, is that it is "theoretical vacuous, as it is explained elsewhere"[34]. For instance, Swain [35][36] defined human error as:

> Any member of a set of human actions or activities that exceeds some limit of acceptability, i.e., an out-of-tolerance action, where the limits of human performance are defined by the system.

The definition provided by Terwel [8] contains more nuance, and is therefore adopted in this research:

> Human error is a departure from acceptable or desired practice on part of an individual that can result in unacceptable or undesired results.

In the definition of Terwel, human error can result in unacceptable or undesired results, with emphasis on *can*. Contrary to Swain, where human error led to an *exceeded limit of acceptability*, human error can also result in a (more) desirable outcome, or counteract other errors. The reason [32] mentioned in his research is that error can facilitate serendipitous innovation [37]. This also applies to human error, where it not that it is not explicitly mentioned by Terwel.

The types of human error that are of interest constitute incorrect inputs to the system. An individual can for instance do something incorrectly, fail to do something or fail to do it in time. A breakdown of the type of errors is provided by Swain [29][31] and is as follows:

- Errors of Omission (OOC)
- Error of Commission (EOC)
- Selection error
- Error of sequence
- Time error
- Qualitative error

The errors of interest are errors of commission, which are described as incorrect performances of a task. If a comprehensive data collection system is connected to design and construction processes, then errors of omission (failure to perform a task) can be included in the model. [38]

The other types of error are also mentioned by Swain and depending on the type of HRA method, they can be of interest. This is not the case for the applied HRA method.

Misconceptions of human error.

The rationale for the approach to human error comes from Read [39]. In their research, they discuss the misuse and abuse of human error. Consequently, they offer an approach to using or implementing the concept of human error in a model. It was divided into three main misconceptions of human error, related to it being a cause, a process or relating the error with the consequence, respectively:

Human error as a cause: Using human error as a cause or explanation stops its investigation and overlooks the factors that contributed to the result of the error. Instead of using human error as "an explanation of failure, it demands an explanation" [40]. The framing of human error as a possible cause of the failure feeds the bias in failure investigations and can result in a negative outcome such as personal blaming.

Human error as a process: Treating human error as a process or event neglects the allowed range of errors. Where a small deviation from the 'correct' process does not ensure an error. The focus on the process could provide unnecessary recommendations for the error. Rather than focusing on the error itself, it is more meaningful to focus on the possible outcomes of the error.

Confounding error with its outcome: An English expression reads: *To Err is Human*, which means that everybody makes mistakes. The idea that negative, or bad outcomes, such as accidents and failures, can be searched back to bad causes is incorrect. Especially when attention is paid to preventing these bad causes with all kinds of measures since this is a lost effort. The same 'bad causes' could result in positive outcomes, as the human error does not necessarily lead to failure or accidents. Also, the bad causes enforce the misconception that someone is to be blamed for the extent of the error effects. To use the concluding words of this paragraph from reading [39]: "The contribution of 'normal performance' to accidents is now widely accepted."

Implementation of human error

Above the misconceptions of human error are described which affect the implementation of control measures. In chapters one and two, many recommendations focused on or dealt with human error. As discussed, human error is not a cause and it is not possible to prevent human error from occurring. That is why the control measures implemented should focus on the outcomes of error along the complete process. Furthermore, control measures should focus on spotting undesired outcomes in the process and steering on interrupting the accident causation. This is in line with the Swiss Cheese model by Reason [41].

One basic indicator of human performance is the Human Error Probability (HEP). The HEP is the probability that an error will occur when a given task is performed.

Modelling human error

A literature review, provided by Alkaissy [42], stated that "all accident causation theories and models developed have considerably increased the understanding of accidents". As a result of growing knowledge, a strong emphasis on the role of human error increased safety awareness and contributed to the training and education of workers. However, the weakness of those models and theory is that they do not provide guidelines for supervision in construction workplaces and therefore leave space to underestimate risk. Important to state is that not all risks are preventable and that preventing human error does not imply that incidents will not happen. This is contrary to what those theories and models teach. As a final result, they conclude that modelling the interaction between accident likelihood and organisational tasks and activities is an initial step to a better safety management system and thus preventing incidents.

To model the effect of human error on structural reliability, several different approaches are investigated in recent years. In his conference paper, published in 2018, Galvão [43] used a survey to identify design and construction errors that represent a higher risk. The corresponding result, given by experts in the field, were analysed with an Analytic Hierarchy Process tool. This tool allowed the identification of the errors with higher consequences and/ or severer probability of occurrence. This tool was applied to his case study, a reinforced concrete bridge. Some conclusions of his paper are applied in this research, as higher risks are directly related to scaffolding and geotechnical issues.

Ren took a different approach to model structural reliability. In her conference paper [44], Ren used an Agent Based Modelling (ABM) approach to evaluate the influences of HOFs. The biggest difference between the approach with Agent Based Modelling and other models is the dynamic basis for evaluating its outcome, the error probability. Although proved in her paper that the model is capable of capturing the influences of the factors on structural reliability, extensive knowledge about the ABM technique is required to set up the model.

Human Reliability Assessment

In general, HRA models apply the judgment of the HRA expert at the centre of the model. In his extensive review of HRA models, Spurgin [38] states the following: "Knowledge about the various HRA models and methods, how to get the best out of them and how best to relate domain expertise to the solution of the HRA problem is key". Expert judgment is needed for defining the application and boundaries of the method. In this research, the expert judgement consists of information from a literature study, with emphasis on work by Hollnagel and De Haan, examples and expertise of the company.

Hollnagels Cognitive Reliability and Error Analysis Method (CREAM) can be defined as a Context-Related HRA method. The reliability of humans is in these types of methods directly related to operational context. Conclusions without knowledge about this context are impossible. Nor the task or time is important to predict the HEP, but more so is the context. The context is directly related to the task and the HEP is determined by each of the influential elements in the context.

For CREAM an expert judgment method is used to determine HEPs. Often the estimation of the weighing factors used to shape the HEPs is decided without any understanding of responses within the system [38]. For this reason, De Haan links CREAM with the model proposed by Stewart & Melchers [45], in which the HEP is connected to an EM.

Conclusion

As De Haans applied model proved to be capable of calculating the failure probability of a building structure, his method is copied in this research. The implementation and adjustments are described in chapter 4 of this research.

The chosen control measures should focus on controlling the outcome of human error. From literature self-checking, internal reviewing, third-party checking, and construction monitoring are all suitable control measures. The measures should be limiting, observing or controlling the design and construction results.

PART II

Case Study

The heart of this research project is the model implementation of the case study. All steps taken in the following chapters lead to extensive knowledge in promoting structural safety. This knowledge is obtained by analysing the design and construction phase via an HRA method. The case study is captured in its essence in task analysis, and these steps are modelled and evaluated in their human error probability and the failure probability of the structural element after each step. The first chapter describes the process and applicability of the method. Every chapter elaborates steps further in the method.

Strikingly, Spurging [38] starts his book by citing the poem of John Godfrey Saxe, *The Blind Men and the Elephant* (a re-telling of the Indian parable). The blind men, each touching a different part of the elephant, concludes that the elephant is like a wall, snake, spear, tree, fan, or rope. Spurgin makes the connection between the telling and the use of HRA methods. As the men in the poem, HRA methods can see and discover some very specific parts of the reality, while it is difficult to generalise.

4. Human Reliability Assessment Model

The first chapter of part two focuses on the working principle of the proposed research model and its application. Furthermore, it briefly explains how the model works and the expected outcome. The chapter also emphasizes the contribution of this model. First, however, more detail about the topic and model is given. In which also some basic terminology is introduced.

Model Overview

The research model is presented as a flowchart in Figure 3. Each node represents a specific step of the assessing process. The arrows dictate the process flow. Finally, the outcome of this model is the estimated structural failure probability.

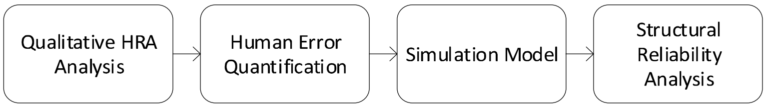

Figure 3 HRA model steps, based on the steps of De Haan applied HRA model [3].

The model applied in this thesis is based on the method proposed by De Haan [3][4]. The four main parts of this method namely: Qualitative HRA Analysis, Human Error Quantification, Model Simulation, and Structural Reliability Analysis, are elaborated in the following corresponding chapter.

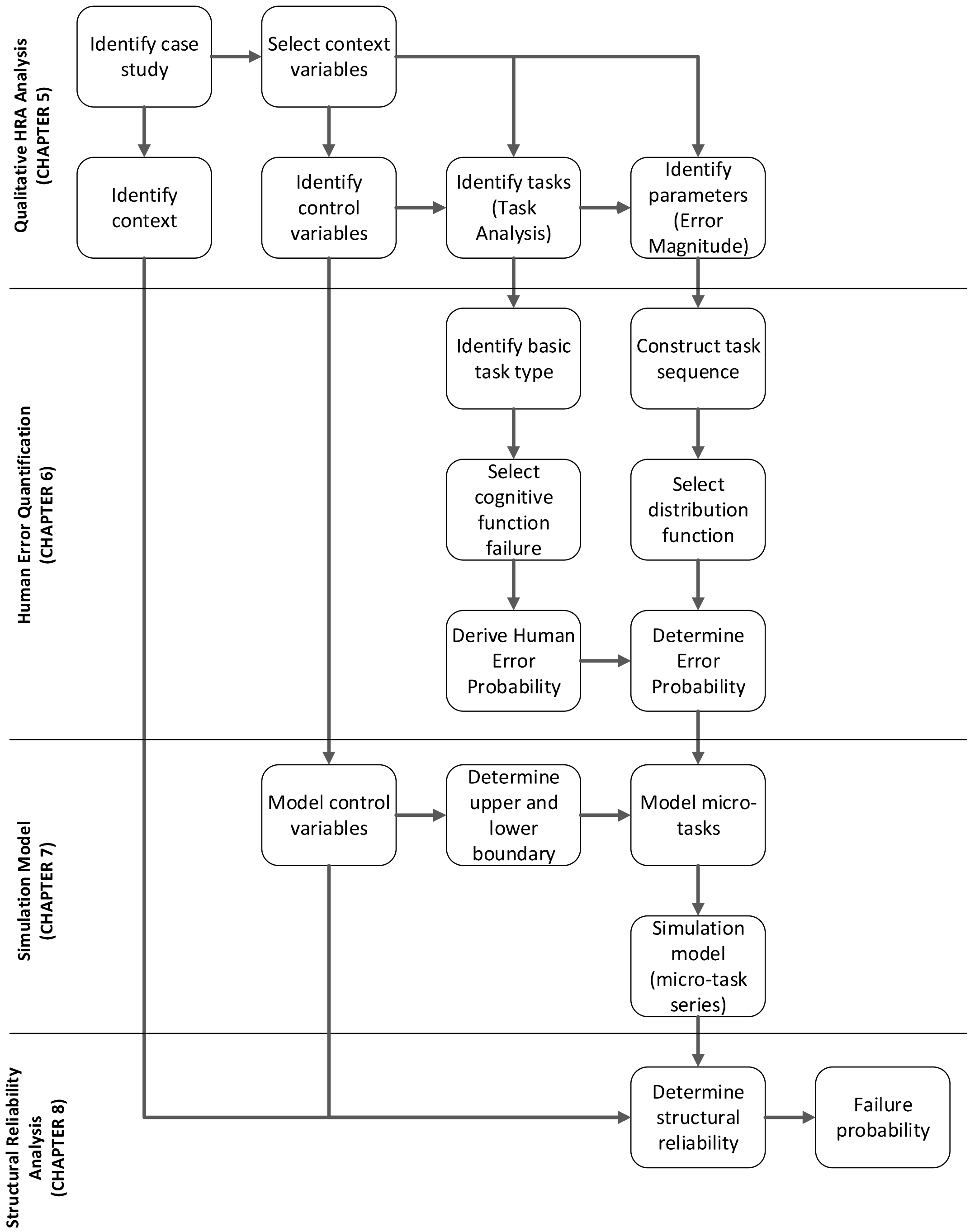

Figure 4 Flowchart of research model based on the HRA model from De Haan [3]. The main parts of the model are on the left and are similar to the following chapters of the report. Every step in the model is treated in its corresponding subsection.

Research model outcome

The first part, the Qualitative HRA analysis, is about the case under study. This step concerns the project's scope, a specification of the involved tasks and their sequence, as well as a description of the selected modelling control variables. Also, part of the chapter clarifies the case study context. The case-specific properties are used in later chapters. The output of this part is the Task Analysis (TA) table, the Error Magnitude (EM) table, and what control variables are of interest for the case study. The TA table contains tasks involved in the design and construction phase. The tasks are acts that involved professionals fulfilling. The EM represents a parameter for the severity of the error.

The second part, human error quantification, is presented in chapter 6. This chapter evaluates the HEP for all basic task types, which are standardisations of the nature of the activity. The basic task type is assigned to every task in the TA of chapter 5. The human error quantification also elaborates the EM specifications, such as the distribution function and standard deviations.
The result of the human error quantification directly influences the outcome of the simulation model, as the parameters from the EM table serve as input for the model. These parameters are also called the Micro-Tasks.

Chapter 7 explains the simulation model. Previously established control variables, from chapter 5, are incorporated into this model. The model applies a Monte Carlo Simulation run in the MATLAB environment. Where the simulation performs micro-tasks and micro-task series. Input for this model is the quantified EM table. The output is a dataset with the performance of the micro-task. These results are in line with what the micro-task parameter is. If this is a load, the results show a spread in the outcome of the micro-tasks performance of the load.

The last step of the model is to reflect on the outcome of the simulation model and calculate the failure probability of the structural elements. The quantitative HRA analysis and the structural reliability analysis are connected via the step scenario selection, which directly influences the structural reliability interpretation performed in chapter 8. The structural reliability and project context are directly related. The results from this chapter only state something about the applied context and environment.

Contribution and additions

The model of De Haan is improved in various aspects. The sections below mention all improvements with a short description of how the improvements influence the outcome.

Identifying control variables is a step in the qualitative HRA analysis that refers to the selection of variables. It means that control measures are part of variables, just like micro-tasks or task sequences. Parameters of this step include where the control measure takes place in the project process, how extensive it is, and what type of control measures are involved. These differences can influence the final failure probability tremendously. For real projects, the choice between variables for normal supervision and third-party checking is made ahead at the start of the project.

Next to self-checking, third-party checking is included in this research as a control measure. It reviews the design, and the result of this checking is a rectification or confirmation of correct values. In practice, third-party checking means that an external company is involved to review the calculations and design. For larger projects, it is often mandatory for the client's wishes, and this measure occurs between the phases of definite design and construction. Chapter 7 explains how this type of checking is implemented and what other different variables are available.

Adding the construction phase to the model is a logical step to analyse the practical use of the model, as around a quarter of failures are caused on the building site [13]. The tasks in this phase are operational and suit very well applying the HRA method. The implementation of this phase means that additional basic task types are necessary, each comes with its specific HEP values. For example, some basic tasks related to the construction phase are stated in the CREAM method [46]. One can think of basic tasks like “verify”, “scan”, “evaluate”, “coordinate”, “monitor”, and “instruct”. Description and selection of these terms are stated in human error quantification.

Note that some parts of De Haan’s method are left out on purpose. The first is the variable option to include the experience of the task operator. Including this does not contribute to the scope of this research as it is already investigated by De Haan.

Furthermore, normal supervision (as De Haan describes internal review) is outside the scope of this research. Besides acting as an extra check on answers, more often the check is to discover if some tasks are missing in the design phase, or if the calculation method is correctly applied. These belong to the category of errors of omission and demand a different way of modelling. The mechanism behind this form of checking is explained in the next chapter, chapter 5. More on this matter is presented in the discussion part of chapter 9.

5. Qualitative HRA Analysis

The benefit of testing the method and model on a real case study is that project members' first-hand feedback is available. Also, the case provides all information necessary to validate the study's outcome. This chapter defines the case study, a part of the project Theemswegtracé in Rotterdam. First, the project of interest is explained briefly. With this, the choice for the project and case is elaborated. Next, the case study's context is given with carefully defined boundaries. Variable identification is the next step in this chapter. As part of the variable identification, the explanation of the control measures is stated. In chapter 7 those definitions of the control measures are translated into the simulation model.
Additionally, the involved tasks and structural parameters involved in each task are identified. Both are part of the TA and EM, respectively. The second-last paragraph discusses the limits, assumptions and contradictions of the current model set-up. The chapter concludes by answering the following sub-question:

What does the design and construction process of the case study look like?

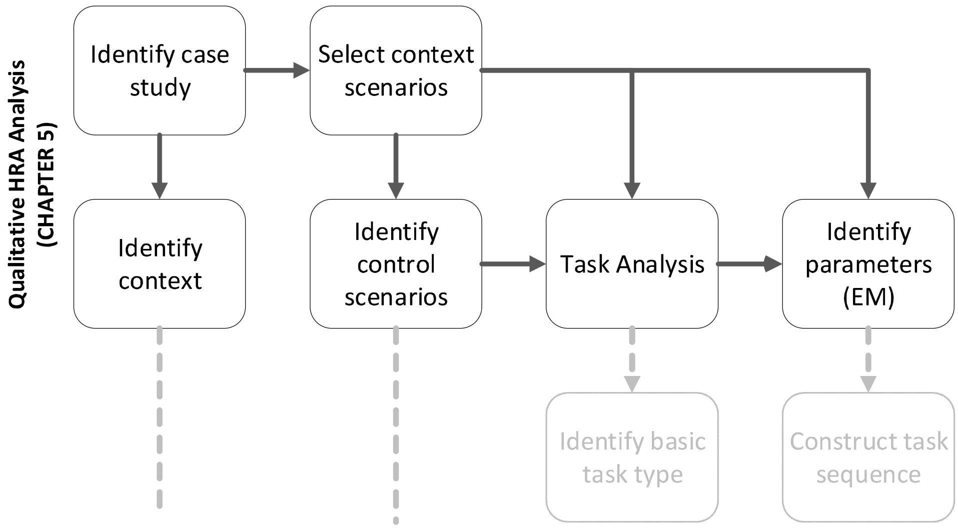

Figure 5 Qualitative HRA Analysis step from HRA model. Six steps are involved in the qualitative HRA Analysis. How they influence each other is represented by the arrows. Including directly involved tasks from other steps of the HRA model. For the complete HRA model, see Figure 4.

The Project

The project of interest is called the Theemwegtracé and is (mainly) commissioned by the Port of Rotterdam. The project functions as a railway viaduct and crosses other railways and roads at different levels. A collaboration of five parties is responsible for the design and construction of the project. The project is suitable for a research case as it represents a typical infrastructural project. The project allowed to visit the site as it was under construction during this research. Therefore, the necessary documents to fully explore the project and case are accessible.

As with many infrastructural projects, the particular solution is unique in the broader sense of the word. The research case study is based on a foundation pile that also functions as a column for a portal; as can be seen in the picture below. The portal is part of a temporary structure that functions as falsework for a prestressed land bridge. Where repetition is limited, the elements are adjusted to meet specific requirements for the land bridge, site, and surroundings.

Figure 6 Picture of the case study; a steel foundation element (highlighted). The case focusses on the width, depth and koppejan calculation of the pile. Also the load and position are variables of the pile in the variables of the case study.

Context identification

Figure 6 shows the pile that is used for the case study. The context of the pile contains various parameters, calculation methods, and the design and construction process. Some context is adjusted to fit the model. In the context identification, the basis is laid for later task analyses.

The pile stands out from the rest of the temporary structure as it is one of the only two portals in the temporary structure. The rest of the falsework is made out of prefabricated repetitive stability elements. The portal proved one of the few feasible solutions to gain sufficient stiffness.

Although the element is not typical because it is frequently applied as a supporting structure, the design approach and challenges are very similar for infrastructural projects. Designing such a project contains many iterations in the design phase and is an integrated process. Therefore, it is challenging to mimic a general design approach or simulate the realistic design phase. For modelling, the project is captured in its essence, and thus, assumptions and simplifications are plenty.

The project team's composition is more or less universal for such a big project. There are more than one party collaborating on the project and sharing more or less the same Human and Organisational Factors among various companies.

The primary flow of the process is adopted from KPCV [47] and represents a traditional construction process. It starts with the tendering, followed by the geotechnical design, and the engineering and construction phases. The traditional process also includes the maintenance phase. This phase is not included in the adaptation used in this research.

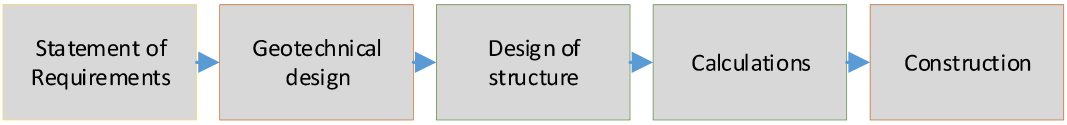

Figure 7 Main flow of research case process, adopted from the KPCV traditional construction process, and adjusted to case context. The five different project moments are in chronicle order and are shown in colour. Each box represents a phase in the project.

Variable Identification

After clarifying the case context, the next step is to identify the different variables scenarios. As the input of the model, this model can run with different variable configurations, By doing so, results from various compositions of the case context are comparable.

The type of variables that are included is about different design options. This is due to the following: To mimic 'practice', the design phase is shortened and more focused on a few calculations in which the micro-task shows coherence. Typical design errors or choices can still result in a reliable structural element. Thus, it represents the different possible typical outcomes for doing such a design process. This means that the variable outcomes are predefined, also known as the environment in which the model is running.

The variables are determined by several parameters (micro-tasks): the diameter of the pile, the diameter of the pile base, and several design tasks such as the position of the pile and acting load. Calculated is the pile base resistance, a Koppejan calculation from NEN1997-01. The tasks involved in the process are shown in Figure 8. The tasks are structured according to the main flow of TA (Figure 5).

The variables applied are:

- Location of pile
- Diameter of the pile
- Diameter of pile base
- Self-checking
- Third-party checking
- Construction checking

How the different variables relate to the design process is simplified and schematically represented in Figure 8.

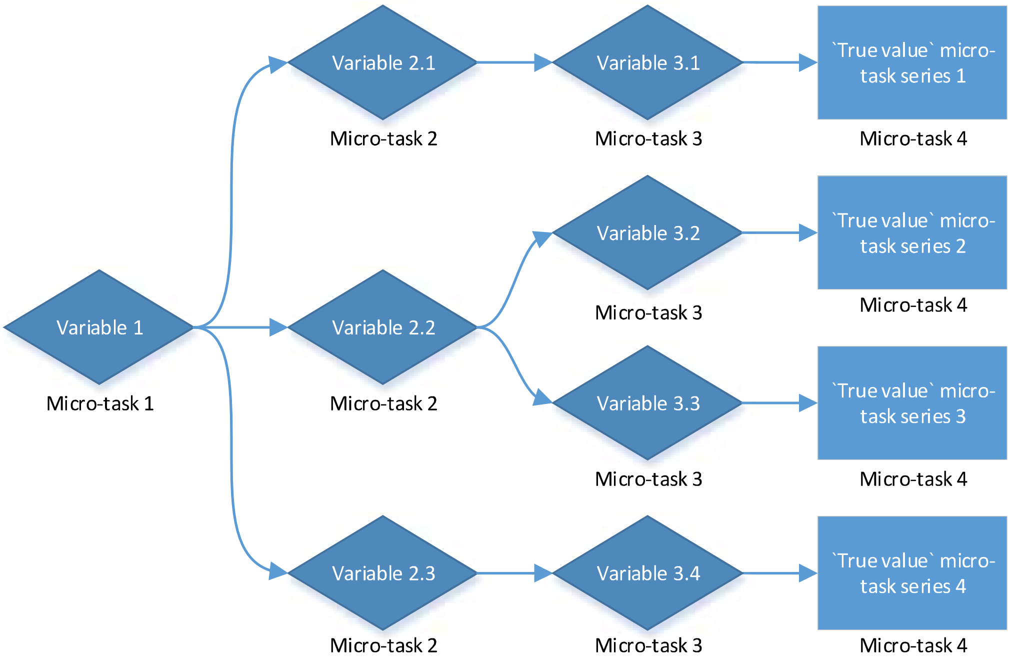

Figure 8 Theoretical example of an event tree of the relationship between variables and micro-tasks.

Other possible variables

It is also possible to consider other variables in this model. For instance, De Haan considered professional experience and different design control measures. With these variables, De Haan was able to do a sensitivity analysis of the tasks in the design process. As a control measure, assigning a minimum experience level to a specific task is possible. It is usually more often that experienced professionals perform tasks that have a high-risk profile. The same applies to the performers of control measures, such as the internal reviewers.

Another possible variable is the personnel change within the project team, such as a member replacement. It is not uncommon in practice that this occurs during a project. It happened to more than one role in the Theemswegtracé project. With every personnel replacement, some information gets lost, or new experience from the new project member leads to change in design. This is another example of a possible model variable. These options can be explored in future research but are left outside the scope of the current study.

Possible other variables to consider are (not an exhaustive list):

- Depth of pile base
- Calculation method
- Different kinds of pile
- Different kinds of pile base
- Change in project team members
- Distinctions in professional knowledge
- Normal supervision/ internal review
- Errors of omission
- Different case context/ context environment
- Different load cases

Control measures

In chapter 1, the definitions of the three control methods from the Eurocode are provided. Chapter 3 concluded that these control measures focus on controlling the outcome of human error. Every control measure is explained and elaborated on how this results in practice.

Self-checking

Self-checking is the simplest form of checking. A critical attitude and educated guess, or experience for the correctness of the outcome is a requirement for this assumption. Though it is the simplest form of checking mechanism, it can be challenging to consciously control the mechanism. Existing biases, external or internal pressure, and other influences can affect how well self-checking is performed. The estimation for the correct values produced from a micro-task can differ between professionals. The self-checking mechanism is simplified in this model and the same stands for each micro-task in the design and construction process. It is neglected in our study that engineers can have different levels of experience or competence to spot and correct false outcomes.

Besides this spontaneous form of self-checking, professionals can intentionally perform self-checking. The two methods are different in practice, as the intentionally self-check can be verified in the form of a checklist. However, they are modelled as the same, in which the professional verifies the outcome with their expected "correct value". This value is estimated (based on experience or a trial calculation).

Internal review (not implemented in this study)

The second checking mechanism that is commonly applied in the design and construction process is internal review. Internal review means control by a supervisor within the project team or company. This type of control is probably the hardest to model, as no guidelines for reviewers exist within most of the company. Most of the time, the supervisor is someone with abundant experience and can apply his knowledge to the review. This control method is heavily relied on the professional competence of the review personnel, as there are scarcely available regulations and norms exist to instruct how this review should be carried out and to what standard it is expected to meet.

Though how internal review is performed differs from one supervisor to another, there are several aspects that all supervisors check. First of all, they check if specific parameters are correctly derived. For instance, assigning correct soil parameters to every soil layer. Secondly, they check some essential values to see if they are consistent with the values they can expect. As the reviewer is often experienced, they can spot errors that self-check would not notice. Thirdly, they check if the task to perform is missing (OOC).

Also, the checking supervisor can ask for more information for tasks in the process. An example of this is when it is unclear if there exists a clay layer underneath the sand layer at the location of the pile tip. When this is unclear or can be expected, the reviewer will require some additional tasks within the process to gain more certainty. This review can make the process go back to previous phases and redo tasks from that point on. This checking process is a so-called *Gate Review*. This flexible character of the internal review, which is to jump back and add tasks, conditions, or assumptions to the task process, makes it hard to predict the activities and thus difficult to model the checking procedure. Therefore, an internal review is left for future research and not included in our model.

Third-party checking

Third-party checking is a form of external supervision. A company is hired, either by the client or the project team, to review the design and construction. This check normally occurs after the internal review and is an additional control measure. Though different from internal supervision, the depth to which a third-party checking occurs is set at the beginning. Therefore, there are several ways of performing this type of check possible by adjusting the specific demands to the depth of control. This includes what type of risks are considered and what type of test strategy is chosen. For risks, the options are the following three: 1) design calculation error leads to failure of the primary structure; 2) error in executing a design that leads to failure of the primary structure; 3) error regarding manufacturability/feasibility. The test strategy varies from 1) simple shadow calculation; 2) extended shadow calculation; 3) analysis of the input, the applied calculation method, and the calculation results. The result from the third-party checking is similar to the internal checking, as they too have a set of questions as the outcome. Depending on the level of control offered by third-party checking, they can make extended or straightforward shadow calculations. Lastly, they can validate the design regarding structural safety and feasibility.

Checking mechanism in construction

The checking mechanism within the construction phase is often in the form of quality control. Other forms could be recalculating the as-built structure to validate the structural reliability or a load test to secure resistance. Quality control comes in many forms, but in essence, they are the same. Visual inspection, a variety of gauges, and supervision of the manufacturing process are ways to validate the desired quality of the structural element. If such an element is not up to standards, a couple of decisions need to be made. For instance, the structure can be recalculated to check if additional (strengthening) elements are necessary, possibly by redesigning the load or adding restrictions in the construction phase. Another option is to redo the construction task for a better outcome. Or to accept the outcome of the construction and bear the consequences. The latter, however, is unacceptable when it comes to structural safety. To re-drive, a pile is also impossible for numerous reasons. Therefore, it is logical to check if the constructed element satisfies the design requirements, and accept the outcome of construction, even though this means additional requirements or additional structural elements are needed.

The construction checking does not influence the outcome of the simulation model, because the simulation model misses a feedback loop for this checking mechanism. The construction check does influence the outcome of the structural reliability analysis. It is a form of checking that provide insight concerning structural reliability for the project team. In other words, it is a way of validating the structural reliability within the model, by verifying if the construction result satisfies the design conditions and case context.

Context environment

The following assumptions are set as the environment for the model concerning the total design and construction phase:

- The *integrated process* is simulated as linear steps. In the TA table, the stated requirements provide a set of assumptions that indirectly influence the case study. Other (wrong) assumptions that influence the case indirectly are neglected. For instance: the maximum allowable deflection of the bridge could be overestimated in the statement of requirements. If the error is noticed, this will lead to a much larger stiffness of the column and pile in a later design stage. Only human error is of interest, not technical requirements.

- The design and construction are executed by standard infrastructural companies. The professionals have access to the necessary computer software, are trained to perform each task, and possess average communication skills. The same standard holds for the sub-contractor.

- *Actors*, *communication methods*, and the influence of other HOFs are neglected. How the errors are made and caused by which factors are not considered in the model. What is included are all properties and factors around the case study, even if the project team neglected them.

- Each task has only one most suitable basic task type assigned, even though the task may fit more than one basic task type.

Task Analysis

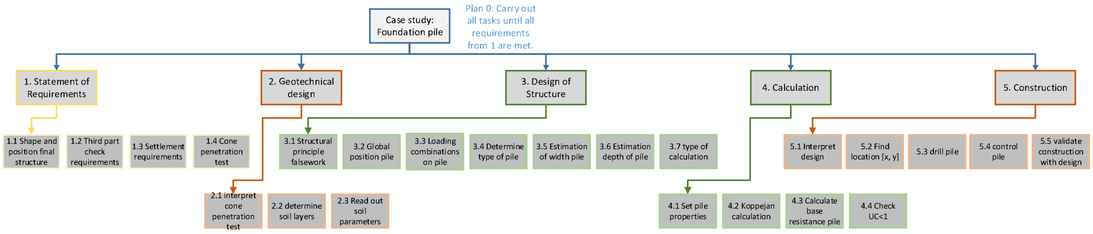

Figure 9 Hierarchical Task Analysis used to determine tasks involved in the process. See

Appendix B Task Analysis for a larger figure.

The case study, see Figure 9, is subdivided into five parts. It starts with the requirement statement, then geotechnical design, structure design, calculation, and lastly, construction. The output of the statement of requirements is a set of assumptions upon which the other phases are built. Often this is part of the Tender, although it can be corrected during the design.

The output of the second part contains all soil parameters for the design phase. Those values come from the geotechnical design part of the project and are part of the site investigation. In practice, this can be done by the client or at the start of the project by the contractor. From chapter 1, it is known that soil structures contain more uncertainties than building structures in material properties.

There are two steps in the engineering process. One is the detailed structure design, where all basic structural principles are applied. This phase starts with determining the order of magnitude of the load, after which the type and dimensions of the structure can be designed. The other step is called calculation which means verifying that the structure can bear the loads that will act on it for its designed lifetime. The calculation also provides the upper and lower limit state values for deviations in the construction process. Both steps are part of the structural design phase performed by the company.

In the last phase, special attention is given to communication and managing uncertainties and deviations in the construction process. The basic task types involved and how the micro-tasks are modelled are slightly different for the construction phase than for the other phases. More details regarding this are illustrated in the following two chapters.

An overview of the TA is shown in

Appendix B Task Analysis. The TA is limited to a standard foundation pile calculation and all tasks related to this calculation, as explained in the context. It makes sense that the TA is incomplete or influenced by a certain amount of subjectivity. The task sequence is obtained via consulting the project engineer, the planner and reviewers that are working at Dura Vermeer.

Error Magnitude

The second part of the human error quantification is the determination of the micro-tasks involved in the process. It is obvious to include parameters from the norm that are used in the calculation. Besides these, micro-tasks relating to the structural calculation but do not directly influence the variables are included. An example is processing the cone penetration test. it can influence finding the correct resistance measured. In Appendix C Error Magnitude, all parameters are found in the EM table.

The EM Table is input for the simulation model and contains all parameters for all micro-tasks. The EM is a variable used to adjust the structural-related parameter when a human error occurred. The adjustment comes in the form of predefined distribution, with one as the mean value and a standard deviation as the representation of the severity of the error. A more complex micro-task contains a higher standard deviation than simpler micro-tasks.
The EM is a factor that adjusts the fixed `true value` of the micro-task in case of error. As this factor is distributed around one, the EM can both increase and decrease the `true value`.

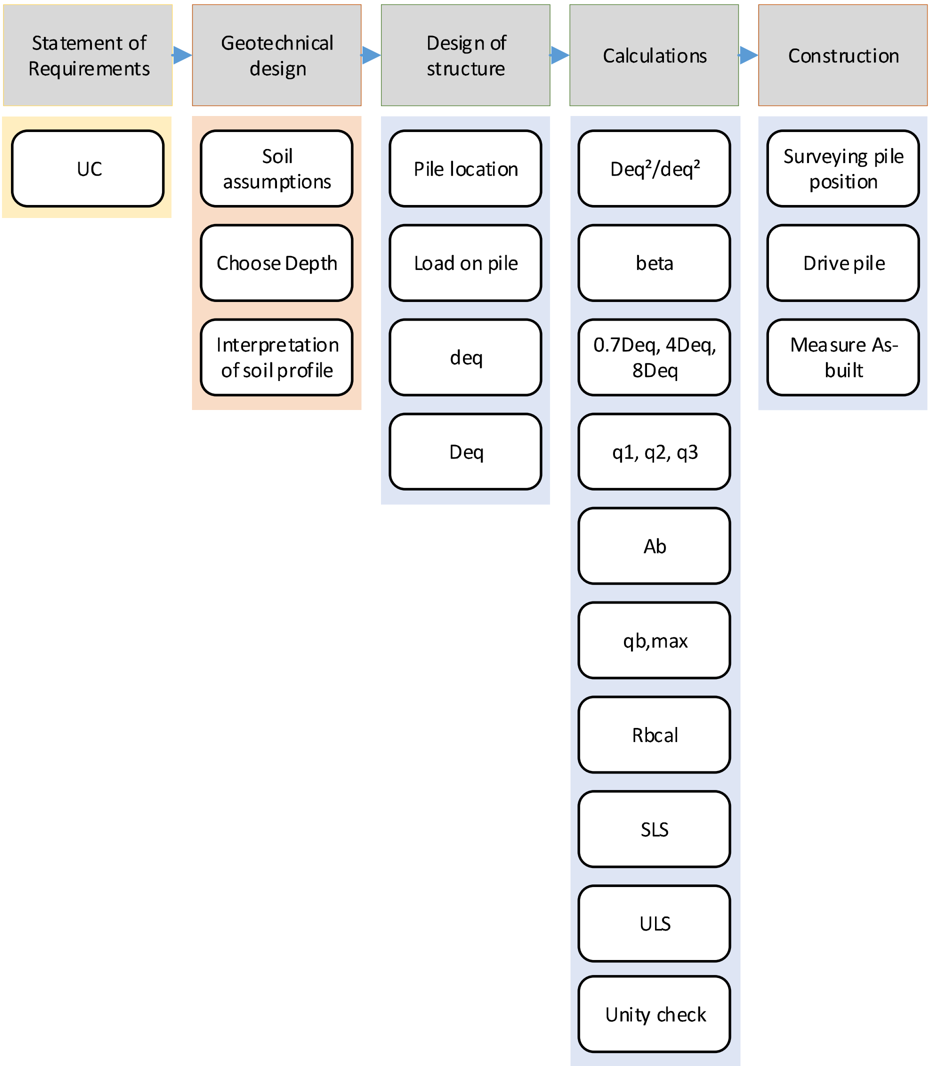

Figure 10 Main flow of project process with all parameters in the Error Magnitude.

Contradiction, paradoxes and assumptions

Task analyses can contain more steps than what is performed in practice. The error probability is overestimated when this is the case. In the same way, task analyses can miss crucial tasks in its process and, therefore, falsely predict a safe structure. These errors of missing tasks are called errors of omission. This non-existent knowledge of what step is missing is solved by consultation, reviewing, and expert judgment but is not guaranteed.

Another paradox is using values as parameters, as is the case in the determination of the Error Magnitude. Those values are regarded as `true values`, and the error magnitude will affect those values by increasing or decreasing these values. However, it is ubiquitous in structural engineering to have different design values but all of them are correct. To take an example of the amount of reinforcement in a concrete element, the area of steel reinforcement that is necessary can be calculated differently. However, if the calculation results in a few bars of large diameter or many bars of small diameter are up to the engineer, not to the pre-set in the model. The same holds for determining the steel strength versus diameter versus thickness of the foundation pile.

Lastly, the project context results in a calculation result that is the input for the EM table. in this calculation, human errors occur, even though they are regarded as the `true values` in the EM table. Therefore, sometimes the true value is falsely regarded as true. These possible errors are neglected.

Conclusion

Because CREAM of Hollnagel is a Context-related HRA method [38], it is a necessity to frame the context of the chosen case study [33]. The calculated structural reliability and failure probability are directly related to the case context and are not directly applicable to different case studies. In line, conclusions from the structural reliability and failure probability are valid with the case context. It is yet to be determined if the conclusions are the same for a different context, variables, or environment.

It is, therefore, of utmost importance to have a clear view of the totality of the scope. The difficulty lies in predefining the interaction of the tasks and fitting the tasks in the area of investigation. Special attention is required in developing this part of the HRA method.

This chapter describes the case context, variable identification, control measures, context environment, TA and EM. Together, they form the scope of the HRA model. The case is the design and construction of a foundation pile, based on a structure of the existing project Theemswegtracé. The used variables in the case are: 1) location of the pile, 2) diameter of the pile, 3) diameter of pile base, 4) self-checking, 5) third-party checking, and, 6) construction checking. The process results in a TA table to determine all involved tasks in both phases. In the EM table, the micro-tasks are determined that influence the case outcome. This resulted in thirteen micro-tasks for the design phase and five micro-tasks for the construction phase. These micro-tasks are further elaborated in chapter 7.

The case study is simplified to make it applicable to the HRA model. The design and construction process is shortened and specified to the structural element. This whole process of tasks is modelled as a linear process. Parallel performed tasks are not considered. For the complete TA table and EM table, see

Appendix B Task Analysis and Appendix C Error Magnitude.

6. Human Error Quantification

One essential input for this model is the quantification of the HEP. The HEP value used here is from the results of existing studies. However, they are obtained statistically from observations of a sample, and cannot be regarded as a precise reflection of practice due to the uncertainties involved. It is important to distinguish different basic task types with known HEP for each type and allocate them to the micro-tasks. This chapter follows the steps in the HRA model below. Steps in the TA include: identifying basic task type, selecting cognitive function failure, and deriving error probability. Determine the EM following the step sequence of the construct task sequence, select the distribution function and then determine EM.

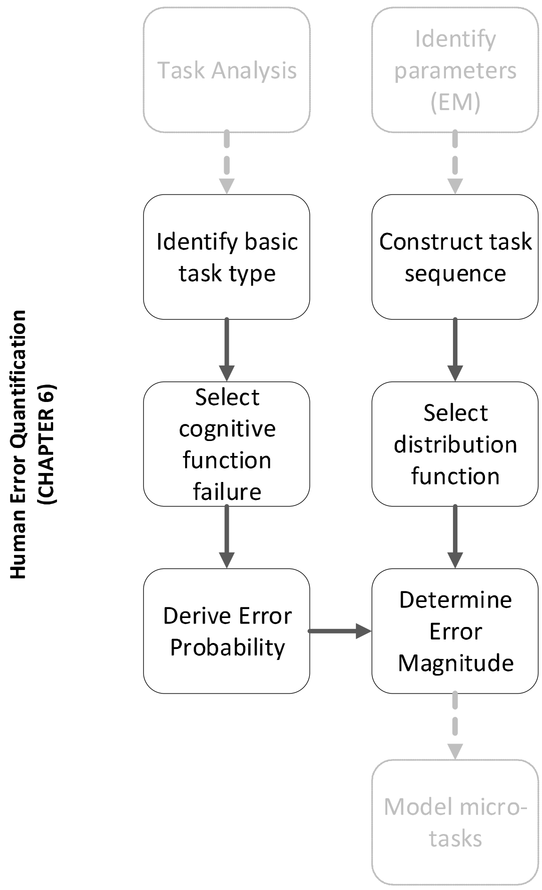

Figure 11 Human Error Quantification step from HRA model. Six steps are involved in human error quantification. How they influence each other is represented by the arrows. Including directly involved tasks from other steps of the HRA model. For the complete HRA model, see Figure 4.

This chapter is ordered as follows: firstly, the definitions and context of basic tasks and error magnitude are given in the subsection *quantification context*. Next, the values are assigned to the EM table in the subsection *quantification values*. An overview of the assumptions is provided in this part as well. In the final part of this chapter, some remarks on the effects of the quantification on the simulation model are discussed.

Quantification context

A study performed by Stewart [11] provides the HEP values of some tasks in structural design and construction. The definitions, context, and EM values of basic tasks are in line with the study from De Haan [3][4]. The seven basic task types for structural design tasks are the same as what De Haan proposed. Therefore, the seven basic task types listed below are for the design phase modelling. Basic task types for the construction phase are adopted from Kim [46].

Consult
Reading and interpreting guidelines or norm requirements. "Consult" typically is more advanced than "obtain". [3]

Obtain
Adopting a design parameter from a resource such as a drawing. Typically for tasks in which thorough interpretation of the resource is not required. [3]

Derive
Select a value from a range of values based on previously determined selection criteria. [3]

Determine
Taken a decision based on engineering judgement and available design parameters. [3]

Calculate
Calculating a parameter based on available design values. This task typically involves inserting values in a calculation program, calculator or hand calculation and retrieving the outcome. [3]

Insert
Placing a calculated/derived parameter in a design program/ design document. "Insert" is the opposite to "obtain". [3]

Communicate
A thorough discussion on basic design parameters, the design or other aspects. This task typically involves passing on or receiving person-to-person information, interpreting the information and reasoning about the implications of the information. [3]

Another group of basic task types used in the construction phase are presented below. Typical basic tasks in the construction phase are *instruct*, *interpret*, *monitor* and *execute*.

Instruct
Explaining or assigning a task to one another. This task is typically performed by the engineer/ construction manager to foreman and/ or construction worker.

Interpret
Read drawings and plans on the construction site. This includes making the latest plan available for all. Though this task is similar to "obtain", this task is strictly limited to the construction phase and differs from performer to obtain.

Execute
Performing tasks with a physical result on the construction site. In the end, all designed elements are realised through the performance of this basic task.

Monitor
During and after construction, there are moments of monitoring. This means the control, inspection and evaluation aspects associated with the performance of an execution task.

Tasks can differ in difficulty even though they belong to the same basic task type. An example is two different calculations, one complex and one simple. To accommodate these different levels of complexity, an additional subdivision is added. As De Haan describes, the "three levels of cognitive operations are distinguished: a skill-based, a rule-based and a knowledge-based level." The cognitive levels are not distinguished in the basic task types for the construction tasks. De Haan provides the definitions for the three cognitive levels as follows:

Skill-based level
Comprising highly routinized activities in familiar circumstances. Errors typically occur when a person's actions are different from their intentions. They often occur during automatic behaviour, which requires little conscious thought, or when attention is being diverted. [3]

Rule-based level
Comprising problem-solving activities using previously established if-then rules. Errors occur when a known rule is incorrectly applied or a situation is misinterpreted. [3]

Knowledge-based level
Comprising problem-solving activities based on a higher-level analogy. Errors result from a deficit of knowledge. A person may intend to implement a plan or action, but the plan or action is incomplete or flawed by a lack of knowledge and does not result in the desired outcome. [3]

Note that some tasks can be linked to more than one basic task type or different cognitive levels. In this case, both the basic task type and the cognition level are chosen which fit the task the most. A different interpretation of tasks is possible and can be found in the chapter discussion.

The HEP values for all basic task types are summarised in Table 2 HEP values corresponding to basic task types, including different cognitive levels. For the engineering phase, the HEP values are directly copied from De Haan [3]. The construction phase is copied from Kim [46] and categorised by different cognitive levels. This table is used to assign HEP values to all tasks in the TA as input for the model.

	Basic task	skill-based	Rule-based	Knowledge-based
Engineering phase	**Consult**	2,25E-3	1,25E-2	2,24E-2
	Obtain	1,28E-5	2,50E-3	
	Derive	5,13E-4	7,63E-4	2,06E-2
	Determine	5,13E-4	1,03E-2	3,00E-2
	Calculate	2,56E-5	7,75E-4	2,02E-2
	Insert	1,28E-5	2,50E-3	
	Communicate	7,68E-4	1,02E-3	1,10E-2
Construction phase	**Instruct**	4,72E-3		
	Interpret	4,615E-1		
	Execute	2,685E-3		
	Monitor	3,22E-3		

Table 2 HEP values corresponding to basic task types, including different cognitive levels. For the engineering phase, the HEP values are directly copied from De Haan [3]. The construction phase is copied from Kim [46]

Error magnitude

The following sequence from Figure 11 Human Error Quantification step from HRA model. Six steps are involved in human error quantification. How they influence each other is represented by the arrows. Including directly involved tasks from other steps of the HRA model. For the complete HRA model, see Figure 4. is to construct the EM table. The filled-in TA highly influences this table, as the error probability of a variable is dependent on the tasks involved. The error probability is the value of the micro-task that describes the sensitivity of failure. The EM table and the TA table are in line with De Haan [3]. To obtain EM, three parameters are required, namely: construct task sequence; select the distribution function; and determine the EM. A short description of each step is provided below.

Construct task sequence

The TA consists of numerous tasks that describe all the work within the design and construction process. These standalone tasks have a HEP, assigned with the procedure described in the previous paragraph. Multiple tasks form a parameter in the EM table, also called the Micro-Tasks. These multiple tasks involved form a task sequence. As a result, the sum of all HEPs correlated to the task sequence is the error probability.

Note that the sum of the HEPs theoretically could result in an error probability greater than one. This is undesirable and can be avoided by dividing the micro-task into more micro-tasks.

Select distribution function

The distribution function provides insight into what the EM looks like. With the chosen basic tasks, only three different distributions are possible: Normal, Lognormal and Discrete function. Sometimes the distribution is called the failure function as the functions are directly related to the failure. The distributions are micro-task specific; however, the Lognormal functions are generally for calculation tasks, the Normal function for other basic tasks and the Discrete function for special situations, like manufacturing properties (such as the diameter of the pile).

Determine error magnitude

As the last step in the EM table's quantification process, the standard deviation is assigned to the micro-task. This standard deviation, accompanied by the distribution function, is an indication of the EM of the micro-task (hence the name of the table). The standard deviation of the micro-task is subjected to task complexity. The more complex the task is, the larger value the standard deviation is. In general, EM represents the estimated impact of the errors made.

The standard deviation is found in Table 3 standard deviations corresponding to the distribution function of the micro-task and the complexity of the micro-task. All values are copied from De Haan [3]. and is directly copied from De Haan [3]. The allocation of the complexity of the micro-task is up to the HRA moderators or determined by a project team or expert panel. Task complexity is levelled up or down depending on the overview of the task sequence. If a clear overview with sufficient information is lacking, complexity increases. The complexity decreases if all information is at hand and the situation is controllable. Discrete functions are case-specific and, therefore, not present in the table. In general, the case-specific options are incremental.

Task Complexity	*Normal distribution*	*Lognormal distribution*
Very complex	1,4826	1,0277
Complex	0,9648	0,6688
Neutral	0,7803	0,5409
Simple	0,6080	0,4219
Very simple	0,4299	0,2980

Table 3 standard deviations corresponding to the distribution function of the micro-task and the complexity of the micro-task. All values are copied from De Haan [3].

Remarks and conclusion

Swain [35] assigned different distribution functions to certain basic task types. Although often not entirely valid, he assumed the normal distribution for the performance of most cognitive tasks. In this research, as is also the case for De Haan, all basic task types are assigned with the normal distribution, apart from calculation tasks.

Although the literature provides a second distribution for calculation task types to compensate for computational and decimal mistakes, those numbers date back to 1984 [48]. It is unsure if those numbers a still relatable to practice, and therefore to keep the process away from ambiguity, the second distribution to compensate for the mistakes is left out.

The allocation of the basic task types is a simple but effective way to set up the framework for the simulation model. To limit the objectivity of the allocation, quantification can be performed by a group of professionals. It is possible though that more than one basic task fits the description of the task. In that case, it is conservative to use the basic task with the larger HEP value. However, this may lead to an overestimated failure probability.

The quantification method is very suitable for the user of the HRA model to generate the input of the simulation model.

One limitation of this developed method is that different allocation of basic tasks, cognitive level, and or task complexity will result in different simulation results. De Haan already concluded that the failure probability is relative. Therefore, a big caveat is necessary: steering on HEP values misses the purpose of this research, as the purpose of the research is to determine the relative effectiveness of the applied control measures.

7. Simulation Model

The third step in the HRA model is about the simulation model and is described in this chapter. The subjects of the paragraphs are in line with the flowchart of the HRA model. The fragment for this chapter can be seen in Figure 10. The methodology of the model is explained in the first paragraph. Then, the three different control measures are explained in the paragraph ‘simulation procedure control measures’. In the step ‘simulate design model’, the results for all control measures are stated. The sub-question related to this chapter is:

How do control measures influence the outcome of the HRA model?

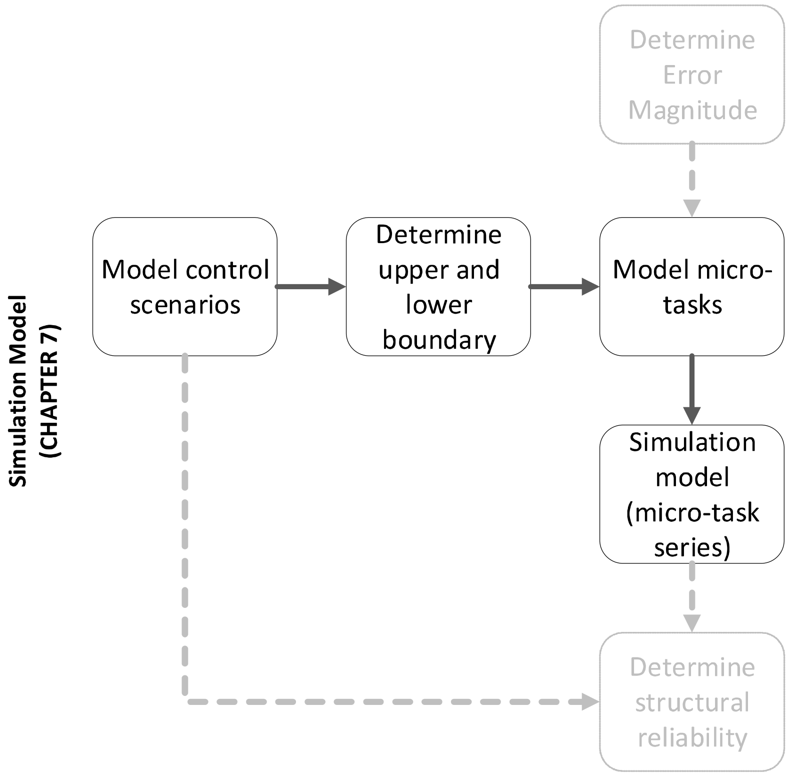

Figure 12 Simulation model step from HRA model. Four steps are involved in the simulation model. How they influence each other is represented by the arrows. Including directly involved tasks from other steps of the HRA model. For the complete HRA model, see Figure 4.

Simulation procedure micro-task and micro-task series

Previous steps of the HRA model, such as the project context and TA, determined the task performance environment and order. The context environment, from chapter 5, explains why the integral process of the project is simulated in a linear order. Apart from these, control loops are added to this linear process simulation.

The simulation runs all parameters from the EM table in sequence. These individual parameters are called micro-tasks. If multiple micro-tasks are involved in the simulation this is called a micro-task series. For a micro-task series, the output from a macro-task is the input for the next.

The design phase consists of thirteen micro-tasks:

1) Interpretation of soil profile.
2) Setting depth pile base.
3) Determining pile location.
4) Estimate load on pile.
5) Determine diameter of pile (deq).
6) Det. diameter of pile base (Deq).
7) Calculating Deq^2/deq^2.
8) Deriving beta factor.
9) Calculating areas of influence (0.7, 4, 8*Deq).
10) Calculating q1, q2, and q3.
11) Calculating area base.
12) Calculating qb,max.
13) Calculating Rbcal,max.

Simulating micro-tasks

Every micro-task is modelled according to the task-cycle approach presented by Stewart [24]. Figure 13 shows the algorithm for this procedure. The outcome is either the "correct value", or a deviated value from the "correct value", which is calculated via multiply the correct value by a randomly drawn value from the EM distribution. Then this outcome value is given to the corresponding structural parameter that influenced this micro-task. The corresponding code is in Appendix D Matlab script.

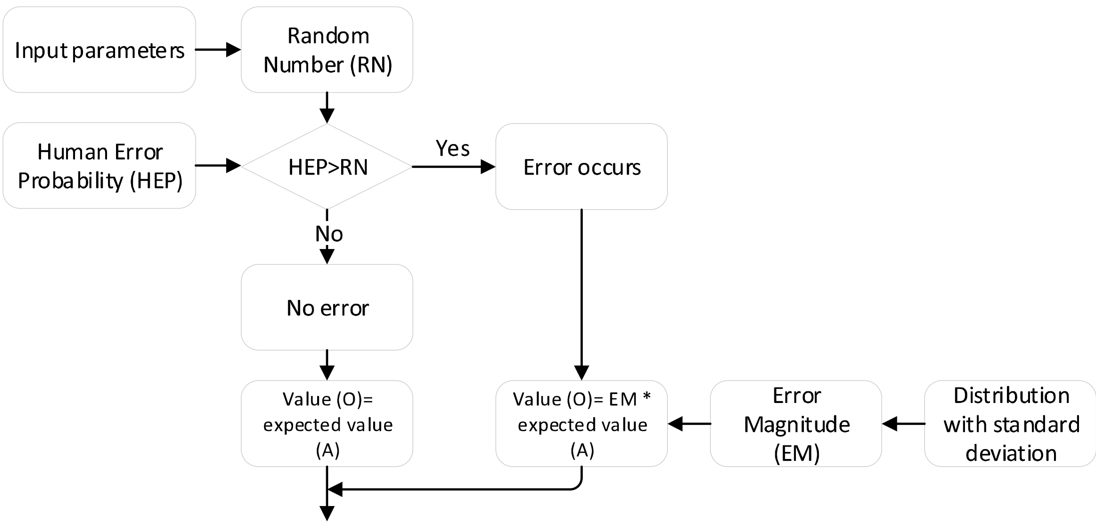

Figure 13 Simulation process of micro-task. The workflow starts with input parameters from the EM table. A random number and HEP value of the micro-task determine if an error occurs. The EM represent the severity of the error. The output of the micro-task is Value (O). The HEP and EM number come from chapter 7.

Construction micro-tasks

The construction micro-tasks work slightly different than the other phases. Contrary to typical engineering or design tasks, some deviation is always present in the construction of foundation pile for instance. These uncertainties are called Aleatory, where the uncertainty "is presumed to be the intrinsic randomness of a phenomenon" [49]. These micro-tasks are modelled with a distribution function and standard deviation, to represent the intrinsic randomness of the micro-task. However, due to human error, an additional deviation is possible. Adding to the construction phase are five micro-tasks. These micro-tasks are simulated with the same principle as the design phase.

The five micro-tasks in the construction phase:

1) Surveying pile location x-axis.
2) Surveying pile location y-axis.
3) Driving pile x-axis.
4) Driving pile y-axis.
5) Monitoring construction result

Simulation procedure control measures

For every micro-task in the simulation, two different control measures are studied: self-checking and third-party check. The order in which the simulation runs is 1) the micro-task, 2) self-checking, and 3) third-party check. This is if the control measures are applied. After running the complete micro-task series, so thirteen micro-tasks and possible control measures, the result for the design phase is complete. This is one iteration. The total number of iterations is 100.000 times. The self-check and third-party check are only applied in the design phase.

Self-checking

The self-checking procedure is cited by De Haan [3] and shown in Figure 12. The flowchart starts with running the micro-task until it outputs a Value (O). This Value (O) is then compared with the predefined boundaries for this value. The boundaries are included in the EM table and are estimated minimum and maximum realistic values for a structural parameter.

These estimated boundaries can change according to the knowledge and experience of the task performer. In this case study, they are determined by the modeller. In the figure below, the minimum and maximum limits are shown with $\xi 1A$, and $\xi 2A$ respectively. Note that $\xi 1A$, and $\xi 2A$, do not necessarily represent a factor. The listing is to show that there is a lower and upper limit.

The obtained outcome of the micro-task, therefore always lies between the lower and upper limit. Therefore, the *expected value (A)* can change due to the *incorrect value (O)* of the previous micro-task. Garbage in, garbage out.

If value (O) fits the boundaries, the result is accepted and the next micro-task is run. If the outcome is outside the boundaries, the micro-task will perform an additional time, until correctly within the boundaries.

1. Self checking:

For tasks:

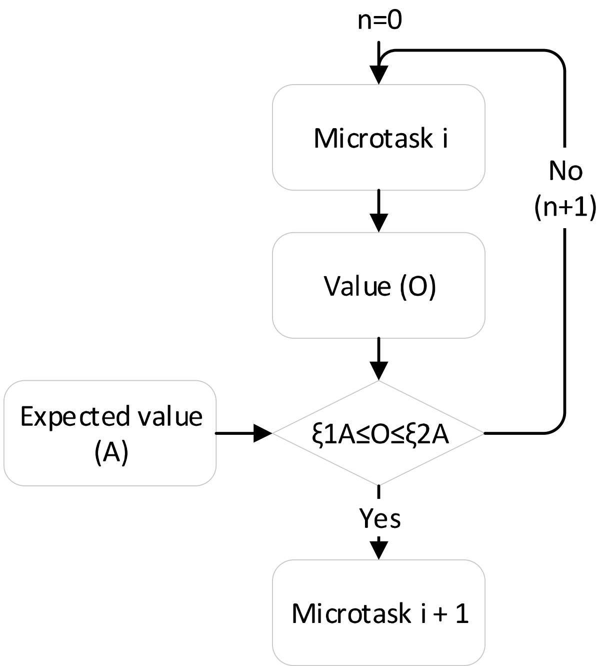

Figure 14 Self-checking procedure. The output is a Value (O) that does fit between the lower and upper boundaries. Those lower and upper boundaries are not necessarily fractions of Value(A) but represent the limits of realistic values.

Third-party check

After simulating the micro-task and self-checking for the whole task series, third-party checking is performed. Within every iteration of the micro-task series, a fixed number of third-party checks are assigned to randomly selected micro-tasks. Third-party checking verifies and, if necessary, changes the micro-task output to a newly calculated value(T). The flowchart of this checking mechanism is visualised in Figure 13.

Just like micro-tasks, the output of the third-party check is subjected to the output of self-checking. The third-party check is modelled very similarly to the self-check of a micro-task. The difference is that the given boundary range for a parameter value is narrower and the "correct design value" is always included within this range. This means that for third-party check, garbage in, garbage out is not the case anymore. This checking mechanism can always correct the output to the acceptable range.

The last part of the check is to compare the outcome of third-party check with the outcome of the (self-checked) micro-task. If the value (O) is within the range of the boundaries (±1%) provided by the third-party check, then the calculated value from this micro-task is accepted and passed to the next micro-task. Otherwise, the outcome of the micro-task is replaced by the outcome of the third-party check, since this value is considered to be more prone to be correct.

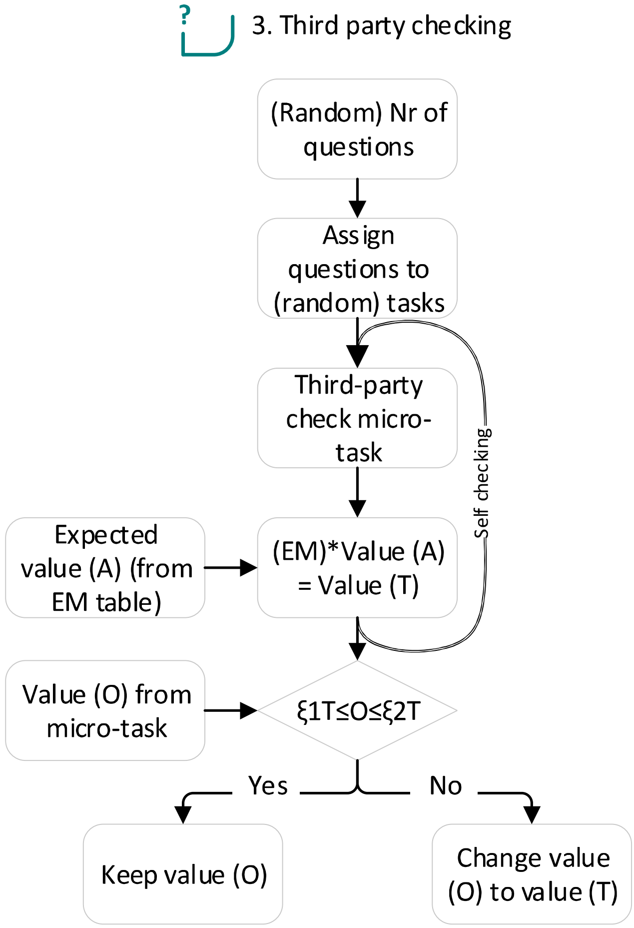

Figure 15 Third party checking procedure. This includes performing micro-tasks in Figure 11 and self-checking in Figure 12. With a difference in self-checking, the output value is not compared with the expected value (A). After performing the micro-task and self-check, Value (T) (third-party check value) is compared with the input value(O)(micro-task).

Construction checking

After completing the design and construction micro-tasks series, there is an option to check the construction output on correctness (for the deviation vs design parameters). This check is a way for a project team to ensure that the construction results meet the design requirements, as this checking measure is strongly recommended to use practice (see chapters 1 and 2).

The algorithm for the construction checking mechanism is shown in Figure 14. It starts with comparing the results of the construction with the design outcome. If those two outcomes are within acceptable limits, the checking task ends here. If the element is constructed outside the limitations, a re-evaluation of the pile, including the load and loads resistance is necessary. The Unity Check and assumptions form the input for the decision in the check. Note that the pile is not redesigned in the design phase. The design is checked with the As-built location for UC requirements.

Lastly, if the position of the pile is outside both boundaries, the element is not sufficiently safe and additional strengthening structural elements are needed.

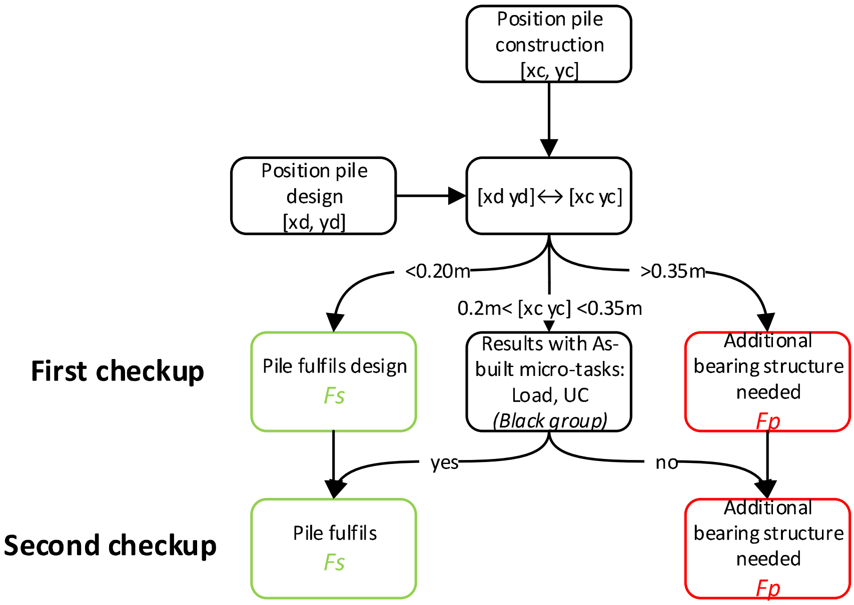

Figure 16 Flowchart of construction checking mechanism. After construction, the position of the constructed pile is compared to the designed position. If the construction result is below 0.2m the pile is accepted. If the result is above 0.35 m the pile is rejected. For the values in between, a re-evaluation of the design takes place, see the black group. In the second checkup, piles from the black group are validated.

The Unity Check for the piles at the start of the construction phase is between zero and one, otherwise, the pile design is automatically rejected.

Results

To answer the chapter's sub-question (*How do control measures influence the outcome of the HRA model?),* the results of the three control measures are listed and explained. This subsection focuses on the human error rate and the distribution of the outcome of the micro-task simulation, not on the structural reliability.

The order of the results corresponds with the order used in this chapter. It starts with showing the results of a micro-task. Then the micro-task series, self-checking, third-party checking and lastly the construction checking.

Micro-task

Figure 17 shows the result of simulating the micro-task 'Load estimation'. The EM table input of this micro-task is shown in Table 4. The result of one micro-task peak on the mean value and the peak value corresponds to the probability that the task is performed without error.

Error Magnitude Properties					Distribution				
Task sequence	Micro-task description	error probability	Parameter	unit	correct value	Distribution function	standard deviation	Lower boundary SC	Upper boundary SC
705	Load estimation	0,1245	LoadULS	kN	250	Lognormal	0.6688	180	380

Table 4 Error magnitude table properties of the micro-task 'Load estimation'.

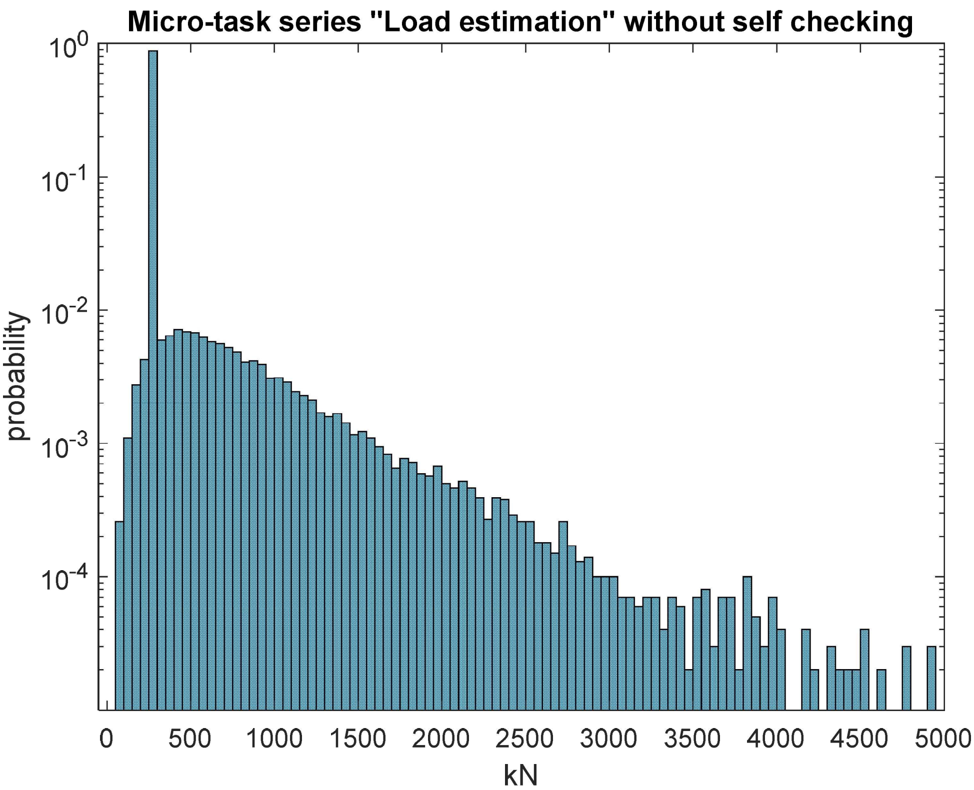

Figure 17 Result of Monte-Carlo simulation of one micro-task 'Load estimation', without self-checking. The lognormal error distribution function is visible.

The percentage of results that are on the mean value of 250 kN is 87.55%. The incorrect values are exactly 12.45%, which is the probability that this micro-task has a wrong output value, see Table 4. The distribution of the EM is lognormal represented, as this particular basic task type is 'calculating', see chapter 6.

Micro-task series

The results for the thirteen micro-task series in the design process are summarised in Figure 18. The figure shows the result after performing the last micro-task, 'calculating Rbcalmax'. To model this micro-task series, all thirteen design phase micro-tasks are simulated in sequence. The corresponding EM table is shown in Table 5.

Note that the four different Rbcalmax options correspond with the four different design variables, see chapter 5.

Error Magnitude Properties					Distribution				
Task sequence	Micro-task description	error probability	Parameter	unit	correct value	Distribution function	standard deviation	Lower boundary SC	Upper boundary SC
7161	Calculating Rbcalmax	0,0006	Rbcalmax	kN	301	Lognormal	0,4299	150	500
7162		0,0006			344,0	Lognormal	0,4299	200	550
7163		0,0006			412,0	Lognormal	0,4299	250	600
7164		0,0006			455,0	Lognormal	0,4299	300	650

Table 5 Error magnitude table properties of the micro-task series 'Calculating Rbcalmax'.

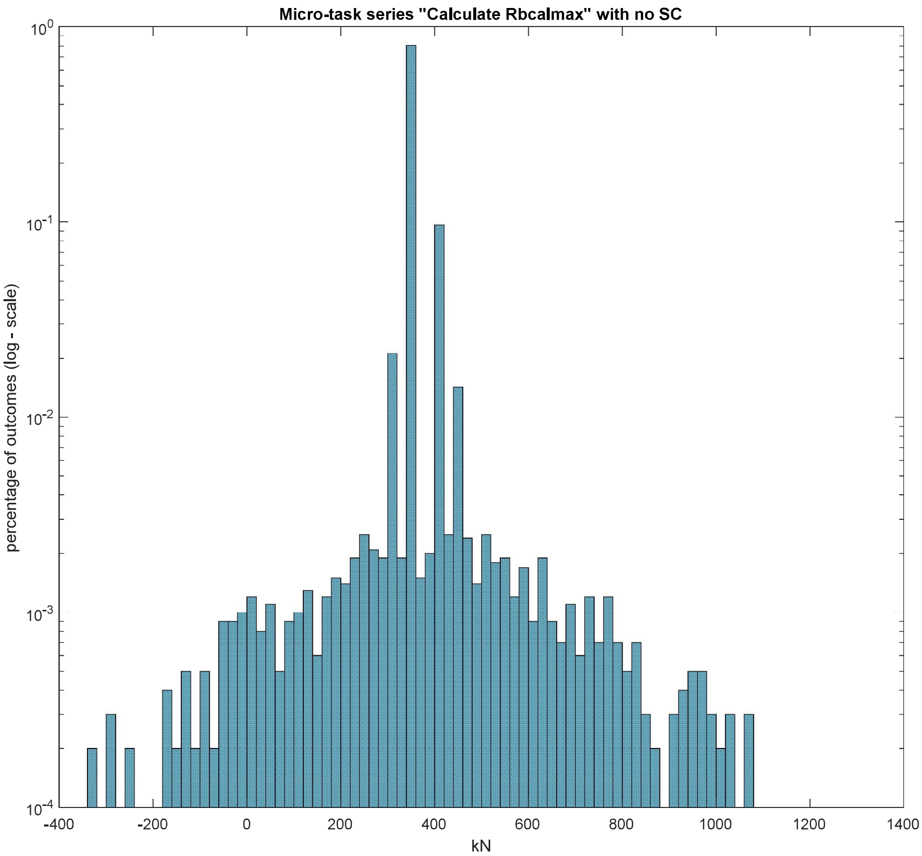

Figure 18 Monte Carlo simulation results micro-task series 'Calculate Rbcalmax', without self-checking.

The results range between -340 kN and 1080 kN. The negative results and extremely large results are unrealistic, and should therefore be excluded to mimic practice.

The percentages of the four peaks are listed below:

Mean value	**Percentage (%)**
301	1.94
344	80.44
412	9.32
455	1.32
Total on peak	93.02

Table 6 Parameter value percentage overview for micro-task series

Self-checking micro-task

Table 7 shows a comparison between the outcome of no self-checking versus self-checking included for the micro-task “Load estimation”. Note that not all data is visible in the graphs, . Table 6 is an overview of the percentage of the data for this particular micro-task.
The error rate after self-checking is reduced significantly, although the precise amount depends on the upper and lower boundaries to which self-checking was applied. The error

probability has decreased from 0.124 to 0.032 for the micro-task “Load estimation”. Furthermore, the boundaries of the error distribution are limited to the upper and lower boundary shown in Table 4.

The error distribution between the lower and upper limit is again according to the lognormal distribution.

Value	**Percentage of correct value output without self-checking (Figure 17)**	**Percentage of correct value output with self-checking (Figure 19)**
<250	0.7%	0.6%
=250	87.6%	97.8%
>250	11.7%	1.6%
Total	100	100

Table 7 comparison of micro-task outcomes with and without self-checking

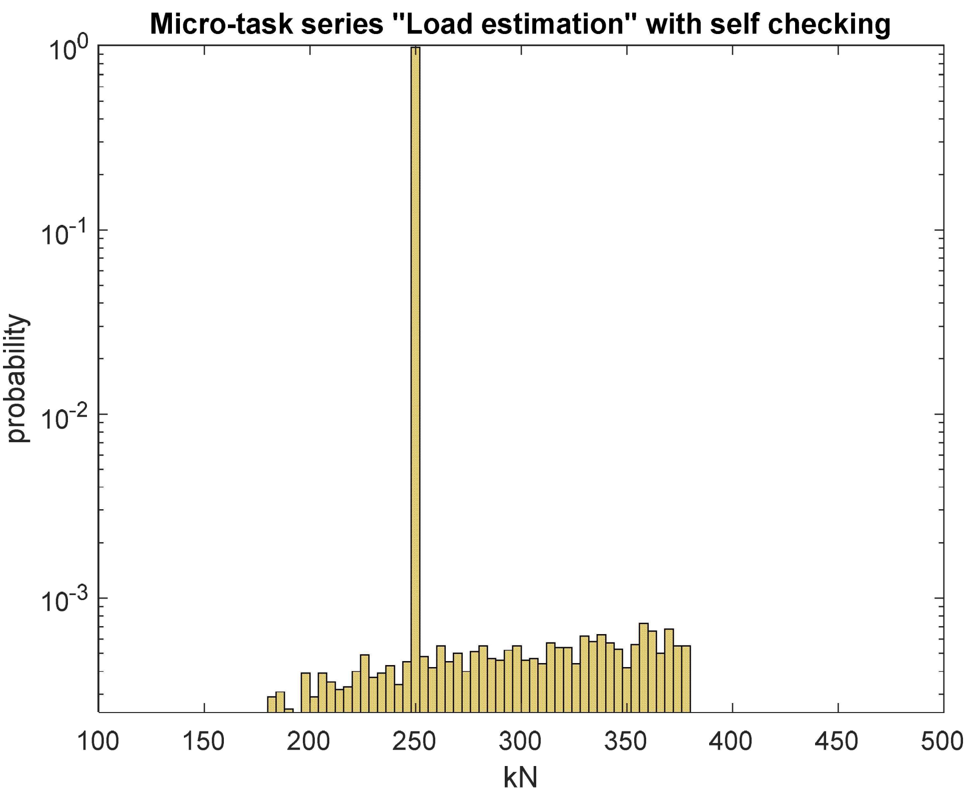

Figure 19 Result of Monte-Carlo simulation of one micro-task ‘Load estimation’, with self-checking. Although not entirely visible, the error distribution follows a lognormal distribution.

Self-checking micro-task series

The effect of self-checking on micro-task series shows the same results as for one single micro-task. Again, the results are from the micro-task series that includes all thirteen design micro-tasks and ends with the micro-task ‘calculating Rbcalmax’.

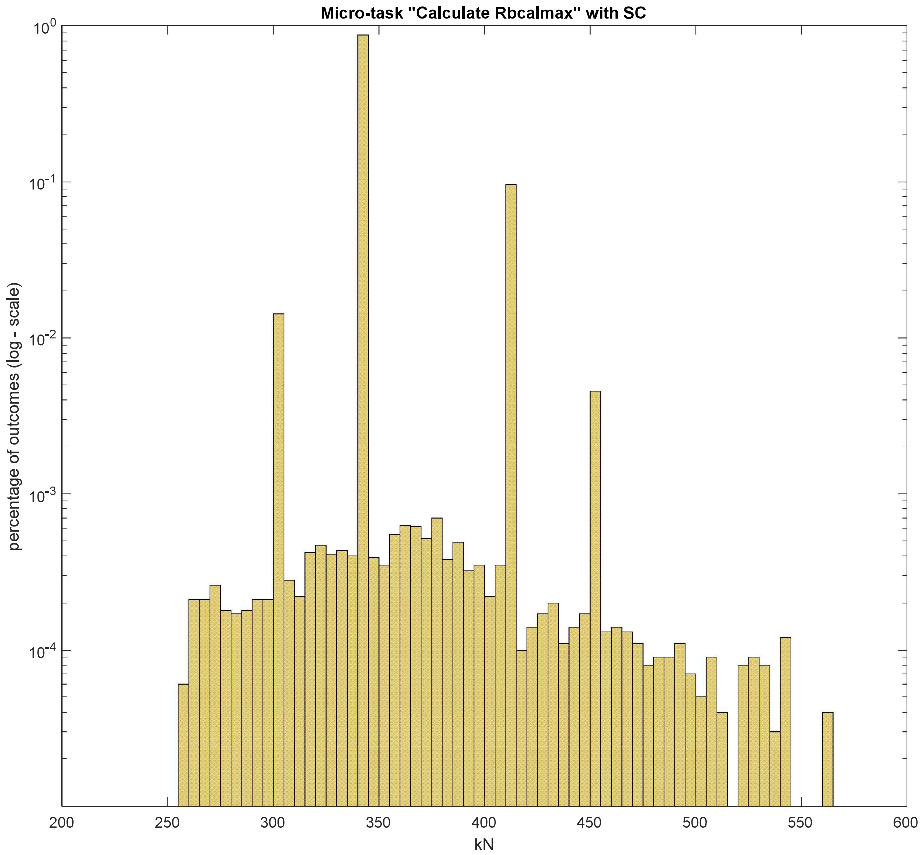

Figure 20 Monte Carlo simulation results micro-task series 'Calculate Rbcalmax', with self-checking.

Value	**Percentage of correct value output without self-checking (Figure 18)**	**Percentage of correct value output with self-checking (Figure 20)**
301	1.9%	1.2%
344	80.4%	87.1%
412	9.3%	9.7%
455	1.3%	0.6%
Total	92.9%	98.6%

Table 8 Comparison of micro-task series outcome with and without self-checking. Percentage overview of logical design answers, see four peak values.

The effect of self-checking on a micro-task series is considerable. Besides improving the outcome of the design significant, from 92.9 to 98.6%, self-checking again limits the error distribution within a smaller range. The values are cut off below 250kN and above 560kN.

Comparing these boundaries to the lower and upper limits from the EM in Table 5, it is remarkable that the cut-off is not at the values 150kN and 650kN. This can be explained by Figure 20, which shows the result of a micro-task series. In other words, every micro-task before the last micro-task is subjected to self-checking. It is probable that previous micro-tasks already limit the EM before the last micro-task. And although theoretically the values 150kN and 650kN are still possible, the probability is as low as almost zero.

The outcome of a micro-task series with self-checking is not always of the same magnitude. This improbability is shown with a boxplot of nine repeated simulation model runs, each with 100.000 iterations and the same input variables. The results show an uncertainty, and that more iterations, for example, 1.000.000 iterations, would show a more reliable outcome. Due to computational limitations, this is left outside the scope.

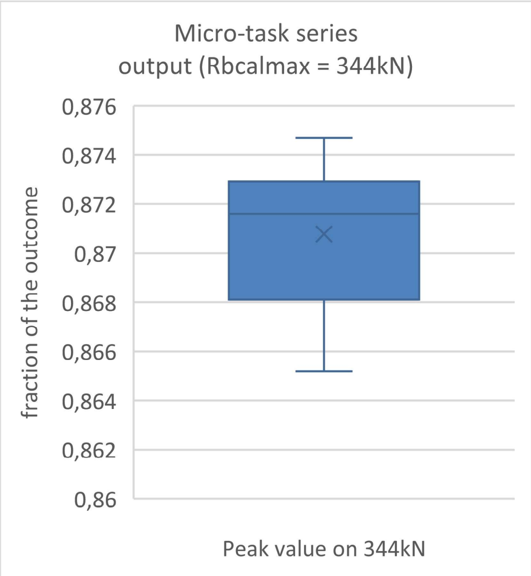

Figure 21 Boxplot of 9 simulation model runs, each with 100.000 iterations. The y-axis represents the fraction of the total outcome that resulted in 344kN. Self-check is applied.

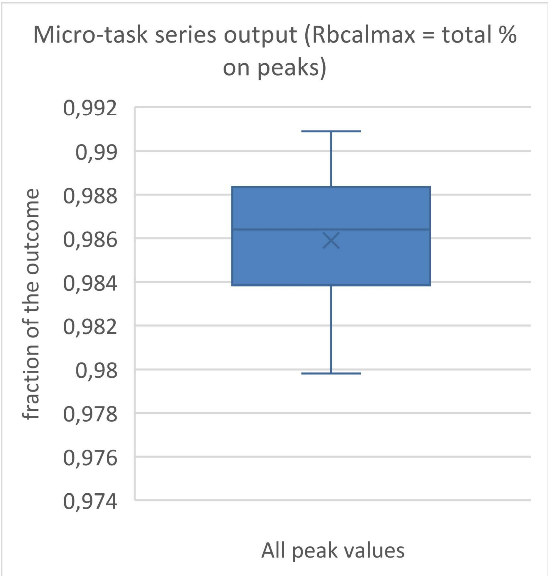

Figure 22 Boxplot of 9 simulation model runs, each with 100.000 iterations. The y-axis represents the fraction of the total outcome that resulted in one of the four peak values. Self-check is applied.

Third-party check and self-checking

A third-party check is the second control measure that is simulated in this chapter. The control measure is modelled as a random check, with a pre-set number of how many tasks are checked. This pre-set is a number, from zero to thirteen, as for every micro-task in the design process a third-party check can be requested.

Because an independent company performs the third-party check, it is regarded as an expensive control measure. With the simulation of the third-party checking mechanism, it is possible to plot how much third-party checks can affect the results of the micro-task series. Figure 23 Boxplots of 9 simulation model runs, each with 100.000 iterations. The y axis represents the fraction of the total outcome that resulted in 344kN. From left to right are the boxplots without third-party checking, up to 13 third-party checks (14 boxplots). Besides third-party check, self-check is applied.Figure 23 shows the results of a micro-task series with zero, one, and up to thirteen tasks being checked.

The increase of the correct value is less than 0.5% with high uncertainty. It is therefore not possible to make conclusions from this figure. The figure changes, however, if all four peak values are included. The deviance of the result displayed is much narrower with a clear increase in the mean value. The absolute increase is less than 0.4%, however, it must be pointed out that almost 99% of the values are the same as the correct outcome. Therefore, almost no errors.

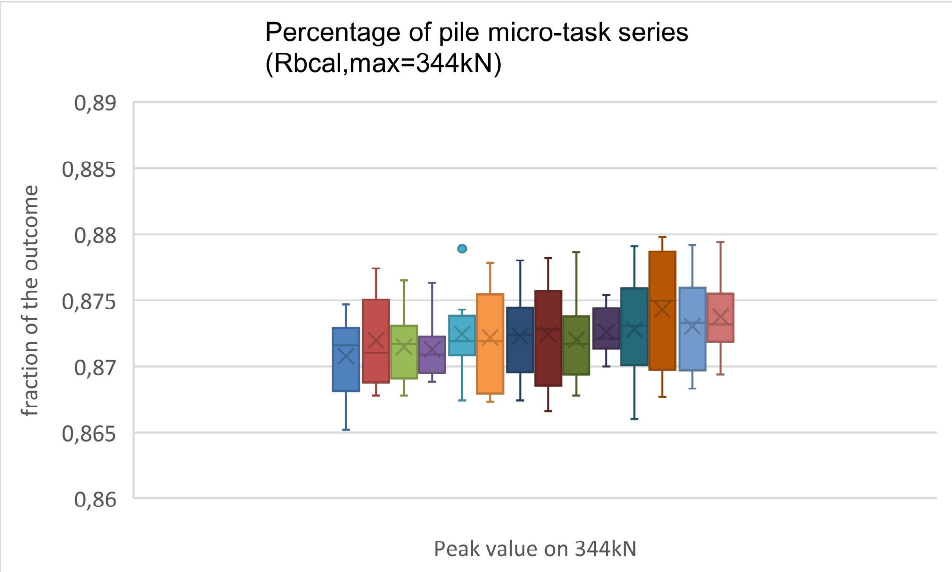

Figure 23 Boxplots of 9 simulation model runs, each with 100.000 iterations. The y axis represents the fraction of the total outcome that resulted in 344kN. From left to right are the boxplots without third-party checking, up to 13 third-party checks (14 boxplots). Besides third-party check, self-check is applied.

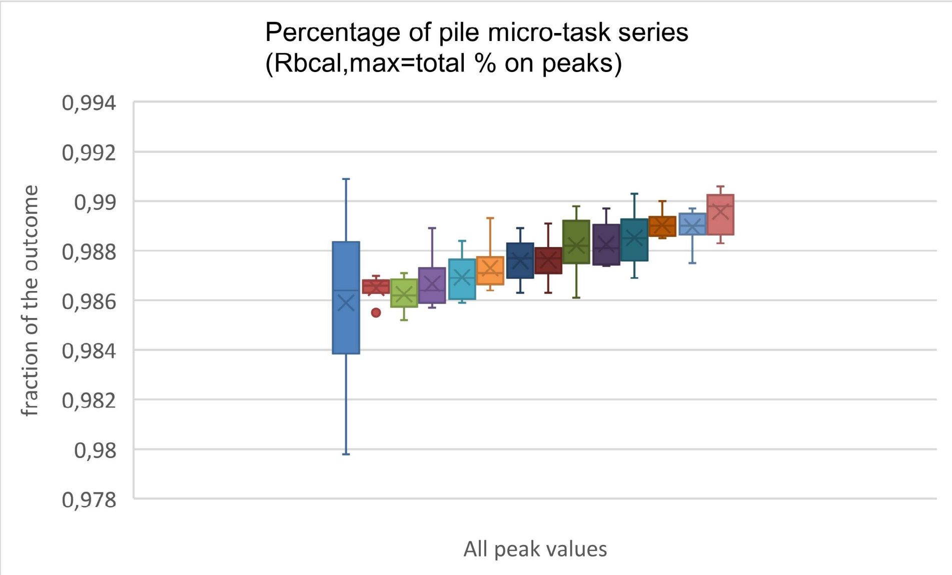

Figure 24 Boxplots of 9 simulation model runs, each with 100.000 iterations. The y axis represents the fraction of the total outcome that resulted in one of the four peak values. From left to right are the boxplots without third-party checking, up to 13 third-party checks (14 boxplots). Besides third-party check, self-check is applied.

Process sensitivity third-party check

The last comparison between different ways to perform a third-party check is a sensitivity analysis with the following different checking variables:

- No third-party check.
- Two third-party checks are assigned at random for every iteration.
- Two third-party checks are assigned to the micro-tasks with the highest HEP value.
- Two third-party checks are assigned to the last two micro-tasks in the micro-task series.

The micro-tasks with the highest risk profile, measured by the highest HEPs, are the parameters ‘interpret depth pile base’, and, ’Determine diameter pile’. The last two micro-tasks are: ‘calculate soil stress qbmax’, and, ‘calculate Rbcalmax’.

Analysing these variables provides insights into whether, and wherein the process third-party check is most effective. Self-checking is always included for all micro-tasks. Table 9 shows the outcome.

	% True value	*% peak values*
No TPC	87.0%	98.6%
2 TPC, Random	87.2%	98.6%
2 TPC, Risk profile	86.5%	98.6%
2 TPC, last micro-tasks	87.2%	98.6%

Table 9 sensitivity analysis of where a third-party check is most effective in the process. The micro-tasks with the highest error probability are determined to have the highest risk profile.

The data shows the third-part checks have scarcely any effect or very marginal effect in decreasing human error influence. This is in line with previous results of third-party check and self-check combined. A critical analysis of these results is provided in the discussion paragraph of chapter 9.

Construction checking mechanism

The construction checking mechanism is the last of the three control measures simulated in the model. In this chapter, only the first step of Figure 16 is presented. This step determines if the deviation of the pile is <0.2m (green), >0.35 (red), or between these limits (black). The rest of the steps in Figure 16 is part of the structural reliability analysis, see chapter 8. For the simulation, only self-checking is included.

The results of the checking phase are plotted in the following Figure 25. Note that each dot represents a pile and that the colour of the dot corresponds with the first part of the flowchart in Figure 16: the pile in the green group has a monitored deviation of fewer than 0.2m from the designed location; the red group has a monitored deviation of more than 0.35m; the rest black dots represent piles between these two values and need to be further analysed of their reliability.

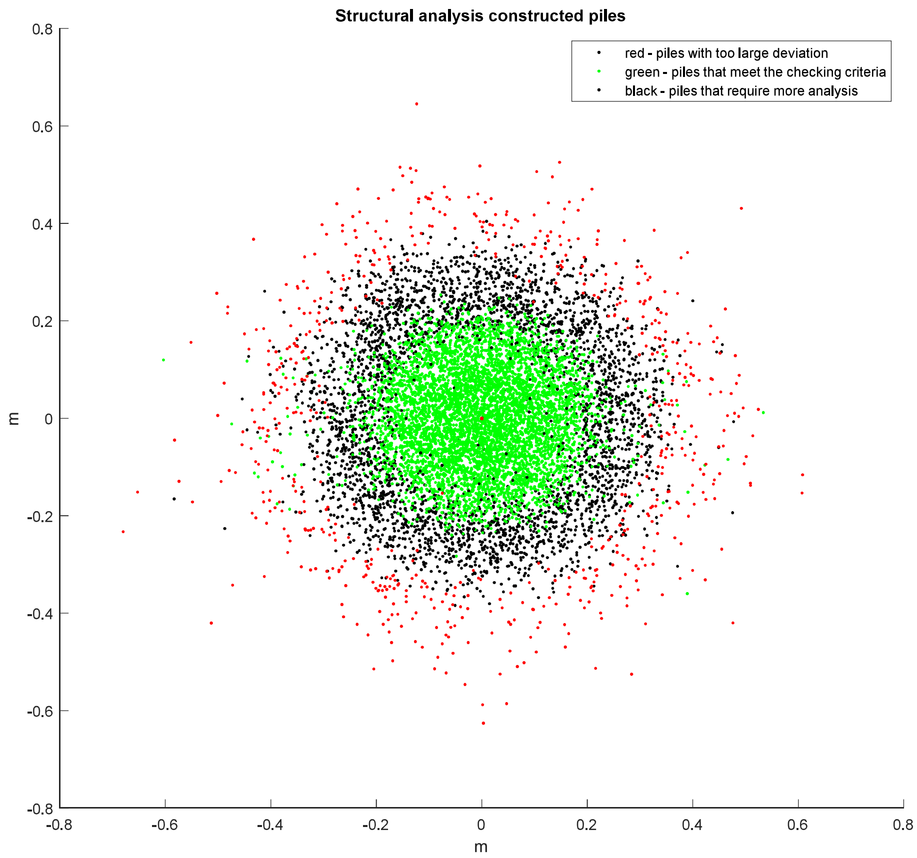

Figure 25 Typical outcome of design and construction micro-task series. Each dot represents a constructed pile. The colouring is according to Figure 16, the initial checkup.

8. Structural Reliability Analysis

The last step within the HRA model is to determine structural reliability. Consequently, the failure probability of the pile is obtained. This chapter explains how the structural properties can affect the outcome of the simulation model (chapter 8) and vice versa. The subsection about the construction phase explains the implications of construction micro-tasks on structural reliability. The sub-research question that this chapter answer is the following:

How effective are the control measures in limiting the failure probability?

Figure 26 shows the last steps in the HRA model, elaborated in this chapter.

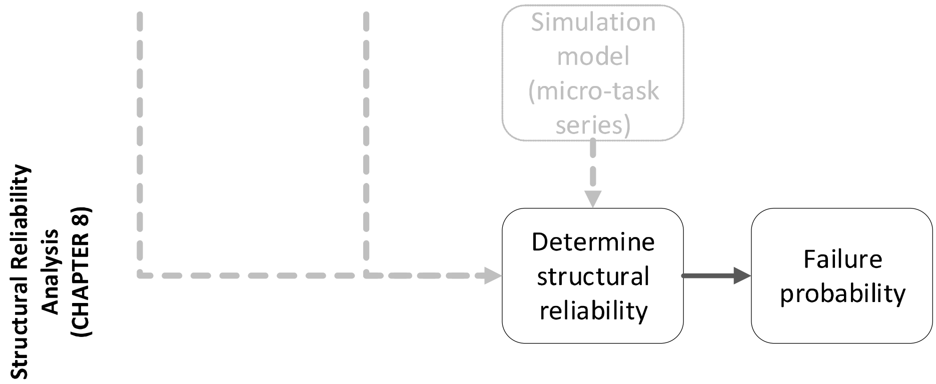

Figure 26 Structural Reliability Analysis step from HRA model. Two steps are involved in the structural reliability analysis. How they influence each other is represented by the arrows. Including directly involved tasks from other steps of the HRA model. For the complete HRA model, see Figure 4.

Simulation model influence

The research context is a big part of chapter 6 and is extensively elaborated. A case study from practice is used to illustrate the applicability of this proposed model. To achieve this, the case study structure is simplified to fulfil theoretical conditions in the model.

One of those assumptions is the increase of the acting load, caused by the deviation in the location of the constructed pile. When the pile is placed or designed at a different location than the supposed one, see Figure 27, the load is assumed to increase. Although this is not the truth, in reality, this assumption enables us to model the influence of the construction phase on the re-design caused by this deviation. For every centimetre of displacement in any direction, the load is assumed to increase by 2.5kN.

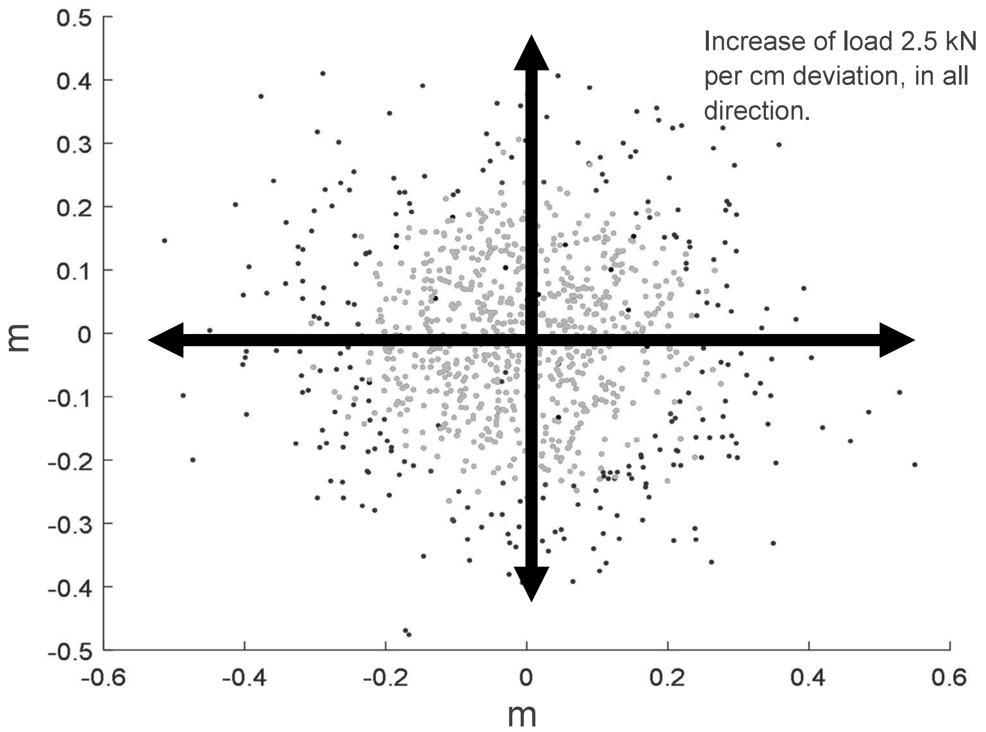

Figure 27 Deviation in any direction will result in an increase of 2.5 kN per cm after construction.

Koppejan calculation

To calculate the structural reliability, a Koppejan calculation is used to determine the resistance of the pile thereafter as input for the Unity Check. Although this calculation is nowadays seldom done by hand, this step-by-step hand calculation is a valid starting point to show the potential of this model and to provide insights into possible effective measures for calculation error mitigation to apply.

A Koppejan calculation is fully explained in the Eurocode [50] and is a typical calculation to determine the resistance of the pile base. The flowchart of the calculation process is shown in Figure 28 below. Some micro-tasks, namely determining the pile type, determining the shape of pile base, and choosing the depth of the soil layer (different than the micro-task ‘interpret depth pile base’) are not included in the calculation simulation. Be aware that these variables are possible to design choices that could be integrated into the simulation model if that is inside the case context. See chapter 5 for more detail on possible variables.

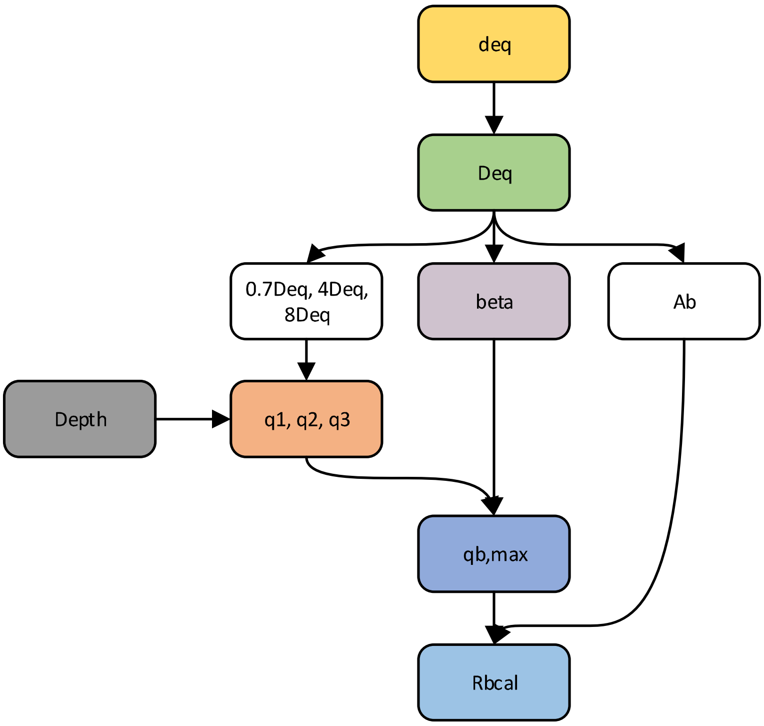

Figure 28 Micro-tasks of Koppejan calculation used in the design phase. The arrows show which micro-tasks influence each other.

The calculation of the pile base resistance is the last micro-task from the design phase. Chapter 7, it is showed that it is also the last step to completing the micro-task series. Combine this with the initiated additional load, 2.5kN for every centimetre of deviation, and both phases are linked through the unity check of the structure.

With this, the reliability analysis after the whole project process, including both the design and construction phase, is possible. The results from the whole HRA model process are presented in this chapter with figures. After this analysis, the effectiveness of the implemented control measures is known.

Construction check

The goal of the structural reliability analysis is to check the probability of success (Ps) and the failure probability (Fp) of constructed piles. A common method to control the construction results is by measuring the deviation between the actual construction and the designed construction, here referred to as 'method A'. See for example Figure 29, where the deviation is indicated by Delta A. The deviation should be within a certain tolerance before acceptance. For example, the maximum allowed deviation for the example of Fig1A is 0.35m. If the deviation is below 0.2m, the construction outcome is accepted. If the deviation is between 0.2 to 0.35 meters, a further design check is necessary. Deviations >0.35 m are rejected
The two parties differ in properties and what they know. The modeller knows the true depth, the true load, the true parameters of the pile, and the true location of the pile. Because the environment is known, the construction check is performed with the outcome of the design phase. Therefore, it is known what the factor of Ps and Pfs are.

Figure 29 shows the deviation of the constructed pile with the designed location. In this case, the deviation, delta A, of the constructed pile is well above the limit of 0.35m and therefore rejected.

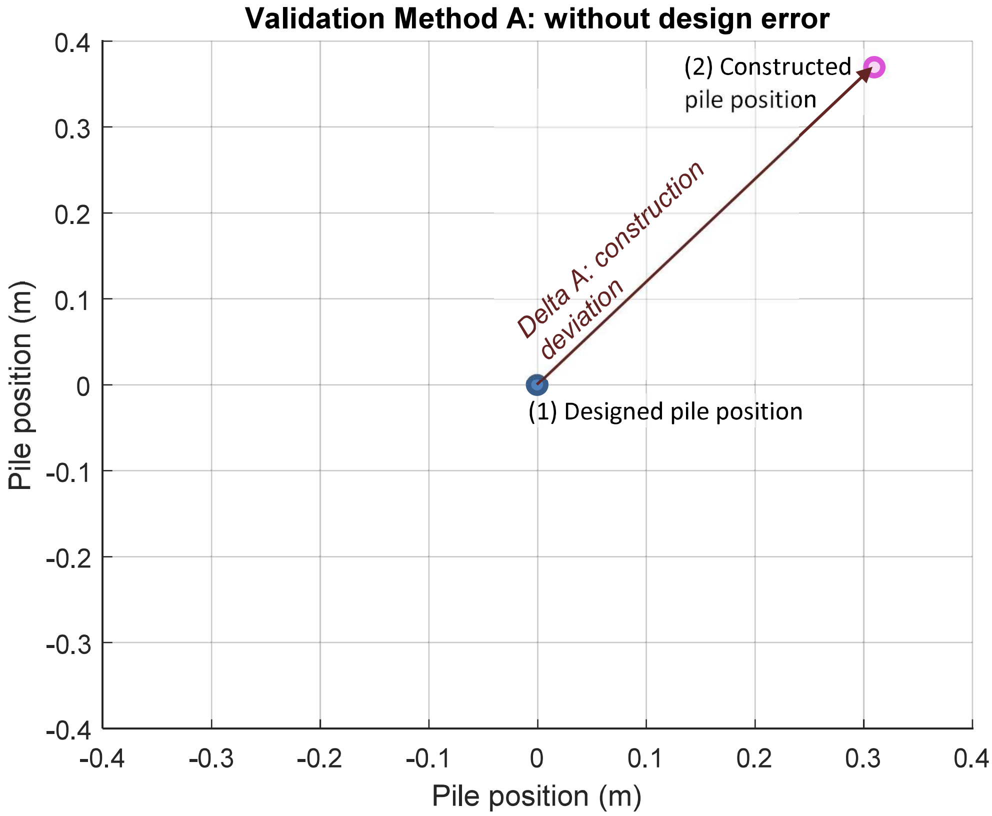

Figure 29 Validation of construction outcome (1) with designed position (2). Delta A represents the deviation of the construction micro-tasks. Method A is without design errors.

However, human errors during the micro-task “Design of the pile position” are also possible and are not taken into account in Method A. To take this into account, it is possible to model the true deviation with method B

An example is given in Figure 30, where the same deviation occurred during construction as in the previous example (Figure 29). However, this time, the potential human errors during the design of the pile location are also taken into account. The defined true deviation, Delta B, is smaller than 0.2m. Both method A and method B are applied, as an engineer is unaware of human error in the design. Method A represents therefore the perspective of an engineer. Method B is the `true result`, within the environment of the model.

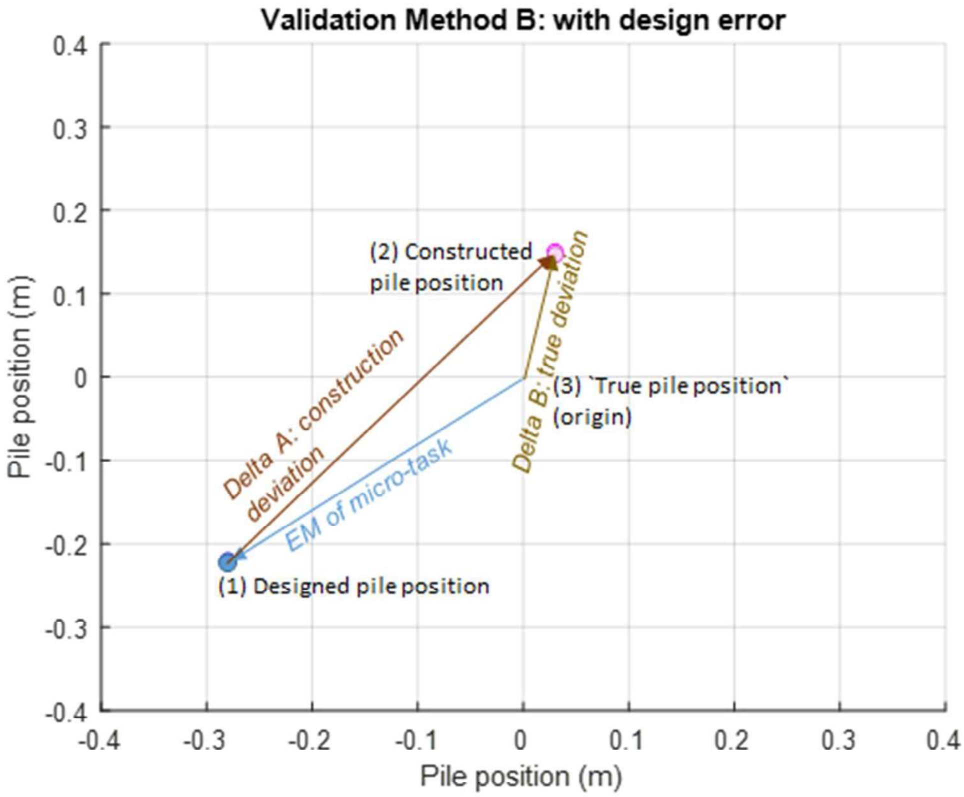

Figure 30 Validation of construction outcome (1) with designed position (2), and the true pile position (If no error occurred, the origin) (3). Delta A represents the deviation of the construction micro-tasks. Delta B represents the true deviation after the construction micro-tasks. Method B is with design errors.

The implications of the difference between method A and method B can be severe. In this example, the pile was incorrectly rejected in method A, as the pile was deemed reliable in method B, leading to unnecessary amendments or fixes during construction. However, for structural safety, it is even more relevant to determine the percentage of piles that are accepted in method A and would fail in method B. These cases are in practice unsafe and could in the worst-case lead to structural failure. Comparing method A with method B, therefore, provides insight into the falsely accepted, and therefore structural unsafe, piles.

For method B, the following micro-tasks are still subjected to human error:

- Location pile [xd yd]
- Design depth of pile
- Constructed location pile [xc yc]

For method A, all micro-tasks are subjected to human error.

Results

Results of the effectiveness of control measures on the structural failure probability are summed up in this subsection. This subsection shows the effect of measures on the final structural reliability.

The pile construction simulation outcome is divided into three groups: a green group, a black group, and a red group. The piles in green are deemed reliable according to the construction checking mechanism. The red group is considered to be unacceptable due to a large deviation in the execution. The black group consists of uncertainties and should be investigated further regarding its reliability. Figure 31, and Figure 32 show the simulation outcome of the design and construction phase, with the first and second of the construction check.

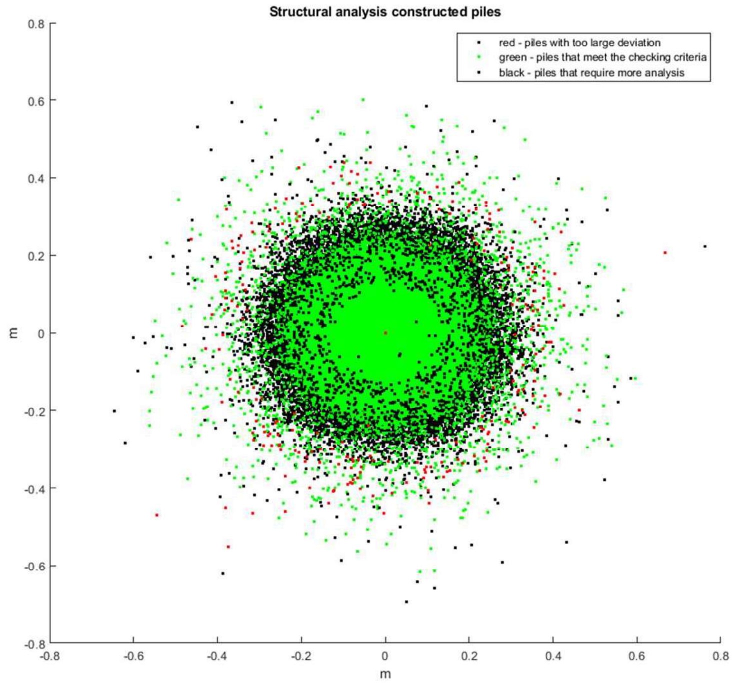

Figure 31 Typical outcome of design and construction micro-task series. Each dot represents a constructed pile. The colouring is according to Figure 16, the first checkup.

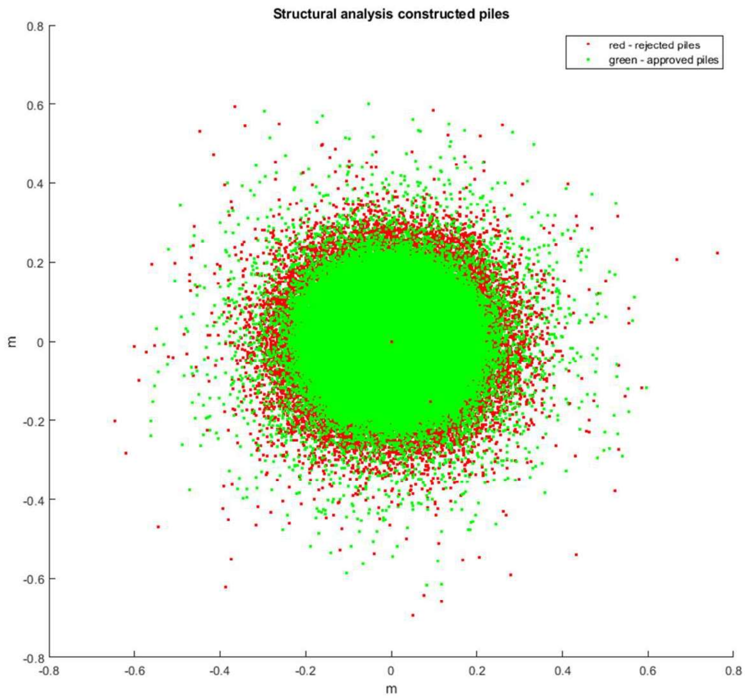

Figure 32 Typical outcome of design and construction micro-task series. Each dot represents a constructed pile. The colouring is according to Figure 16, the second checkup.

Table 10 is an overview of the performance of all control measures.

Type of measure		Method B perspective		Method A perspective		
		First checkup	**Second checkup**	**First checkup**	**Second checkup**	Incorrectly approved
No measure	*Fs*	78.7%	88.2%	71.4%	79.5%	1.31%
		18.6%		14.8%		
	Fp	2.7%	11.8%	13.7%	20.5%	
Self-check	*Fs*	79.9%	89.3%	81.4%	90.4%	1.32%
		17.9%		16.8%		
	Fp	2.2%	10.7%	1.8%	9.6%	
5x random third-party check	*Fs*	79.1%	89.3%	72.6%	80.5%	1.31%
		18.6%		14.8%		
	Fp	2.3%	10.7%	12.6%	19.5%	
5x random third-party check +self-check	*Fs*	79.5%	89.0%	81.3%	90.4%	1.32%
		18.1%		17.0%		
	Fp	2.3%	11.0%	1.7%	9.6%	

Table 10 Structural reliability analysis after construction check, with various control measures applied. The green rows represent reliable piles. The red rows represent rejected piles. The grey rows represent the black pile group from the first checkup, see Figure 16. Method A perspective means, without knowledge of errors in the design phase. Method B takes into account this knowledge and represents the true outcome of the structural reliability. See subsection construction check of this chapter.

Self-checking

Calculating the structural reliability after completing simulating the whole process (including design and construction), the complete results for both method B and method A are shown in Table 10.

Out of 100.000 times simulations, self-check increases the number of reliable outcomes by 1.2 % point in the first checkup and 1.1 % point after the second checkup. This is the true increment, as calculated from the method B perspective.

In the same comparison between no measures and self-check, from the method A perspective, the absolute difference increases from 71.4% to 81.4%, a change of 10.0 % point. After the second checkup, this increase is 10.9 % point. This is regarded as effective.

Note that the method A perspective determines the group reliable piles 90.4%. 1.1% point higher than method B. This overestimation of approved piles is occurring due to the nature of the construction check, as explained in a previous subsection.

Third-party checking

The same comparison for third-party check shows that third-party check increases reliability by 1.1 % point, from 88.2% to 89.3%. This increase is about the same from the method A perspective, 1 % point.

Even though this is still an increase and therefore considered effective, it is a tenth of the increase of self-check. This is because a third-party check has no self-check for its output, as the self-check variable is not applied.

If self-check is applied, the effect of the third-party check is negative, although very small. This negative effect is not significant, and obtained with one simulation run, and therefore not deemed reliable (see chapter 7 results for the difference in multiple simulations runs). One possible explanation for this is that self-checking solves most of the errors, see Table 10 from chapter 7. Not many errors are left to adjust for third-party checking, and the effect is therefore not noticeable.

It can conclude from the simulation results that third-party check, as modelled in the way it is in this research, is only improving structural safety without applying self-check. It shows a small increase in structural reliability, although this increase is less from the method A perspective. This result is in contrast with literature and practice, where it is considered a proven method used to improve structural safety.

Construction checking
This checking method is a prominent recommendation from literature to increase structural safety. This structural reliability analysis supports this recommendation, as the method A perspective match the method B perspective, with a slight overestimation of the reliable outcome.

One important aspect is that within the group of approved piles, 1.3 % point is incorrect and should be designated as Pf. This explains the overestimation of about 1.1% point. Remarkable is that this 1.3% point is the same for all different control measure variables. Therefore, it is concluded that this overestimation is because of human error in the construction phase, where self-checking and third-party checking have no effect.

The simulation model also shows the effect of the construction micro-tasks, combined with the design phase, on structural reliability. Therefore, the HRA model could be used as a tool to verify construction checking measures in practice.

9. Conclusion and recommendations

This research focuses on simulating the human error influence on structural safety to determine the effectiveness of control measures. As stated in the introduction, the objective of this research is: *To find the applicability of the HRA method in practice doing so by evaluating the effectiveness of control measures considering human errors for the design and construction phase of a foundation pile element.* Conclusions and findings from every chapter are discussed and summarised in this chapter. This leads to answering the following main research question in this chapter:

What are effective control measures to apply in practice for structural design and construction, when considering human errors?

The research consists of two parts that together provide an answer to the research question. In part one, a desk study defined the research gap and concluded what type of control measures are used in part 2. Additionally, the first part elaborates on human error and human reliability assessment methods. Further, the proposed HRA model is applied to a case study in part two. The Theemswegtracé project of Dura Vermeer is used as a case study to simulate the effect of human error and control measures on the structural reliability of a temporary structure.

Part one

First, the desk study includes various guidelines, norms and research reports on failure cases, deriving the lessons learned. Additionally, the control methods within the company are reviewed. Both highlighted the gaps in the retention of structural safety in literature and practice. The literature study provides a set of recommendations from which control measures will be derived. One of the most prominent recommendations is: The construction phase is often critical, as errors mainly occur during construction. It is strongly advised to adopt a monitoring plan in the design phase to validate and verify the construction outcome.

Other recommendations are summed up in the corresponding chapters. In chapter 3, the recommendations are reflected on their working principle, and whether or not this is aligned with the human error mechanism. This step distinguished unjustified recommendations from effective recommendations and converged to a possible set of control measures.

> Human error cannot be stated as an explanation for failure [40]. It is not an event or process, and is always present, even sometimes beneficial. Control measures should focus on possible outcomes of the error to be effective [39]. The used measures focus on errors of commission, where errors of omission are neglected in this research.
>
> As an effect of the outcomes of chapter 3, the type of control measures applied in this research is focused on controlling the outcome of an error, rather than preventing the error from happening. Control measures of interest are Self-Checking, Internal Review, Third-Party Checking, and Construction Checking.

Part two

In part two the findings of the literature study are included in an adopted HRA model to simulate the effect of the control measures on the structural reliability in the case study. The HRA method of De Haan is improved in several aspects. First, the construction phase is added to the model, next to the existing design phase. Second, two additional control measures are included in the model; third-party and construction checking. Finally, normal supervision is excluded from the model, because this type of supervision focuses on errors of omission, which requires extensive data to determine what tasks are prone to the error of omission.

The first step in the HRA method is to define the project context and to set up a TA and EM table. The process of a realistic case study should be simplified on all variables to allow for simulation. Additionally, the typical integral way of designing a structure does not fit the HRA model. Therefore, a linear process is used to set up the design and construction phase. In this design and construction phase, it is possible to include different variables. It is advised to limit the number of variables as every additional variable results in a multiplication of the scope of the research. However, as the applied HRA method is a Context-Related method, with adding variables, a more in-depth analysis of the case study is possible. And so, the effectiveness of control measures is more meaningful in this broader context.

The simulation model is used to determine the error probability per micro-task and micro-task series. The working principle for self-checking is based on literature [3] and adjusted to fit the case context. The same is done for third-party checks and construction checking. All control measures are directly related to the case context and only applied in this environment.

Self-checking and third-party checking can influence the simulation outcome of micro-task and micro-task series. Self-check adjusts the simulation result by restricting it between a set of expected acceptable minimum and maximum values. Unrealistic values are mitigated during iteration until the values are within the acceptable range. Where self-checking only corrects the outcome of micro-tasks and is not able to observe the outcome in a broader overview, third-party does. This is in line with the conclusions of how control measures should affect human error, based on literature from chapter 3.

Construction checking is a form of checking that connects the design values, i.e., the results from the micro-task series in the design phase, with the results of the construction phase. This form of checking does not adjust results but is a tool to verify the structural outcome of the constructed element from the perspective of the project team.

The effectiveness of control measures is measured by the amount of reduction of the failure probability in the reliability analysis. The reliability analysis is applied to four different checking variables: 1) no measures, 2) self-checking, 3) 5 random micro-tasks checked by a third-party, and 4) self-checking plus 5 random micro-tasks checked by a third-party.

Self-checking and third-party checking are effective to control measures to implement in the design phase. The effectiveness is relative and is subjected to the assumptions and context of the case study. Self-checking shows an absolute increase between 10.9% point of the Ps outcome. For third-party checking with 5 random checks besides self-checking, this increase is between 0-1.1% point in success probability.

The effect of third-party checking is almost neglectable. As third-party checking is deemed in literature and practice to be very helpful and effective, this conclusion is probably flawed. The cause of the ineffectiveness is most likely, that the implementation of third-party check is not a reflection of practice and focuses on the wrong outcomes of micro-tasks. Another possible cause is that after self-checking, not many errors are left to correct.

Construction checking is an effective addition to the other two checks in design as it is capable to link the construction phase results to the results for the design phase. It is effective in reflecting on the construction results, and therefore, it is likely that it is effective in reflecting on results in practice. It is most effective with self-checking or self-checking and third-party checking, as it shows only a slight overestimation. Without control measures or only third-party checking, the construction check results are underestimating the structural reliability.

The more effective control measures to apply in practice for a structural design and construction, when considering human errors, are self-checking and construction checking, compare to third-party checks. Both are recommended to apply in every project, as is already often the case. For self-checking, it is advised to obligate it as part of the engineering practice norm. In this way, it is ensured that deliberate self-checking is always present.

The construction check is set up in the design phase and should be kept up to date along the process. As it is a rather low effect control measure, it is most effective if it is applied to all structural elements.

Discussion

The HRA model proved to meet the objective of this research, as the applicability of the HRA model in practice is tested. A real project is transformed into a case study to fit the HRA model and shows the results of the effectiveness of measures. The results of the simulation are in line with the findings of De Haan [3], which is expected but is nevertheless useful.

The implementation of the construction phase is successful, which makes the method more suitable for practice. This extension enables a broader case context and therefore more opportunities for further research.

To find the case context and fit the HRA model, however, a crude simplification of the reality is made. This simplification is in every aspect of the context, and the research concludes more about the applied HRA model than the practical case study. Although De Haan already offered proof of principle of the model in basic form, progression towards a practical implementation is offered in this research. But further research is needed.

Opportunities for further research

Sharpen the case context
The case context is one of the bigger steps within the HRA model and determines the base of the structural reliability conclusion. Additional research to better guide this step in the HRA model is recommended. This increases the practical use of the method.

Construction phase
In line with the case context, open for further research is to sharpen the link between the design and construction phase, possibly by adding a two-way dependency. The dependency of the structural reliability analysis, on the construction phase and the design phase, was simplified in this research and is not a reflection of reality.

Internal review
Including internal review as a control measure is recommended for further research. The assumption used at the beginning of this research was to not use internal review as an ennobled form of self-checking. However, this setting might result in missed opportunities, which could be: additional checking variable, more in-depth sensitivity analysis, and, less crude distinction between self-checking and no self-checking (and thus more practice

focussed). For this form of checking, a definition and explanation are provided in this research, see chapter 5.

Calibration of the model
With this research, the use of HRA models in the building industry is further explored, though the HRA model still needs additional calibration. The missed calibration of the model is shown in the differences in the effectiveness of the self-check and third-party check, where self-check was multiple times more effective than third-party check. Reviewing how to incorporate third-party check in the model is advised for further research.

Analysis of the accuracy of the simulation outcome
In chapter 7, the results of third-party check are represented with a boxplot. The results showed irregularity between simulation runs. It is likely that with a higher number of iterations of the Monte Carlo simulation, the irregularity decreases. More analysis on this inconsistency is advised as it increases the reliability of all results and conclusions.

CREAM by Hollnagel
Hollnagel's view on CREAM and the (human) error has evolved, as he describes on his website [34]. His view on CREAM is that it focuses on the failure of actions. This misconception of human error is acknowledged and highlighted in chapter 3 of this thesis. His renewed beliefs made him switch to FRAM, a way to accommodate resilience in structures and systems.

Even though his new FRAM method could be of use, and the development should be followed, the CREAM has still a lot to offer in the construction industry. When the principle of human error is carefully applied and the focus of the HRA model is not just on failure, there is still further development and research possible.

10. Glossary

ABC registration
Database of structural incidents. Not active anymore.
Agent Based Modeling (ABM)
A class op computational models for simulating the actions and interactions of autonomous agents with a view to assessing their effects on the system as a whole. [51]
Basic task type
A value coherent to a specified activity.
Cognitive Reliability and Error Analysis Method (CREAM)
Context-related HRA method developed by Hollnagel
Construction check
Control measure to validate to execution of a structure on the design requirements.
Construction phase
phase in which the elements of the structure are produced and the structure itself is assembled. [8]
(Case) Context
The circumstances that form the setting for an event in terms of which it can be fully understood. – Oxford languages
Control Measure
Actions that are taken to predict or prevent a negative outcome, or to encourage a positive outcome.
Design phase
phase in which the structure is designed and calculated. The result is a technical design with specifications. [8]
Effectiveness
How much a measure can decrease the calculated structural failure probability obtained via comparing different results. Effectiveness is a relative concept.
Environment
The conditions in which the system operates.
Error
See Human Error
Error Magnitude (EM)
A parameter for the severity of the error, determined by a distribution function, standard deviation, and the mean.
Error of Commission (EOC)
Incorrect performance of a task (or action). [35]
Error of Omission (OOC)
Failure to perform a task (or action). [35]
Error Probability
Value of which error is likely to happen. In this case, a failure value related to the micro-task obtained by summing the HEPs of all involved tasks for that micro-task.
External Review
See third-party checking
Failure probability (Pf)
the chance for exceeding a limit state within defined requirements.
Falsework
Supporting structures in the building industry, including temporary structures.
Gate Review
A control measure to reflect on content or process, often performed by specialists.
Human Error (HE)

A departure from acceptable or desired practice on part of an individual that can result in unacceptable or undesired results. [8]

Human Error Probability (HEP)

The probability that an error will occur when a given task is performed. [35]

Human Error Quantification

Step in the HRA model, to estimate the HEPs from tasks.

Human and Organisational factor (HOF)

Aspects of influence in the process of an activity, often related to success or failure.

Human Reliability

The probability of successful performance of the human activities necessary for either a reliable or an available system, specifically, the probability that a system-required human action, task, or job will be completed successfully within a required time period, as well as the probability that no extraneous human actions detrimental to system reliability or availability will be performed. [35]

Human Reliability Assessment (HRA) Method

A method by which human reliability is estimated. [35]

Human Reliability Assessment (HRA) Model

A framework to implement and process a HRA method.

(Structural) Incident

a near miss or a failure [8]

Internal Review

Checking by different persons than those originally responsible and in accordance with the procedure of the organization. [17]

Macro Level

Industry or national level

Matlab

Software package for modelling

Meso Level

Organisation or project level.

Micro Level

Professional level.

Micro-task

The simulation performance of one variable in the model

Micro-task series

The simulation performance of multiple variables in the model. The micro-task series consist of two or more micro-tasks.

Model simulation

A single run of complete analysis on observed system. Within the Monte Carlo simulation, one run of model simulation is 100.000 iterations.

Monte Carlo simulation

Computational algorithm to obtain numerical results, by repeated random iterations. Applied are 100.00 iterations.

Normal supervision

Collection of self-checking and internal review.

Probability of Success (Ps)

Ps is calculated as *1-Pf*. Also: Reliability

Project/ Case Context

All related content to the element(s) of interest.

Project/ Context Environment

The boundaries of the project context in which the project is applied

Qualitative (HRA) Analysis

Step in the HRA model, to determine the case context, environment and variables.

Reliability (Ps)

The ability of a structure or a structural member to fulfil the specified requirements, including the design working life, for which it has been designed [8]

Risk Analysis

the identification and assignment of risks, associated with structural safety of the building product and the building process

Robustness

the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause. [8]

Safe Structure

An element that can withstand the loads acting upon it adequately, during its lifetime.

Safety attitude

Someone's view or feeling towards safety and/ or safety culture.

Safety Culture

the total of practices, conventions and habits that affect the way the organisation is dealing with risks. [8]

Safety Engineering

Discipline that focuses on improving safety and preventing incidents.

Safety Experience

Psychical state that describes the (dis)comfort due to (the absence of) hazards

Safety Management

An organisation process that facilitates a positive safety culture

Safety Policy

Acts to accommodate the safety culture

Self-checking

Checking is performed by the person who has prepared the design. [17]

Simulation Model

Step in the HRA model for generating data outcome.

Soil structure

See Geotechnical structure

Structural Failure

Inadequate performance of a structure that creates or might create an unsafe situation [8]

Structural Reliability (Ps)

See reliability

Structural Reliability Analysis

Step in the HRA model to determine the Ps value

Structural Safety

The absence of unacceptable risk associated with failure of (part of) a structure

Swiss Cheese Model

Accident causation model

Task

Activity that is part of a larger process.

Task Analysis (TA)

Demarcation of the process in a smaller task that together meets the context

Temporary structure

A (supporting) element used for constructing the project

Third-party check

Checking performed by an organization different from that which has prepared the design. [17]

Value(A)

The expected outcome of the micro-task, either obtained from the EM table or as a logical result from previous micro-tasks.

Value (O)

The obtained outcome of a micro-task.

Value(T)

The obtained outcome of a micro-task, performed by the third-party check.

Unsafe situation

a moment in time, in this thesis caused by structural failure or near-miss failure, that can harm the (safety) goals.

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PART III

Appendices

12. Appendix A case context

Pile type

Paal nr.	Paaltype	Afmeting [mm]	Kwaliteit	Hoek	Paalkop [m NAP]	Paalpunt [m NAP]	Lengte [m]
16	Tubex + g.i.	Ø457x12.5/560	S355	Te lood	8,800	-14,000	22,800

Table 11 Pile properties, from the pile used in Theemswegtracé.

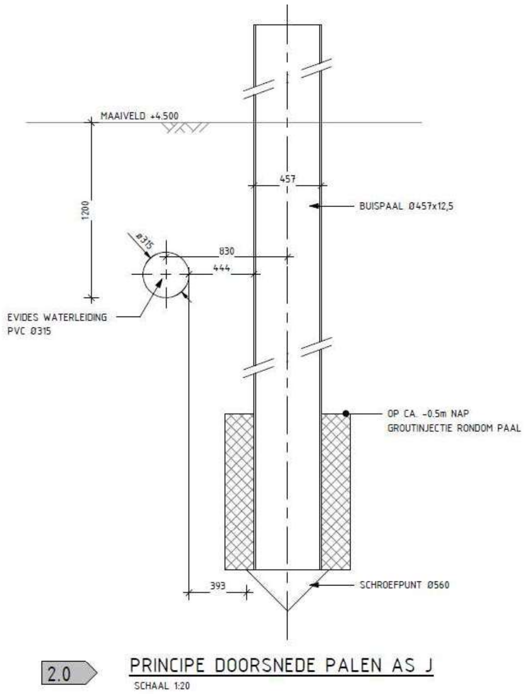

Figure 33 principle drawing of typical pile of Theemswegtracé

BOUWQ

BEOORDELEN VAN HET ONTWERP (uitsluitend in geval van berekeningen)

BIJLAGE bij rapportage "43 Rapportage beoordeling (ontwerp)document(en)", ronde 1.

Algemene informatie
Beoordeling door Kees Tak op 10-01-2019
Getoetste document(en) (kenmerk document; datum; vesie; omschrijving): SAV-TM.WVB.CIV.DT2.05-BER-0001; 21-12-2018; 1.0; DO berekening ondersteuning trog veld A SAV-TM.WVB.CIV.DT2.05-BER-0002; 21-12-2018; 1.0; DO berekening ondersteuning trog veld B SAV-TM.WVB.CIV.DT2.05-BER-0004; 21-12-2018; 1.0; DO berekening ondersteuning trog veld C en D SAV-TM.WVB.CIV.DT2.05-BER-0005; 21-12-2018; 1.0; DO berekening ondersteuning trog veld E
Overige informatie:

1. Welke risico's worden beschouwd bij de beoordeling van dit document?

OC1 Ontwerprekenfout leidt tot falen van primaire constructie

OC2 Fout in uitvoeringsontwerp leidt tot falen van primaire constructie

OC3 Fout ten aanzien van maakbaarheid / uitvoerbaarheid

2. Welke toetsstrategie wordt gekozen?

☐ Uitgebreide schaduwberekening

☑ Eenvoudige schaduwberekening

☑ Analyse van invoer, toegepaste berekeningsmethode en berekeningsresultaten

☐ Anderszins, namelij

Toelichting bij gekozen strategie:

De in- en uitvoer alsmede de berekeningsmethode is gecontroleerd op basis van document inspectie en de bestudering van de digitale AxisVm-bestqanden.
Daarnaast zijn diverse schaduwsommen gemaakt om de resultaten te toetsen.

3. Toetsing van de door opdrachtnemer gehanteerde uitgangspunten en randvoorwaarden.

Zijn de door de opdrachtnemer gehanteerde uitgangspunten en randvoorwaarden opgenomen in de berekening?

☑ Ja

☐ Nee

4. Door toetser gekozen uitgangspunten en randvoorwaarden.

-

5. Toelichting

De stabiliteitsvoorzieningen van de frames loodrecht op het vlak van de frames moeten nog uitgewerkt worden.

Theemswegtracé
18220-OB43-1-Schaduwsommen ondersteuningsconstructie DT2_bijlage 01

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Figure 34 Third-party check options available for Theemswegtracé

13. Appendix B Task Analysis

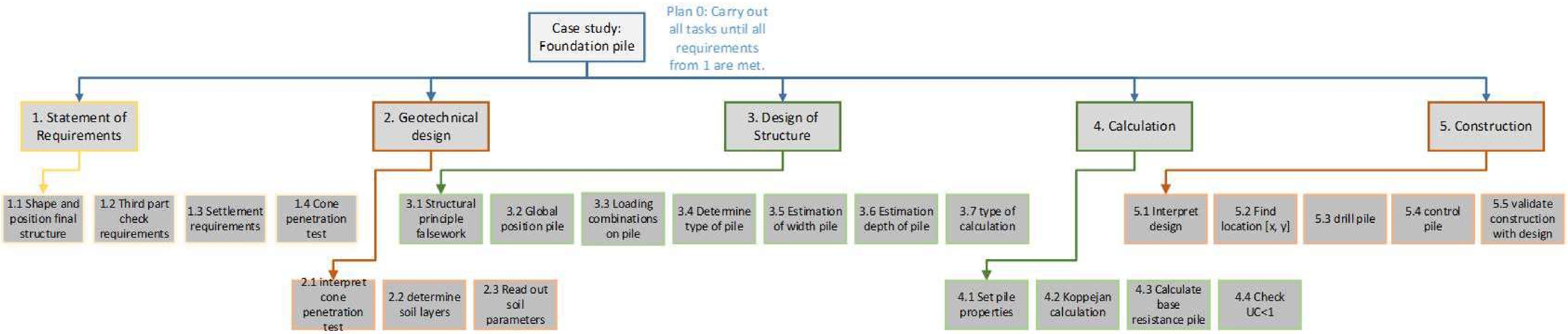

Figure 1 HTA from chapter 5

Human Error Probabilities (HEP)			Proporties Task	
	Task no.	Task desription	Basic task type	Cognitive level
statement of	1.1	interpret tender	Consult	RB
	1.2	global position final structure	Obtain	RB
	1.3	Third party check requirements	Communicate	SB
	1.4	Settlement requirements	Communicate	RB
	1.5	Site investigation	Communicate	KB
Geotechnical design (soil)	2.1	Interpret required soil investigation tender	Obtain	RB
	2.2	Dicuss additional investigation	Communicate	KB
	2.3	Perform cone penetration tests	determine	SB
	2.4	Interpret cone penetration test	Obtain	SB
	2.5	compose soil profile project	Insert	SB
	2.6	Read out soil parameters	Insert	RB
	2.7	Link requirements to site and soil	Derive	SB
	2.8	Conclude geotechnical design with report	Communicate	RB
	2.9	Add drawings	Communicate	RB
Design of structure (extern - pile/column)	3.1	interpret SoR	consult	RB
	3.2	interpret geotechnical report	Consult	RB
	3.3	Set requirements design	Communicate	KB
	3.4	Determine final structure globally	determine	RB
	3.5	Consult Nen-en 1991	Consult	RB
	3.6	Determine CC1, CC2 or CC3	determine	SB
	3.7	Determine actions	determine	RB
	3.8	Set load cases ULS	determine	RB
	3.9	Set load cases SLS	Determine	SB
	3.10	determine load combination	Determine	RB
	3.11	Design structural principle falsework	determine	RB
	3.12	construction cases (different stages construction)	Determine	RB
	3.13	work out structural principal falsework	Determine	KB
	3.14	Work out stability principle	Determine	KB
	3.15	Assign global position pile	Determine	KB
	3.16	design pile requirements	Communicate	RB
	3.17	set type of pile	determine	RB
	3.18	choose pile specifications	Communicate	SB
	3.19	choose calculation type	Communicate	SB
	3.20	Read out cone penetration test	Obtain	SB
	3.21	Determine soil layer base pile	Derive	SB
	3.22	estimate depth pile	determine	SB
	3.23	estimate width pile	determine	RB
	3.24	Review manufacturers	Communicate	RB
	3.25	Set up design document	Insert	RB
	3.26	Set up drawings	Insert	SB
Calculations (soil/ pile)	4.1	Read out design document	obtain	RB
	4.2	Read out drawings	Obtain	SB
	4.3	Read out geotechnical report	Obtain	RB
	4.4	Consult Nen-en 1997	consult	SB
	4.5	Copy results structure design	Obtain	RB
	4.6	set pile depth	Derive	SB
	4.7	Set probable deq	determine	SB
	4.8	Choose corresponding Deq	Derive	SB
	4.9	Consult Nen-en 1997	Consult	RB
	4.10	Read out beta factor	Consult	RB
	4.11	read out reduction factor alpha p	Consult	SB
	4.12	read out reduction factor s (pile shape factor)	Consult	SB
	4.13	calculate 0.7 Deq	calculate	SB
	4.14	Calculate 4 Deq	calculate	SB
	4.15	Calculate 8 Deq	calculate	SB
	4.16	Determine influence zones pile in soil profile	Insert	SB

	4.17	Find lowest resistant value between 0.7-4 Deq below base level	Obtain	SB
	4.18	estimate qI	Obtain	SB
	4.19	estimate qII	Obtain	SB
	4.20	estimate qIII	Obtain	SB
	4.21	fill in Koppejan calculation	Insert	SB
	4.22	obtain qbmax	calculate	SB
	4.23	calculate pile base Area Ap	calculate	SB
	4.24	Insert Ap in calculation with qbmax	Insert	SB
	4.25	Calculate Rbmax	calculate	SB
	4.26	Interpret Rbmax	determine	SB
	4.27	Calculate UC Load over resistance	calculate	SB
	4.28	evaluate design with resistance pile	determine	RB
	4.29	decide deq	determine	SB
	4.30	decide Deq	determine	SB
	4.31	update pile properties	insert	SB
	4.32	update work document	Insert	SB
	4.33	update drawings	insert	SB
construction	5.1	interpret drawings	obtain	SB
	5.2	interpret work document	obtain	SB
	5.3	Manufacture piles	Instruct	RB
	5.4	Communicate work document with contractor	Instruct	RB
	5.5	assign task to worker	instruct	SB
	5.6	instruct measures	instruct	RB
	5.7	surveying pile position	execute	SB
	5.8	to picket	execute	SB
	5.9	built machinery	execute	SB
	5.10	drive pile	execute	SB
	5.11	Adjust pile for every sand layer	monitor	SB
	5.12	check centre line	monitor	SB
	5.13	recheck with as built parameters	obtain	RB

Table 1 Task analysis table and with all tasks involved

14. Appendix C Error Magnitude

Error Magnitude Properties	Error Magnitude Properties							First distribution			
	micro-task number	Task sequence	micro-task describtion	error probability	Parameter	unit	mean value	Distribution	standard deviation	Lower boundary SC	Upper boundary SC
Design phase	1	2.1 2.3 2.4 2.5 2.6	Soil Layer assumptions	0,0055386	SL	[...]	1	Normal	0,608	0,9	1,1
	2	3.3 3.4 3.15	pile position x from origin	0,0638000	PPX	m	0	normal	0,15		
	3	3.5 3.6 3.7 3.8 3.11 3.13 3.14	load estimation ULS	0,1245130	LoadULS	kN	250	Lognormal	0,6688	180	380
	4	3.2 3.3 3.20 3.21 3.22 4.3 4.5 4.6	Depth pile base	0,0300518	depth	m	1	lognormal	0,9648	0,92	1,2
	5	3.1 3.16 3.17 3.18 3.23 3.24 4.1 4.3 4.5 4.7	Determine deq	0,0439210	deq	mm	457	Normal	0,9648	250	600
	6	3.17 3.24 4.8	Determine Deq	0,0118330	deq	mm	560	Normal	0,7803	400	800
	7	4.9	Deq2deq2	0,0000256	[...]	[...]	1	Lognormal	0,4219	0,8	1,2
	8	4.10 4.11	Calculate pile base factor (Deq^2/deq^2 --> table NEN1997)	0,0250000	β	-	0,7	Normal	0,7803	0,6	0,9
	9	3.17	Determine pile class factor	0,0228256	αp	-	0,7	Normal	0,7803	0,2	0,3
	10	3.17 4.9	Determine shape factor	0,0125756	s	-	1	Normal	0,7803	0,5	0
	11	3.13 4.14 4.15 4.16	Calculate 8*Deq (influence zone)	0,0028142	xDeq	mm	1	Normal	0,608	0,7	1,3
	12.1	3.19 4.2 4.3 4.17 4.18 4.19	Soil conus resistance zone I	0,0033320	qcI	N/mm^2	5,693	Lognormal	0,6688	3	8
	12.2	4.20	Soil conus resistance zone II	0,0025640	qcII	N/mm^2	2,13	Lognormal	0,5409	1,5	6
	12.3	4.20 4.21	Soil conus resistance zone III	0,0025640	qc31	N/mm^2	1,079	Lognormal	0,5409	0,8	4
	13	4.22 4.23	Calculate qbmaxEM	0,0000512	qbmaxEM	N/mm^2	1	Lognormal	0,5409	0,5	1,5
	14.1	4.24	Calculate area pile base	0,0005390	Ab	mm^2	246301	Lognormal	0,5409	200000	600000
	14.2	4.24	Calculate area pile base	0,0005390	Ab	mm^2	352565	Lognormal	0,5409	200000	600000
	15.1-15.4	4.25 4.26 4.27	Calculate Rbcalmax EM	0,0000640	Rbcalmax	kN	1	Lognormal	0,4299	0,5	1,5
	16	4.28 4.29	ULS	0,0636386	Fduls	kN		lognormal	0,7803	0,5	1
	17	3.9	Unity Check	0,0158514	UC	-	<1				
Construction phase	1		Position pile x	Aleatory	locpx	m	0,000	normal	0,03		
	2		Position pile y	Aleatory	locpy	m	0,000	normal	0,03		
	3		drill pile x	Aleatory	drillx	m	0,000	normal	0,1		
	4		drill pile y	Aleatory	drilly	m	0,000	normal	0,1		
	5	5.1 5.3 5.4 5.6 5.7	Position pile x HE	0,47631	locpx	m	1,000	normal	0,4299		
	6	5.1 5.3 5.4 5.6 5.7	Position pile y HE	0,47631	locpy	m	1,000	normal	0,4299		
	7	5.2 5.5 5.8 5.9 5.10 5.11	drill pile x HE	0,47835	drillx	m	1,000	normal	0,4299		
	8	5.2 5.5 5.8 5.9 5.10 5.11	drill pile y HE	0,47835	drilly	m	1,000	normal	0,4299		
	9	4.28 4.29 5.12	Construction check monitor	0,01605	monitor	m	1,000	Normal	0,7803		

15. Appendix D Matlab script

Micro-task

```
function[n] = n(ndataS3);
[r] = ndataS3(ndataS3.VarName3==??,:); %find task EM table
FP=r.VarName5; %find error probability EM table
Correct=r.VarName8; %find mean value
EM=random('Normal',1,r.VarName10); %determine EM
RN=rand(1); %random number for HEP
if RN<FP; %error
n=EM*Correct; %result micro-task
else n=Correct; %result micro-task
end
end
```

Self-check

```
function[SCn] = SCn(ndataS3);
SCn=n(ndataS3);
[r] = ndataS3(ndataS3.VarName3==,:);
count=0;
Lb=r.VarName11; %lower boundary
Ub=r.VarName12; %upper boundary
while Lb > SCn || SCn > Ub; %result outside boundaries?
SCn=n(ndataS3); %redo micro-task
count=count+1;
if count==5;
break
end
end
end
```

Random assignment of third-party check

```
function[qn]=qn;
task=randperm(13);
qn=task(1:???); %how many steps involves third party (1:???);
end
```

Third-party check

```
Load(ii)=LoadSCn(ndataS3); %micro-task
Load3(ii)=Load3SCn(ndataS4); %third-party check micro-task
if any(qn==2) && (Load(ii)<0.99*Load3(ii)|Load(ii)>1.01*Load3(ii));
%if random appointed and Load differs from third-party check
Loadend(ii)=Load3(ii); %new value(T)
else
Loadend(ii)=Load(ii); %keep value(O)
End
```

Construction phase x coordinate

```
locx(ii)=locpxn(ndataS3);
locxHE(ii)=locpxHEn(ndataS3); %determine HE
locpx(ii)=locx(ii)*locxHE(ii); %apply EM in case of error
drilx(ii)=drillxn(ndataS3);
drillxHE(ii)=drillxHEn(ndataS3);
drillx(ii)=drilx(ii)*drillxHE(ii);
conpilex(ii)=locpx(ii)+drillx(ii); %Constructed location
x(ii)=drillx(ii)+locpx(ii)+PPX(ii); %True location
constrcheck(ii)=constrcheckn(ndataS3); %EM from monitoring
```

Structural reliability analysis

```
LoadPP(ii)=Loadend(ii)+250*((((conpilex(ii)*constrcheck(ii)).^2)+((c
onpiley(ii)*constrcheck(ii)).^2)).^0.5); %calculated ULS load
adjusted with construction with HE
TrueLoadPP(ii)=250+250*(((x(ii).^2)+(y(ii).^2)).^0.5); %true ULS
load
UC(ii)=LoadPP(ii)/Rbcalmaxend(ii);%Calculated UC
UCoff2(ii)=TrueLoadPP(ii)/Rboff(ii);%true UC


%Method A
if UC(ii)>=1.0 ||UC(ii)<=0 %discard piles UC>1 & UC<0
redUC2x(ii)=x(ii);
redUC2y(ii)=y(ii);
elseif((((conpilex(ii)*constrcheck(ii)).^2)+((conpiley(ii)*constrche
ck(ii)).^2)).^0.5)<0.2%deviation <0.2m
   green2x(ii)=x(ii);
   green2y(ii)=y(ii);
elseif
((((conpilex(ii)*constrcheck(ii)).^2)+((conpiley(ii)*constrcheck(ii)
).^2)).^0.5)<0.35 && UC(ii)<=1 %deviation >0.2 & <0.35 & UC<1
    black2x(ii)=x(ii);
    black2y(ii)=y(ii);
elseif
((((conpilex(ii)*constrcheck(ii)).^2)+((conpiley(ii)*constrcheck(ii)
).^2)).^0.5)>0.35; %deviation >0.35
    red22x(ii)=x(ii);
    red22y(ii)=y(ii);
else
    red2x(ii)=x(ii); %deviation >0.2 & <0.35 but with UC>1
    red2y(ii)=y(ii);
end

Method B
if (((x(ii).^2)+(y(ii).^2)).^0.5)<0.2 && UCoff2(ii)<=1.0 %deviation
<0.2m
   greenx(ii)=x(ii);
   greeny(ii)=y(ii);
elseif (((x(ii).^2)+(y(ii).^2)).^0.5)<0.35 && UCoff2(ii)<=1
%deviation >0.2 & <0.35 & UC<1
    blackx(ii)=x(ii);
    blacky(ii)=y(ii);
elseif (((x(ii).^2)+(y(ii).^2)).^0.5)>0.35; %deviation >0.35
    red1x(ii)=x(ii);
    red1y(ii)=y(ii);
else
    redx(ii)=x(ii); %deviation >0.2 & <0.35 but with UC>1
    redy(ii)=y(ii);
end

%Incorrect approved piles method A compared to method B
if
(((conpilex(ii)*constrcheck(ii)).^2)+(((conpiley(ii)*constrcheck(ii)
).^2)).^0.5)<0.35 && UC(ii)<=1 && UCoff2(ii)>=1
    red3x(ii)=x(ii);
    red3y(ii)=y(ii);
elseif
(((conpilex(ii)*constrcheck(ii)).^2)+(((conpiley(ii)*constrcheck(ii)
```

```
).^2)).^0.5)<0.35 && UC(ii)<=1 &&
(((x(ii).^2)+(y(ii).^2)).^0.5)>0.35;
    red33x(ii)=x(ii);
    red33y(ii)=y(ii);
else
    x3(ii)=x(ii);
    y3(ii)=y(ii);
end
```

16. Appendix E Koppejan

$$q_{b;max} = \frac{1}{2} \times \alpha_p \times \beta \times s \times \left(\frac{q_{c;I;gem} + q_{c;II;gem}}{2} + q_{c;III;gem} \right)$$

waarin:

$q_{b;max}$ is de maximumpuntweerstand, in MPa, die niet hoger mag zijn dan 15 MPa;

α_p is de paalklassefactor voor de berekening van de draagkracht van de paalpunt, bepaald volgens 7.6.2.3(f);

β is de factor, die de invloed van de paalvoetvorm (figuur 7.i) in rekening brengt, bepaald volgens 7.6.2.3(g);

s is de factor, die de invloed van de vorm van de dwarsdoorsnede van de paalvoet in rekening brengt, bepaald volgens 7.6.2.3(h);

$q_{c;I;gem}$ is de gemiddelde waarde van de conusweerstanden, in MPa, (zie 7.6.2.3(j t.m. l) over het traject I, dat loopt vanaf het paalpuntniveau tot een niveau dat ten minste $0{,}7 \times D_{eq}$ en ten hoogste $4 \times D_{eq}$ dieper ligt. Als $b > 1{,}5 \times a$ is, dan moet $D_{eq} = a$ zijn genomen. Het eindpunt van traject I moet binnen de hiervoor gegeven grenzen zo zijn gekozen dat $q_{b;max}$ minimaal is.

$q_{c;II;gem}$ is de gemiddelde waarde van de conusweerstanden, in MPa (zie 7.6.2.3(j t.m. l)) over het traject II, dat loopt van het eindpunt van traject I naar het paalpuntniveau, waarbij de in rekening te brengen waarde voor de conusweerstand nooit hoger mag zijn dan de eronder liggende waarde;

$q_{c;III;gem}$ is de gemiddelde waarde van de conusweerstanden, in MPa (zie 7.6.2.3(j t.m. l)) over traject III dat van beneden naar boven wordt doorlopen van paalpuntniveau tot een niveau dat ($8 \times D_{eq}$), of in het geval dat $b > 1{,}5 \times a$, ($8 \times a$) hoger ligt, waarbij de in rekening te brengen waarde voor de conusweerstand nooit hoger mag zijn dan de direct eronder liggende waarde, te beginnen met de laagste in rekening gebrachte waarde van de conusweerstand over traject II. Voor avegaarpalen geldt dat, als deze laagste waarde groter is dan 2 MPa, voor het begin van traject III aan de onderzijde een conusweerstand ≤ 2 MPa in rekening moet zijn gebracht. Hiervan mag zijn afgeweken als uit na-sonderingen is gebleken dat er geen achteruitgang van de conusweerstand op paalpuntniveau is opgetreden. Deze na-sonderingen moeten zijn uitgevoerd op ten hoogste $1{,}5 \times D$ m vanaf de zijkant van al in de grond gebrachte palen die zich het dichtst bij de sonderingen bevinden die vóór het inbrengen van de palen ten behoeve van het ontwerp op de bouwplaats zijn gemaakt. De nasondering moet op paalpuntniveau op ten hoogste $3{,}0 \times D$ m vanaf de zijkant van de al in de grond gebrachte paal zijn uitgevoerd. Per avegaarpaal moeten drie na-sonderingen in een regelmatig patroon rond de paal zijn uitgevoerd. Per bouwwerk moet ten minste bij 5 % van de avegaarpalen op deze wijze worden na-gesondeerd.

Copied Koppejan method from Eurocode.

Deq	Deq2	0,7Deq	4Deq	8Deq	Ab	deq	s	r	phi	beta1	beta2	alphap	alphas	alphat
450		315	1800	3600	159043	324	0,892106	1	0,698132	0,7		0,7	0,014	0,012
450	560	315	1800	3600	159043	355	0,602443	1	0,523599	0,8	0,65	0,7	0,014	0,012
560		392	2240	4480	246301	406				0,7	0,625			
560	670	392	2240	4480	246301	457				0,8	0,68			
670		469	2680	5360	352565	508				0,73				

Table 13 Input parameter for different Koppejan calculations

	Deq 560	Deq 670
qc1	5,693	5,693
qc2	2,130	2,130
qc3	1,079	1,071
qbcalmax	1,091	1,089