Licentiate Thesis in Civil and Architectural Engineering

Pile driving in glacial soil: stochastic modelling of boulder-induced premature refusal

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Pile driving in glacial soil: stochastic modelling of boulder-induced premature refusal

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Abstract

Pile foundations provide support to structure by distributing external loads to deeper and firmer soil layers. The most efficient installation method consists in driving piles into the soil using impact hammers. However, the presence of obstructions inside the soil can compromise an efficient pile driving operation. A natural type of obstructions in glacial soils are boulders, rock fragments resulting from glacial erosion. The random presence of boulders within the soil can severely damage the piles, compromise their structural integrity and leading to structural failure, referred to as premature pile refusal.

Large uncertainties related to the spatial distribution of boulders, their geometric properties and mechanical resistance, as well as the variability of the soil layers and the dynamic interaction between pile and boulders in firm soil, aggravate the complexity of the problem. Failing to properly quantify the risk of premature refusal can cause large additional costs and delays, as well as inefficient use of environmental resources, for a given construction project.

The current approaches available to practicing engineers are ambiguous and mostly deterministic, relying mainly on practical experience. The construction industry especially in Sweden, where a large part of the landscape is covered in a glacial soil known as till, could greatly benefit from a risk-based approach that accurately and systematically identify and model the significant sources of uncertainties of the problem, while remaining intuitive, practical and simple to use. Such an approach is especially crucial in the design stage, to select the most suitable pile material and installation method for specific soil conditions, towards more economical and sustainable pile design solutions.

This licentiate thesis presents a systematic method to analyse the risk of premature refusal during pile driving in glacial till. This includes the development of a one-dimensional homogeneous Poisson process to probabilistically model the presence of boulders and the variability of the soil layers thickness along the pile driving direction. This thesis also presents a cost model to identify and quantify the key economic implications of premature refusal, to achieve a better balance in pile design between cost, construction time and environmental efficiency.

Keywords: Uncertainty, Risk, Pile Design, Pile drivability.

Sammanfattning

Pålgrundläggning innebär att man fördelar laster från en överbyggnad till djupare och fastare jordlager. Den mest effektiva installationsmetoden är att slå ned pålar i marken med hjälp av en snabbslående hejare. Förekomst av hinder i jorden kan dock försvåra installationen. Ett naturligt hinder i glaciala jordar är block, vilka bildats genom glacial erosion. Den slumpmässiga förekomsten av block i marken kan allvarligt skada pålen vid installationen, vilket leder till så kallad bortslagning av påle.

Stora osäkerheter kring blockens rumsliga fördelning, deras geometriska och mekaniska egenskaper, variationen i jordlagertjocklek och den dynamiska samverkan mellan påle och block i fast jord, bidrar till att försvåra problemet ytterligare. Att inte korrekt kvantifiera risken för bortslagning kan leda till betydande kostnadsökningar, förseningar i projektet och ineffektiv resursanvändning ur miljösynpunkt.

De bedömningsmetoder som idag står till buds för praktiserande ingenjörer är otydliga och till största delen deterministiska, ofta baserade på erfarenhetsmässiga tumregler. Byggbranschen – särskilt i Sverige, där stora delar av landskapet är täckt av den glaciala jordarten morän – skulle därför ha stor nytta av en riskbaserad metod som identifierar och modellerar de viktigaste osäkerhetskällorna på ett noggrant och systematiskt sätt, men som samtidigt är intuitiv, praktisk och lätt att tillämpa. Ett sådant angreppssätt är särskilt avgörande i projekteringsskedet, för att välja lämplig påltyp och installationsmetod utifrån specifika jordförhållanden – i syfte att möjliggöra mer ekonomiska och hållbara pålningslösningar.

Denna licentiatuppsats presenterar en systematisk metod för att analysera risken för bortslagning av pålar i morän. Arbetet omfattar bland annat utvecklingen av en sannolikhetsbaserad modell, baserad på en endimensionell Poisson-process, som modellerar förekomsten av block och variationen i jordlagrets mäktighet. Uppsatsen innehåller även en kostnadsmodell som identifierar och kvantifierar de viktigaste ekonomiska konsekvenserna av bortslagning, för att uppnå en bättre balans mellan kostnad, byggtid och miljömässig effektivitet i dimensioneringsarbetet.

Nyckelord: Osäkerhet, Risk, Påldimensionering, Påldrivning.

Preface

The research presented in this licentiate thesis was carried out between the years 2022 and 2025 at the Division of Soil and Rock Mechanics, Department of Civil and Architectural Engineering, KTH Royal Institute of Technology in Stockholm, Sweden.

The work was supervised by Dr. Johan Spross, Professor Stefan Larsson and Dr. Anders Beijer-Lundberg. I wish to express my sincere appreciation for their expert guidance and constructive feedback.

I extend my thanks to every single member of the reference group involved in this project, an extraordinary team of professionals from the Swedish construction industry, whose insights and engagement have been deeply appreciated. I am also grateful to Pålkommissionen (Commission on Pile Research) for the opportunity to present my project at the national conference *Påldagen 2024*, as well as for providing technical reports and reliable data on piling in Sweden, which significantly helped in the development of this work.

I express my gratitude to the researchers and colleagues I had the privilege of meeting through KTH, whose support, insights and friendship contributed to a rewarding and intellectually enriching experience.

I am also deeply thankful to my inspiring colleagues at Treeline Consulting AB for their constant encouragement throughout this journey and for creating a collaborative and supportive working environment.

Finally, this thesis is dedicated to my family, with special love to my niece Elisa. A special thank you goes to my mother Mariarosa, a true example of strength, grace and perseverance.

Stockholm, May 2025

Chiara Cannizzaro

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List of publications

This licentiate thesis contains the following scientific articles.

Paper A

Cannizzaro, C., M. Alinejad, A. Beijer-Lundberg, S. Larsson and J. Spross (2023). Effect of uncertainty in design decisions for driven piles in soil with high boulder content. Geo-Risk 2023, ASCE Geotechnical Special Publications (GSP) 347, 268 - 276.

Cannizzaro performed the literature review, compared existing methodologies, developed the theoretical design framework and wrote the paper. Alinejad contributed by providing the previously developed numerical model and offering feedback on the manuscript. Beijer-Lundberg, Larsson and Spross oversaw the project planning, provided valuable insights and support throughout the work, and assisted with comments on the manuscript.

Paper B

Cannizzaro, C., A. Beijer-Lundberg, S. Larsson and J. Spross (2024). On the probability of boulder encounter for piles driven in glacial till. 7th International Conference on Geotechnical and Geophysical Site Characterization (ISC2024), Barcelona, Spain, 1746-1753.

Cannizzaro developed the statistical model, performed the calculation and wrote the paper. Beijer-Lundberg, Larsson and Spross oversaw the project planning, provided valuable insights and support throughout the work, and assisted with comments on the manuscript.

Paper C

Cannizzaro, C., A. Beijer-Lundberg, S. Larsson and J. Spross (2025). Risk-based approach for modelling premature pile refusal in glacial till. Submitted to a journal paper.

Cannizzaro developed the methodology and the algorithm, performed the calculation and wrote the paper. Beijer-Lundberg, Larsson and Spross oversaw the project planning, provided valuable insights and support throughout the work, and assisted with comments on the manuscript.

Scientific papers not included in the thesis

Cannizzaro, C., A. Beijer-Lundberg, S. Larsson and J. Spross 2023. Limitations of the current approach for assessment of pile drivability in soil with high boulder content. Grundläggningsdagen 2023 [Foundations Day 2023], Stockholm.

Contents

1 Introduction

1.1 Background

Due to the wide variety of soil conditions in practice, pile foundation design necessarily involves simplifications, useful as aids to engineering judgment rather than definitive solutions (Terzaghi, 1943). Every structure in contact with the ground requires a robust foundation system, to safely transfer loads to the underlying soil or rock for adequate support. In particular, pile foundations can vertically distribute the external loads to deeper and stiffer soil layers or directly to the bedrock. This type of deep foundation is extensively used in many construction projects worldwide, which can include urban and commercial developments, large-scale infrastructures, and offshore energy projects. The design of pile foundations requires scientific knowledge, technical expertise and engineering judgement to ensure the desired pile performance in terms of load-bearing capacity, structural integrity and stability and tolerance to settlements or deformations of the superstructure (Randolph, 2003). However, design with full awareness of the effects that the installation method can have on the surrounding soil and on the structural integrity of the pile itself is one of the challenges that many professionals and practicing engineers experience still today. Selecting the most suitable combination of piling system, including pile material, installation method and equipment for a specific project geological area can help prevent structural issues, such as permanent pile damages during installation. Pile drivability assessment is a significant part of the work of pile design, and it is often based on empirical methods and practical experiences. Thus, such assessment methods are frequently conservative and highly dependent on the experience of the individual designer. A more systematic approach requires innovative risk-based approaches and more scientifically grounded problem-solving methods to reduce excessive resource use in construction.

Promoting a more efficient use of global resources has emerged as a key focus in contemporary scientific and political discussions. The construction industry is among the largest sources of global CO_2-emission (Huang et al., 2018), consequently experiencing significant external pressure to reduce emissions through more efficient construction methods. The United Nations Sustainable Development Goals (2015) emphasize the importance of the development of sustainable cities, as well as sustainable consumption and production patterns. Achieving these goals requires also new reliable approaches in foundation design, ensuring minimal environmental disruption. In this context, optimal pile design solutions can reduce material usage, minimize construction time, lower carbon emissions and other environmental consequences by not wasting resources, limiting excessive equipment use and energy consumption (Dunant et al., 2021). Sustainable and more efficient engineering practices, such as risk assessments, can significantly enhance the efficiency of urban constructions.

However, one of the main obstacles is pile installation, which is strongly affected by the geological conditions. As an example, Sweden, part of the Scandinavian region, has experienced repeated glaciations throughout history, which have strongly influenced its landscape. The Swedish stratigraphy often consists of very soft soil formation overlying denser and firmer soil sediment over very hard bedrock, which requires to install pile foundations, especially for urban development projects. Data released by the Swedish Commission on Pile Research (2024) show that 70 % of all the piles in 2023 were constructed by pile driving with impact hammers, often by DTH hammers. Pile driving ensures rapid progress of the work, shorter time of installation and less equipment, making it more economical appealing than drilled piles. However, the presence of obstructions inside the soil can compromise an efficient pile driving operation. Pile drivability should then include the likelihood of encountering obstructions that may delay or even prevent the full installation of the piles.

A natural type of obstructions in Scandinavian soils are boulders, large rock fragments resulting from the erosion of rock by glaciers (Ditlevsen, 2006). Traditionally, boulders have been classified based on their dimensions, with sizes larger than 256 mm in diameter (Wentworth, 1922). According to the modern standard ISO 14688-2, boulders are defined with a diameter greater than 200 mm. Nonetheless, boulders are large enough to prevent the piles from reaching the required depth. A large part of Sweden is covered by till, an unsorted and not stratified glacial soil sediment transported and deposited by glaciers, which contains significant amounts of boulders (Lundqvist, 1977).

Encountering boulders during pile driving can compromise the structural integrity of the pile and the achievement of the design requirements in terms of the desired depth of penetration and bearing capacity. In fact, in the case of a collision with boulders, the pile can potentially experience premature refusal, which can result in permanent damages and in structural failure of the pile. After premature refusal, the pile cannot provide the necessary design requirements, leading to the rejection and removal of the specific pile from the pile group, and a replacement pile must be driven. The challenge in accounting for the content and properties of boulders, the variability of the soil, as well as the potential consequences from the impact between pile and boulder, exponentially increases the complexity in a reliable evaluation of the risk of premature refusal (Sa et al., 2013). Many construction projects have been, and are still today, experiencing extensive loss of piles during driving in till, leading to large additional cost and delays, which may include the urgency to change the design in progress. The current available approaches to practicing engineers are ambiguous and mostly deterministic, relying on practical experience. The construction industry, including in Sweden, can benefit from a risk-based approach that accurately capture and systematically addresses the significant sources of uncertainties of the problem, while remaining intuitive, convenient and simple to use.

Hence, the need for a reliable approach to the issue of boulders-induced premature refusal has been the starting point of this research project. Clear guidelines may prove valuable in the tender stage of a project. If a design is selected without properly addressing the risk of premature refusal, the contractor, whose responsibility is typically limited to the installation of the piles at the construction site, may encounter difficulties during driving in glacial till, which can lead to premature refusal and pile rejections. The consequences will ultimately fall on the project owner, who may not be fully aware of the economic risk related to premature refusal. A clearer assessment on the issues that may come up during pile driving can mitigate potential disputes among project stakeholders regarding risk ownership and assist decision makers.

1.2 Aim of the thesis

The aim of this licentiate thesis is to present a systematic method to analyse the risk for premature refusal during pile driving in glacial till. The specific goal is to present a reliable tool that is both accurate and practical in the industry, to achieve a better balance in pile design between cost, construction time and environmental efficiency, while addressing the problem of premature refusal.

1.3 Research methodology

The theoretical model development of this thesis includes:

- Reviewing the current state of research and existing approaches for the problem of premature refusal within international construction industries, comparing their advantages and their limitations, with a specific focus on their implications in the Swedish context.
- Developing a one-dimensional representation of the complex system of driven piles in bouldery soil and formulating a probabilistic model to represent the presence of boulders and the variability of the soil layers thickness along the pile-driving direction.
- Developing a Monte-Carlo based simulation tool to implement the probabilistic model for premature pile refusal.
- Developing a cost model to quantify key economic implications of premature refusal, which can be used to compare several design alternatives.

1.4 Outline of the thesis

This thesis is presented in the form of a compilation, consisting of a comprehensive summary and three appended papers (A-C). The comprehensive summary includes six chapters. Chapter 2 provides a background on the problem of pile driving in glacial soil and an overview of the current state of research. In Chapter 3, the probabilistic model is presented, together with the cost estimation model for premature refusal. A summary of the appended paper is included in Chapter 4. Chapter 5 presents a discussion of the results, while conclusions and future research directions are outlined in Chapter 6.

1.5 Limitations

This licentiate thesis investigates the problem of premature refusal for pile driving in Swedish glacial soil containing boulders. Pile types and properties are limited to the practices in construction projects in Sweden. The investigation focuses on the presence of boulders inside the layer of till, excluding possible boulder encounters in other soils such as clay or backfill material.

Other potential causes of pile structural damages, such as hammer failures, material damages during transportation, human errors or inexperience of the crew, are not considered. Thus, the problem of premature refusal is assumed to be purely related to the random distribution of boulders in the soil layer of till, and to the interaction between piles and boulders.

The geotechnical investigation method of soil–rock sounding is recognized in this work as the main source of information for boulders detection, as it is extensively used in the Swedish industry, especially for housing and commercial construction projects. The potential source of information from seismic and other geophysical investigation methods are outside the scope of this thesis.

2 Pile driving in glacial soil

2.1 Historical background

Piles have been used in construction long before soil mechanics emerged as a scientific discipline in the early 1900s (Terzaghi, 1943, Ulitskii, 1995). The oldest historical piles were made from timber, which were used to support structures such as quays, houses and bridges, when building the first communities. These piles were driven into the ground with manpower to achieve sufficient bearing capacity, which later was substituted by more advanced fall-weight machines. Nowadays, the traditional method for pile installation is driving with an impact hammer, where the dynamic load gradually drives the pile into the ground (Figure 1-2). Driven piles are typically made of timber, reinforced concrete, or steel, with the choice of material depending on factors such as load requirements, soil conditions, and durability. An alternative method is drilling the piles into the ground, which is often used in Scandinavian soil conditions, to ensure anchoring of the pile to the bedrock. Figure 3 shows a pile drilling rig, which can also be used for casings for rock anchors. Drilled piles are exclusively made of steel, which can be drilled into very hard formation or bedrock. Other pile installation methods include grouted piles, bored piles, pressed piles and cast-in-place piles (Tomlinson and Woodward, 2007).

Figure 1. A pile driving rig for pre-cast concrete piles. (Image provided by Anders Beijer-Lundberg)

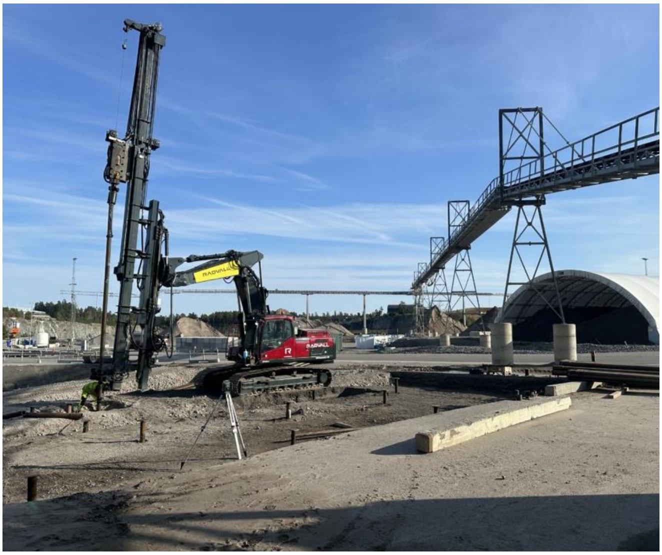

Figure 2. A pile driving rig for driven steel piles. (Image provided by Anders Beijer-Lundberg)

Figure 3. Equipment for drilled piles. (Image provided by Anders Beijer-Lundberg)

2.2 Pile design requirements

The design of pile foundations requires a combination of empiricism and scientific knowledge. Creativity, technical expertise and engineering judgement are required to select the most suitable pile type for the project, along with solid engineering principles to predict the complex interaction between pile and soil layers, to prevent any potential damage to the pile that can compromise the required bearing capacity and structural integrity of the planned foundation system. The decisions regarding pile design should consider the specific loads and tolerance in settlements required from the project and the ground condition at the site. The design is typically carried out in stages, involving the following:

- Design of the structure and loading conditions.
- Evaluation of soil investigations and preliminary pile design.
- Execution of piles and verification of load capacity.

Piles can be designed to withstand several loading conditions, such as compressive or tension axial loads, lateral loads or bending moments. For compressive axial loading conditions, the resistance encountered during pile driving is often used as an indicator of the bearing capacity of the pile (Maizir and Suryanita, 2018). For piles subjected to tension, lateral loads or bending moment, the embedment of the piles has a large influence on the bearing capacity (Poulos and Davis, 1980). The design specifies a target depth for the individual pile, and the consequence of a shallower pile embedment can significantly affect the bearing capacity. The methods for designing piles are outlined in Randolph (2003) and incorporated into modern design codes, such as the Eurocodes (CEN, 2004).

2.3 Pile drivability analysis

Establishing whether a chosen piling method is suitable for a project location requires an assessment of pile drivability. Drivability is an indication of the feasibility of pile driving in the soil, assessing the compatibility of both pile design and driving equipment to the specific soil conditions at the project site (Randolph et al., 1991). Drivability also raises the question of whether the pile can withstand high compressive and tensile stresses caused by hammering, while still ensuring the desired bearing capacity. From a more technical prospective, a drivability analysis is a quantification of the sufficient driving energy to set safely the pile in the soil, which is expressed in kNm or blows per cm of pile head settlements.

For driven piles, the drivability depends upon:

- Pile type and design (e.g. friction or point-bearing piles, material, dimensions and bending stiffness).
- Soil mechanical properties (e.g. resistance and compression modulus).
- Driving equipment (e.g. hammer type and properties such as weight, length, drop height, motors).

Although the prediction of pile drivability can be often left to experience and personal judgement, numerical solutions from wave equation theory were developed over the years, with the very first contribution from Isaacs (1931) to the design of safe loads for driving reinforced concrete piles. Another important milestone in pile-driving theory was the discrete one-dimensional idealization of the system hammer-pile-soil as series of masses, springs and dashpots, proposed for practical applications from Smith (1960). Afterwards, the development of software has enabled the prediction of the energy required to drive the pile, in terms of anticipated blow counts. It also allows to estimate the ultimate bearing capacity and the driving stresses acting on the pile, and to simulate the soil resistance to driving (Rausche et al., 2004, Kourelis et al., 2022). The implementation of new formulas and new models for the dynamic interaction of pile and soil with the use of machine learning algorithms have also shown to improve the reliability in the prediction of the bearing capacity and the assessment of pile drivability (Salgado et al., 2017, Zhang et al., 2019). However, the inability to adequately account for the variability of the site conditions often leads towards a more empirical approach. Since dynamic pile testing is used to assess the pile capacity in site, it also be helpful in identifying potential local problems while pile driving (Goble and Rausche, 1980, Mokwa and Brooks, 2009). Accelerometers and strain transducers can measure stresses in the pile during driving operations to record magnitude and velocity of stress waves. Obstructions, pile damages or deviations from intended alignments are recorded. However, neither the cause nor the nature of those obstructions can be confirmed; thus, prediction of the pile during driving cannot be based only on the results of testing.

2.4 Boulders in glacial till

Glaciers played a crucial role in shaping the Swedish landscape, as for most of the countries in Northern Europe, acting as agents of erosion, transportation and deposition of debris and sediments. Glacial till is a type of soil aggregate transported by glacial ice and deposited beneath, at the side, or at the toe of a glacier. Tills are very poorly sorted sediments consisting of a soil matrix of sand, silt or clay and often containing stones, cobbles and boulders. While all of these are considered anomalies within the till, the primary focus in this thesis is on boulders. Their size, which can range from 200 mm to several meters, poses significant challenges to pile driving. Tills exhibit a significant spatial variability in strength and density, which makes it challenging to take representative soil samples and to provide an accurate quantification of their boulder content.

Existing geological studies based on the Swedish glacial history and landscape aimed to classify and describe different types of till as well as theirs boulder content (Knutsson, 1973, Lundqvist, 1977, Lundqvist et al., 2004, Stendahl et al., 2009). From these studies, it can be inferred that the thickness of till tends to be greatest in valleys and topographic depressions, gradually thinning at higher elevation and often being absent in mountainous regions. Classification with mapping of the surface or from shallow excavation can provide a first assessment and description of the surface boulder frequency. Existing relationship between the surface boulder frequency and boulder content inside the soil can be used only within geologically homogeneous areas and only for a few cm in depth. Another approach for classifying boulder content in tills can be based on the lithological origin of the parent rocks forming the boulders.

Metamorphic sedimentary rock, as well as porphyries and quartzites rock, may result in fine grained tills with low boulder content. Granites and veined gneiss may instead result in medium-grained tills with large boulders. However, the presence of boulders does not only depend on the possible source of rocks eroded by glaciers, but also on the mode of deposition and distance of transportation.

General guidelines regarding field investigation for tills, including the one proposed by Clarke (2018), recommend that the number of borehole and tests should exceed the standard, with the initial investigation serving as a basis for planning a more detailed follow-up study. Currently, to detect the presence of boulders within tills in Sweden, a widely used geotechnical investigation method known as soil–rock sounding is performed. This method can penetrate through the soft soil into the firm till and hard rock, detecting the presence of boulders. This method requires the penetration of a metallic rod through the till, followed by drilling 3 to 5 meters into the bedrock, which can also help in confirming the depth of the bedrock and in assessing the quality of the bedrock. Soil–rock soundings can then identify the presence of boulders and can record their length along the borehole. Considering both the firmness of the till and the hard resistance of boulders to be drilled, only soil–rock soundings can detect the presence of boulders in till. Other investigation methods, such as weight sounding, cone penetration test (CPT) and dynamic ram sounding can be used as complementary source of information, to detect the soil stratigraphy and the mechanical properties of the soil above layers of till. Dynamic ram sounding is particularly used in piling to estimate the depth of penetration and, consequently, the required length of piles. However, due to their dimensions and hammer limitations, this method is not suitable to detect boulders and, thus, to predict premature refusal. Paper B includes pictures of boulders in till, along with a comprehensive description of the procedure and results of soil–rock soundings.

2.5 State of research

2.5.1 Pile driving in offshore projects

The problem of boulder encounters has been investigated for many offshore construction projects, typically involving large-diameter steel monopiles (Holeyman et al., 2015). However, design practices in offshore geotechnical engineering diverges from land-based design practices. In offshore projects, pile design places greater emphasis on bearing capacity, as piles have to withstand significant environmental loading conditions, in addition to the static load for the structure (Randolph et al., 2005). This difference influences the approach and strategy behind site investigations, e.g. methods, types and quantities of data. The majority of piles used in offshore are driven open ended steel piles, with general range of diameters from 1 to 2.5 meters, up to 10 meters for wind turbines. The problem of premature refusal can be caused by obstructions like soil plug or boulders. A possible first course of action in offshore can include the operation of drilling out the internal obstruction from inside the monopile, to be able to continue driving (Manceau et al., 2019). However, local stresses from impact with boulders can trigger progressive failure mechanism like extrusion buckling (Nietiedt et al., 2023) or, among the most catastrophic consequences, can lead to failure at the pile tip (Stevens et al., 2019).

A risk assessment of pile refusal accounting for the presence of boulders was first proposed for an offshore wind farm project by Stuyts et al. (2017). An estimation of the boulder linear encounter rate was performed for each geological unit, assuming that the occurrence of obstruction may be non-random, with a lognormal distribution anticipated for boulders size. The contribution of an obstruction during driving is calculated in term of expected energy required to drive the pile, depending on boulder size and depth inside the geological unit, soil matrix strength in which the boulder is embedded, and on the eccentricity of the encounter. A refusal criterion in term of soil resistance to driving is set in function of obstruction size and eccentricity. However, the connection between the results from investigation and the estimation of boulder encounter rate remains unclear and impractical for land-based construction applications. The latest work on probabilistic modelling for the same offshore wind farm is from Luo et al. (2023), predicting the rate of boulder-induced refusal for installed large-diameter monopiles. The boulder sizes were inferred by drilling data from 140 boreholes, assuming a spherical shape of boulders and a lognormal distribution for boulder size. The expected total number of boulders was generated by a Poisson point process in a 3D boulder field.

The assumption of a spherical shape of boulders was first mathematically formulated by Tang and Quek (1986), who also observed that a uniform distribution would be appropriate for the location of boulders over an horizontal plane. The boulder diameter distributions were derived from a large database of intercepted length of boulders in a sedimentary deposit in Singapore.

Although the proposed solutions appear to be useful, their reliance on large quantities of data, often consisting of multiple drilling data and including both geotechnical and geophysical investigation methods, makes them difficult to apply in different industries and for smaller projects.

2.5.2 Boulder-related issues in land-based infrastructure projects

The presence of boulders poses a significant challenge in many land-based construction projects, particularly in large-scale infrastructure projects. Ditlevsen (1997, 2006) studied the problem of encountering boulders in till for the East tunnel project in the Great Belt region in Denmark, estimating the distributions of locations and dimensions of boulders for several cliff beach locations. The study proposed an estimation of the probability of boulder occurrence based on field data from aerial photos of boulders on the beach locations and on a series of seismic scanning along the tunnel line. For most of the locations, the study observed that a Poisson model was a good fit for the spatial density of boulders, defined as the average number of boulders per unit reference volume of till deposit.

The work of Veneziano and Van Dyck (2006) for boulder encounter during excavation is worth to be mentioned for their investigation of the bias while using statistics directly from borehole samples. Without proper adjustment for the probe dimensions, this can lead to underestimating both the likelihood of boulder encounters and the length of obstructed shaft drilling. The authors also outlined the limited accuracy in infering boulder spatial density and diameter distribution using only 1D borehole data.

Another strategy can involve transitional probability, as proposed by Felletti and Beretta (2009) for tunnelling in glacial till, reproducing a distribution of boulders along the tunnel by 3D Markov chains. The complexity of the algorithm and the level of expertise required highlights the challenges of applying this method to other construction projects.

2.5.3 Pile driving in Sweden

In the Scandinavian construction practices, it is common to drive a large number of small-diameter piles, in contrast to offshore projects where a smaller number of large-diameter piles is usually driven. As a result, for piling in Sweden, a certain number of piles experiencing premature refusal can generally be expected; however, the main challenge lies in accurately predicting the ratio of refusals.

The state of research in Sweden currently accounts for a study conducted by Magnusson et al. (1994) on predicting pile drivability in term of driving energy, based on dynamic ram soundings. The aim was to gather all the information from the soundings to optimize pile design and prevent the underestimation of pile length. A correlation between dynamic probing and full-scale pile testing was found, with a site-dependent scale factor of 30, which could help in estimating the required driving energy and, consequently, a more appropriate selection of pile design and driving equipment. However, as dynamic ram sounding cannot detect boulders in the soil, this study did not address drivability issues in case of boulder encounters.

An empirical approach to estimate the probability of boulder encounter is suggested by the Commission on Pile Research (2007) . The results of soil–rock soundings are used to estimate the boulder density in the soil by assessing the number of encountered boulders per meter of penetrated soil. Then, the probability of encountering boulders is estimated based on the number of encountered boulders per borehole. A detailed description of this approach is provided in Paper A. This classification leads only to a qualitative interpretation of the boulder content within the soil, lacking a clear quantification and definition of each probability.

An assessment of the boulder content from the result of soil-rock soundings is also developed and presented by Alinejad and Lundberg (2024). The random boulders are first generated with a forward analysis, then an inverse simulation of the site investigation is proposed to find the correlation between the site investigation results and the volumetric boulder content for a fixed volume of soil. This probabilistic inverse analysis can help in understanding the amount of site investigation required.

Although the approaches mentioned above are advanced, involving also three-dimensional simulations of boulders in the soil, what is truly needed is an approach that conveniently leverages the properties of the pile –boulder system and presents the uncertainties in a practical and convenient way. The approach should provide a deeper understanding of the stochastic background, allowing to test the influence of various source of uncertainties, while also being practical for implementation in the industry and accurate enough to estimate the risk of premature refusal.

3 Modelling of boulder-induced premature refusal

3.1 Pile design under large uncertainties of boulder encounter

Before investigating the uncertainties in the pile –boulder encounter, a design framework was developed to include the systematic drivability assessment in the design process for piles (Figure 4). The design work can be conceptualized as a set of decisions towards a preliminary design of the foundation. Starting from the initial input of the project requirements and the first assessment of the soil conditions at the construction site, a preliminary design can be formulated. Between the initial and final preliminary design, a drivability assessment is carried out to account for the possible hazards that could emerge during pile driving. This pile drivability assessment should confirm the selection of pile dimensions, type and installation method. Because of the remaining uncertainty, i.e. the firmness of the soil, the variability of boulder content and the limited volume of the soil investigated, early pile testing are often carried out, with the aim to verify the suitability of the preliminary design. This can be performed by high-strain dynamic pile load testing at the site, according to the Eurocode 7 (2007) and the Commission on Pile Research in Sweden (2014).

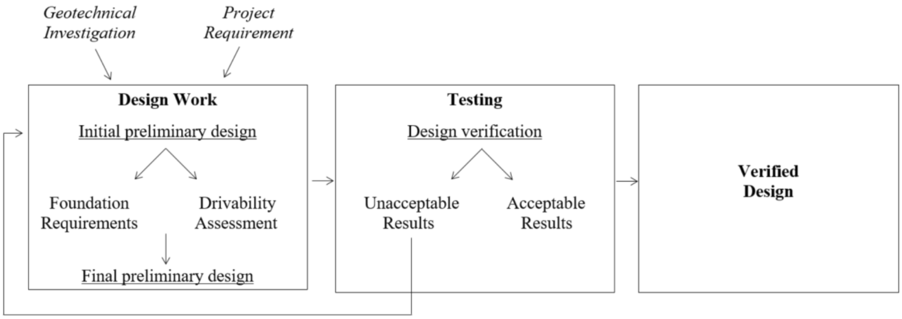

Figure 4. Conceptualized design process for driven piles in soil with high boulder content (Paper A).

3.2 Probabilistic modelling of premature refusal

3.2.1 One-dimensional boulder encounters

Many uncertainties complicate the problem of driving piles in glacial till. These uncertainties are related specifically to the presence, spatial distribution, dimensions and mechanical properties of boulders in the till. The spatial variability of the till, both in term of mechanical properties and distribution), along with the pile response to a potential boulder encounter are also recognized as a significant source of uncertainties. The latter depends both on the eccentricity of the boulder encounter and on the properties of the driving system, including weight and height of hammer and the type of cushion between hammer and pile. A stochastic approach to solve the problem involves firstly identifying the most significant sources of uncertainties and formulating the problem in terms of these random variables. For instance, the probability of an event A occurring may depend on the occurrence, or non-occurrence, of a set of events E_i, provided that these events are mutually exclusive and collectively exhaustive. Thus, the probability of occurrence of A, denoted as $P(A)$ is said to be conditioned to other events. This relationship can be described using conditional probability and the law of total probability (Ang and Tang, 2007):

$$P(A) = P(A \mid E_i) \cdot P(E_i) \tag{1}$$

Similarly, the probability that a driven pile, of a given design D, experience premature refusal depends on the probability of encountering boulders along its driving path:

$$P(\text{premature refusal for design D}) = \\ = P(\text{premature refusal for design D} \mid \text{encountering boulders}) \cdot P(\text{encountering boulders}) \quad (2)$$

In formulating the problem, the presence of boulders in a defined soil layer is defined as the principal uncertainty of this problem. The uncertainty in the presence of boulders within the layer of till arises from both the natural variability of the soil and the lack of knowledge of the actual number of boulders. Existing approaches to model the probability of occurrence of boulders in soil are based on case studies for large infrastructure and offshore construction projects with large dataset available, which most of the time includes both geotechnical and geophysical investigations. The models require also inferring 3D geometric properties of boulders from several theoretical assumptions, enhancing the dependence of the presence of boulders to other random variables.

Due to the significant lack of information especially on the boulder properties, a boulder encounter within the layer of glacial till is modelled as an undesirable event. The boulders are considered dimensionless, and the pile-soil system during driving is simplified in one-dimension. In fact, the dimensions of the cross-sectional area for a driven pile in the Scandinavian context are usually less than 300 mm (Commission on Pile Research, 2024), which is very small compared to the length of the pile that will penetrate the soil layer of the order of 10 to 30 meters, which supports a one-dimensional approach.

Since the results from soil–rock soundings can provide the linear rate of boulders along the borehole, a further reasonable assumption consists in considering the borehole as a sample driving path of a pile. Every boulder encountered during soundings is considered an anticipated boulder encounter for the pile. Hence, the number of boulders k along a 1D-line through the layer of glacial is identified as a random discrete variable in a homogeneous Poisson process.

Homogeneous Poisson field is a widely employed stochastic process to model random events, to predict independent events occurring along a continuous axis with a constant average rate of occurrence. In this context, homogeneity refers to the assumption that the boulders are equally likely to be encountered at any depth within the soil layer, independently. Furthermore, from the available geological assessment on boulder sizes, it is highly unlikely that the boulders in glacial till are large enough to simultaneously affect two or more piles.

The boulders should be at least 1.5 meters wide to hit two consecutive piles, based on pile diameters and minimum spacing of around 1 meter between two piles, which is considered very rare, especially in Stockholm area. Each pile will then independently encounter different boulders while driving.

As shown in Eq. 2, the probability that a driven pile experience premature refusal depends on the occurrence of boulders, which now is formulated as the Poisson probability to encounter k boulders in a soil layer with thickness L:

$$P(k, \lambda L) = \frac{\lambda L^k}{k!} e^{-\lambda L} \tag{3}$$

The parameter λ is defined as the mean occurrence rate of boulders per unit interval of thickness of the soil layer. This rate accounts for the uncertainties due to the random distribution of boulders within the till layer. The information used in the model comes from the results of soil-rock soundings, which are normally performed with 15 - 20 meters within an investigation area. The assumptions for a homogeneous Poisson process to model the presence of boulders for the soil layer with uniform thickness L are clearly defined in Paper B. A summary of these assumptions is provided below:

- The boulders are randomly expected at any depth within the layer of glacial till; consequently, the pile may encounter boulders randomly within the layer.
- The occurrences of boulder encounters are statistically independent: the presence of a boulder at a certain depth within the soil layer does not imply increased probability of another boulder at the subsequent depth, failing to model potential boulder clusters.
- Two or more boulders cannot be encountered at exactly the same depth in till for the same pile driving, but the model does not consider the size of the boulders, so boulder encounters can occur more closely spaced than the average realistic boulder size. This can be an issue when analysing soils with very high boulder content.

Paper C discusses another source of uncertainty that influences the problem of boulder encounter in till: the high spatial variability in thickness of till. For the proposed one-dimensional model, the variability is identified only in the vertical direction (i.e., driving direction) for the thickness of the till, as shown in Figure 5. The homogeneous Poisson process is still implementing to predict the occurrence of k boulders per meter of till thickness, as shown in Eq. 3. By modelling the thickness of till as a random variable, whose probability distribution should fit the empirical data from investigations, each pile is considered to be driven through different thickness of the soil layer.

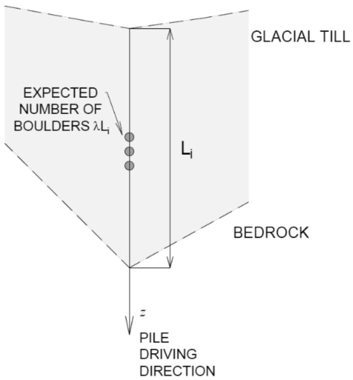

Figure 5. One-dimensional idealization of boulders along the pile driving direction z *in a till of variable thickness* L.

3.2.2 Stochastic modelling of pile driving

After modelling the event of a boulder encounter, the next large source of uncertainty is the outcome of the dynamic interaction between piles and boulders during a driving operation. The possible scenarios from this interaction are *pass* or *stop*. The *pass* scenario implies a satisfactory pile installation in which the pile can be driven through the till layer without damages to be set to the desired depth of penetration. Conversely, the *stop* scenario refers to the case of the pile encountering a boulder along its driving path without being able to advance any further: the driving stops and the pile can potentially reach the failure state in premature refusal. Since multiple boulders may be encountered consecutively during pile driving, the *stop* scenario can occur more than once for the same pile. Hence, the number of *stops* X due to k consecutive boulder encounters in a single driving operation through a till thickness can be modelled as a categorical distributed random variable, with Poisson probability of k boulder encounters used as input:

$$P_B(X = x_k \mid P) = \prod_{k=0}^{kmax} P(K = k; \lambda L)^{[x_k = k]} \tag{4}$$

where $[x_k = k]$ is the Iverson bracket, which is set to 1 if $x_k = k$, otherwise to 0.

3.2.3 Premature refusal sensitivity

When a pile encounters a boulder, i.e. in case of stop scenario, the resistance that the pile has against the boulders needs to be accounted for. The impact between a pile and a boulder can induce possible stresses and damages to the pile, potentially leading to misalignments and large internal forces in the pile, denting of the pile shoe, or, ultimately, collapse of the pile element.

The severity of all these effects depends, among other factors, on pile dimensions and material properties as well as boulder dimensions and mechanical properties. In countries with hard crystalline and metamorphic bedrock, such as Sweden, medium-grained tills containing large boulders are commonly encountered. These boulders can offer significant resistance against the impact with driven piles and are unlikely to break apart upon contact. Since the boulder–pile interaction is studied in one-dimension here, each boulder encounter can potentially lead to pile structural failure.

When many piles are driven, some ratio of the piles will experience premature pile refusal. Since the actual mechanism of the pile-soil system is highly complicated, suitable simplifications are needed. Here, a coefficient r_d is proposed to account for the pile's sensitivity to premature refusal, i.e. its tendency to experience structural failure if a boulder is encountered. The coefficient r_d takes a value between 0 and 1 and represents the probability that any pile of a specific design d that has encountered a boulder (i.e., the *stop* scenario) will experience premature refusal. The probability that a pile with design properties D (considered in coefficient r_D) experiences premature refusal can be expressed as:

$$P\left(\text{premature refusal for design D}\right) = \\ = \sum_{k=1}^{k\max}\left[1-\left(1-r_{\mathrm{D}}\right)^{k}\right]\cdot P(K=k;\lambda L) = \sum_{k=1}^{k\max}\left[1-\left(1-r_{\mathrm{D}}\right)^{k}\right]\frac{\lambda L^{k}}{k!}e^{-\lambda L} \tag{5}$$

If a pile encounters multiple boulders, the probability of successfully passing each boulder should be considered. Details of the analysis are provided in Paper C, including the values of the coefficient r_d for several design alternatives d= 1, 2, 3.

3.3 Cost modelling for premature refusal

A cost estimation model is proposed to realistically quantify the economic implications of premature refusal during pile driving. The objective is to identify the relevant economic weights that each pile failure imposes on the overall piling cost for a project. The model is developed for Scandinavian piling practices, but it can be adapted for other industries, such as offshore construction, by adjusting the cost-risk balance. In the event of premature refusal for one pile at the construction site, the most common remedial action is to drive a new pile. This results in additional costs associated with the procurement of a new replacement pile (i.e., material cost) and the execution of a second installation (i.e., installation cost). A cost function C can be expressed as the sum of these two primary cost components: the material cost C_M and the installation cost C_I. Each cost component can be further defined as a linear function of unit per respective key design parameters a_j:

$$C = C_M + C_I \tag{6}$$

$$C_M = C_{M,1} \times a_1 + C_{M,2} \times a_2 + \ldots + C_{M,j} \times a_j \tag{7}$$

$$C_I = C_{I,1} \times a_1 + C_{I,2} \times a_2 + \ldots + C_{I,j} \times a_j \tag{8}$$

In this context, unit rates serve to identify the key design parameters influencing piling costs and to facilitate a quick cost estimation when these parameters vary. The material cost component may include a unit rate per meter of pile, along with an additional rate for elements specific to the pile design, such as pile shoes or connection components, as shown in Eq, 9. The cost component for installation typically consists of a unit rate per meter of pile that accounts for mobilization, crew, rig, and equipment, as shown in Eq. 10. By substituting Eq. 9-10 in Eq. 6, the total cost C can then be formulated as shown in Eq. 11. The proposed cost model can be easily used to estimate the initial piling cost for a project, based on the total number and total length of the piles planned to install at the construction site, as well as the additional cost in the event of premature refusal, using updated inputs for the new number and length of piles, to replace the rejected ones.

$$C_M = C_{M,1} \times \sum_{i=1}^{n} L_i + C_{M,2} \times n \tag{9}$$

$$C_I = C_{I,1} \times \sum_{i=1}^{n} L_i \tag{10}$$

$$C = C_{M,1} \times \sum_{i=1}^{n} L_i + C_{M,2} \times n + C_{I,1} \times \sum_{i=1}^{n} L_i \tag{11}$$

3.4 Implementation using Monte Carlo simulations

A straightforward approach to implement the probabilistic model is through Monte-Carlo simulations. The corresponding algorithm is presented in Paper C.

4 Summary of appended papers

4.1 Paper A

Effect of uncertainty in design decisions for driven piles in soil with high boulder content. Cannizzaro, C., M. Alinejad, A. Beijer-Lundberg, S. Larsson and J. Spross (2023). Geo-Risk 2023, ASCE Geotechnical Special Publications (GSP) 347, 268 - 276.

Driven piles can be severely damaged during driving into soil with high boulder content and can potentially lose their structural integrity, resulting in premature pile refusal. Geotechnical uncertainties related to the spatial variability of the boulders in the soil aggravate the complexity of the problem, making it difficult to assess the probability of boulder-induced premature refusal and to identify the optimal pile design and driving strategy. Existing tools for drivability assessment are excessively simplistic, relying on the technical expertise of the personnel involved in the design and execution of the project rather than adopting a systematic treatment of the uncertainties at the specific geological location. A transparent methodology to support the decision-making in pile design is necessary for a cost-effective driving and optimal design solutions. This paper discusses how pile design can be understood from a risk perspective, with specific focus on the assessment of pile drivability.

4.2 Paper B

On the probability of boulder encounter for piles driven in glacial till. Cannizzaro, C., A. Beijer-Lundberg, S. Larsson and J. Spross (2024). 7th International Conference on Geotechnical and Geophysical Site Characterization (ISC2024), Barcelona, Spain, 1746-1753.

Considering that a large part of Sweden is covered by glacial till, which is classified as an unsorted sediment formed by glaciers that can contain fragments of rock known as boulders, driving piles constitutes a substantial economic risk. Piles driven into glacial till may encounter boulders and undergo structural damages leading to *premature refusal* and to the loss of piles. Even though geotechnical investigations as of today form a solid basis for the design of pile foundations, the unpredictable presence of boulders and their hard resistance to breakage, makes it challenging to penetrate boulders by standard investigation methods. Currently, the only available source of information used by the Swedish construction industry to confirm the existence of boulders is a dynamic penetration test known as soil–rock soundings. Relying on the results from only one testing method may for most projects underestimate the existence of boulders and their potential impact to piles, leading to an unsuitable design of the entire piling system. This paper discusses the benefit in using the input from soil–rock soundings for quantifying the probability of boulder encounters in glacial till based on Poisson process.

4.3 Paper C

Risk-based approach for modelling premature pile refusal in glacial till. Cannizzaro, C., A. Beijer-Lundberg, S. Larsson and J. Spross (2025). Submitted to an International Scientific Journal.

Premature pile refusal induced by the presence of boulders in glacial till may pose a significant economic risk in construction projects. Encountering boulders can prevent the pile from reaching the bearing capacity at the anticipated penetration depth and induce additional stresses that ultimately compromise the pile structural integrity. Given the uncertainties in the detection of boulders and in the interpretation of the dynamic interaction between boulders and pile, a reliable procedure to predict boulder encounters during pile driving and their potential consequences in the project is needed. This paper proposes a method to estimate the economic risk related to premature refusal caused by the presence of boulders in glacial till. The method employs one-dimensional

Poisson process for modelling the event of boulder encounters while driving piles in till, to estimate the probability of premature refusal for several design alternatives and estimate the final piling cost for each design, including the effect of premature refusal. This risk-based approach intends to guide practitioners towards a more cost-effective and risk-conscious decisions on pile design under large uncertainties. A practical application of this approach is discussed for a commercial construction project in the city of Stockholm.

5 Discussion

5.1 One-dimensional stochastic pile-boulder interaction

The approach proposed in this licentiate thesis intends to probabilistically model in one dimension:

- The presence of boulders within the layer of till with varying thickness.
- The pile sensitivity to premature refusal.
- The outcome of each pile-driving operation.

The one-dimensional simplification fits well the geometric conditions of driving piles in till and allows for an immediate use of the number of boulders observed from soil–rock soundings. Previous studies have also proved the suitability of Poisson probabilistic theory for modelling the presence of boulders in soil. In particular, a Poisson point process was implemented for representing the distribution of boulders per unit volume of till (Ditlevsen, 2006) and for estimating the total number of boulders in a three-dimensional boulder fields (Luo et al., 2023). Hence, integrating a Poisson-based model for predicting boulder encounters appears well-justified, both from a theoretical standpoint and from current engineering practices.

However, boulders size, shape and orientation, as well as eccentricity of the encounter, are also identified as uncertainties. The limitation of neglecting the boulder size can result in simulating the presence of two or more consecutive boulders very close to each other, even if it is not physically possible. In addition, boulder shape and orientation affect the eccentricity and any possible alternative interactions between pile and boulder that do not result in permanent pile damages, such as relative movements and rotations of boulders nor inducing possible boulder modes of failure (Holeyman et al., 2015). In the model, any boulder encounter has the potential to cause permanent damages to the pile, which is ultimately governed by the coefficient r_d. The boulders are modelled as intact fragments of very hard crystalline rocks, among the most prevalent rock types in the Scandinavian region. This assumption justifies the neglect for local boulder failures and considers the boulders highly resistant. Geological assessments and industry practices concerning pile sizes indicate that boulders can be large enough to potentially block the entire cross-sectional area of the pile, but not too large to obstruct two consecutive piles at the same time. Each pile is then likely to encounter boulders independently during driving, which simplifies further the problem and allows for considering the single pile driving. Hence, the real situation of the soil containing boulders is simplified to a suitable level and the model does not require inferring any other properties of boulders to deduce their presence in the soil. Thus, while transitioning to a three-dimensional model will not significantly improve the accuracy of predicting boulder encounters, it may improve the representation of pile–boulder interaction. Nonetheless, the model already offers more significant and useful insights for pile design decisions, compared to available approaches (Commission on Pile Research, 2007). It is also sufficiently robust for simulating the effects of several factors contributing to premature refusal, to serve as a solid foundation for further model development.

The premature refusal sensitivity of a pile design is assigned with a coefficient r_d (for a generic pile design *d)* which encompasses the pile–soil system during driving. Results from Paper C show that the behaviour of the model is strongly influenced by this coefficient, as it directly affects the number of piles that may experience premature refusal, and therefore the economic risk for a certain pile design. A reliable estimation of this coefficient is crucial to improve the accuracy in identifying the most cost-efficient pile design alternative. More observations of the real behaviour and outcome of driving pile and their dynamic interaction with boulders in till at the construction site can improve the quality of the input in the model, especially for specific pile–soil driving system. A progressive failure of the pile while encountering one or more boulders could also improve the accuracy of the model result.

5.2 Practical implications in the industry

The cost estimation model proposed in Paper C, while linear and simple, can quantify the relevant cost components of the economic risk for premature refusal. The relevance of the cost model was shown in the illustrative example for the decisions on the preliminary design. Additionally, its simplicity, combined with its accuracy, makes it an insightful addition in the official tender documents for a construction project. By addressing the economic risk earlier, the project stakeholders can allocate and manage risk more consciously, reducing potential disagreements over risk ownership. With a significant portion of the economic risk properly and transparently acknowledged, it also becomes easier for the client to formulate a strategic response, such as a clear course of actions and decisions in the event of premature refusal, potentially supported by a quantification of a minimum allowable number of pile rejections during the execution of the piles, from the results of the probabilistic model and from a comparison with observations in the field.

Paper A highlights that the observational method, when combined with pile testing, can be particularly effective to address the issue of premature refusal. The testing verifies that the preliminary design, which must have a reasonable success probability, is a suitable solution for the specific construction site. It can also provide an indication of the necessity for design modifications. In cases of large construction area or imprecise field investigation results, negative results of initial tests, such as inadequate load-bearing capacity or failure to reach the desired depth of penetration, could justify a change in the design. This proactive change, involving modifications in pile material and/or installation method, could lead to savings time and cost, avoiding extensive pile rejections. While this approach may not be ideal nor practical for offshore construction projects, due to the high cost of rigs, crew and design, as well as the challenges in procuring new piles in remote locations, it could be suitable for land-based construction projects. At this stage, the probabilistic model can provide valuable guidance: if the number of rejected piles during testing aligns with the predictions from simulations, it may indicate the need for further design adjustments.

The model is a natural extension of the current empirical approach used in the Swedish construction industry, in which the ratio of the boulders to the total investigation length of till observed from soil–rock soundings (λ), accounts for a qualitative classification of the probability of boulder encounter. To increase the quality of input data in the model's parameters λ, a detailed campaign of investigations, conducted prior to the final preliminary design phase, can further clarify the occurrence of boulders in till. As demonstrated in Paper C, the model behaviour is highly sensitive to increases in λ, which for the illustrative example led to the selection of a different optimal design alternative, compared to the one based on the initially assumed mean occurrence rate.

6 Conclusions

This licentiate thesis investigated the problem of premature pile refusal for pile driving in glacial till. The main conclusions are summarized here. Regarding the design work and the recommendations for new decision-making practices, the work concluded:

- For soils layers with suspected high boulder content, the accuracy of the pile drivability assessment becomes crucial for the success of the project.
- The simplified qualitative probability of encountering boulders provided by current practice in Sweden limits the opportunity to optimize pile design with respect to risk.
- An observational method is suitable to confirm the preliminary design with dynamic testing in the field.

Regarding the new proposed one-dimensional probabilistic model for the probability of boulder encounters, the main conclusions included:

- The method facilitates the modelling of the random distribution of boulders within varying soil layer thickness and allows for the estimation of the probability of premature refusal. Therefore, it represents a significant leap forward compared to the existing empirical approach, where such probability is not properly quantified.
- The proposed probabilistic model is rigorously grounded in scientific principles, in contrast to the current empirical approach.
- The boulder encounter is simplified in 1D within a soil layer and relies directly on the results of the geotechnical investigation method used currently used in the industry.

- The method can account for varying soil layer thickness and for multiple boulder encounters for each pile driving.

Regarding the stochastic model for the probability of premature refusal and the estimation of its economic risk, the main conclusions were:

- The proposed risk-based decision support tool analyses the probability of premature pile refusal and the potential cost of the premature pile refusal for multiple design alternatives.
- The model then allows for the simultaneous evaluation of multiple design alternatives to identify the optimal solution for a specific project condition.
- The application of the tool to the illustrative example demonstrates how the results of the model can support in the decision of the optimal pile design, providing the estimated expected total cost for each design alternative.
- A quantitative risk analysis in the decision-making process can increase the awareness of the potential consequences of failure during installation and assist in optimizing the piling design process, which ultimately may improve the efficiency of piling construction operations.

6.1 Future research

Suggestions for future research and investigation include the following:

- One portion of the risk, in terms of monetary cost, has been taken in consideration. Not less important, a time estimation and CO_2- emissions models should be quantified for the problem of premature pile refusal.
- The influence of other source of uncertainties in the dynamic interaction between pile and boulders, such as boulders geometric and mechanical properties, as well as the eccentricity of the encounter, should be investigated.
- Further modelling of the resistance capacity of piles against the boulders is recommended to improve the predictive accuracy of the probabilistic method. This should also include further research into the interpretation of dynamic measurements during pile testing, to enhance understanding and prediction of pile behavior in soil containing boulders.

- A comprehensive risk assessment framework, incorporating a structured design decision-making process, should be developed to support the designer in the optimal decision for pile design, considering cost, time and environmental impacts.
- A cost-benefit analysis for geophysical investigations can be carried out to assess their effectiveness in detecting boulders geometric properties, as well as their suitability to be implemented in the Swedish construction industry for medium to small-size projects.

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