On the probability of boulder encounter for piles driven in glacial till

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ABSTRACT

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 sounding. 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 point process.

Keywords: Glacial till; boulder encounter; pile foundations; site investigations.

1. Introduction

Piles driven in glacial soil can undergo severe structural damage due to the presence of boulders. This is a major issue in Sweden, as a large part of its land is covered by glacial till (Lundqvist 1977, Lundqvist et al. 2004). Tills have been deposited direcly from or by glacier ice and can exhibit a wide range of particle size from clay to boulders (Charlesworth 1957, Evans 2017). Boulders are defined as fragments of rock larger than 256 mm in diameter (Wentworth 1922), and can be randomly distributed throughout tills (Clarke 2018). The predominance of very hard crystalline rock in the Swedish geology indicates that boulders are most likely hard-rock fragments. If the pile encounters boulders while driven into glacial till, the impact can cause lateral movements and damages that can compromise the pile structural integrity, leading to *premature pile refusal*, here abbreviated as PPR. Thus, the unpredictable presence of boulders affects both the design and the execution of pile driving, potentially aggravating on project cost, delays and environmental impact. If there is a considerable probability of extensive PPR due to boulders, the consequences in terms of costs for a necessary re-design of the pile foundations and costs of delays can be severe in comparison to the total budget of a project. This affects especially small-scale construction projects using driven reinforced concrete piles, which are more deformable than other pile materials; still, concrete piles are today the primary choice for deep foundations in Sweden, according to the Commission on Pile Research (2023). Assessing the risk of PPR can in such cases validate the suitability of a pile design for a construction project.

However, currently there are no clear guidelines offered to designers on how to assess the probabilities of PPR and of boulder encounter. Simplified qualitative assessments of the probability of boulder encounter are provided by the Swedish construction industry, yet they lack scientific basis and a standardized procedure on how to interpret the results and make desisions. This forces the designers to rely on their individual judgment and expertise for making decision on pile design, failing to address the large uncertainties of the problem. This can ultimately create disputes between designers, contractor and client, especially when significant PPR occurs. The industry is currently in need of a simple but accurate method to estimate the probability of boulder encounter, with a more robust scientific foundation.

The problem of boulder encounter for driven piles leading to PPR has been studied mostly for offshore construction projects, involving large-diameter steel monopiles installed in marine deposits. The solution is based on the model of hammer-pile-soil system of 1D wave equation (Smith 1960) that can simulate the soil resistance to drive in function of the blow counts from the hammer (Stevens et al. 1982). Recent research studies showed how the soil resistance to drive can account for the presence of boulders and how the PPR can be predicted (Stuyts et al. 2017, Luo et al. 2023). The properties of boulders (size, rock quality and eccentricity respect to the pile) are inferred from investigation methods, which can consist of multiple drilling data and can include both geotechnical and geophysical investigations, making the proposed solutions very hard to be applicable in different industries and for small projects.

However, the problem of the erratic boulders in Sweden is aggravated by the lack of information from site investigations regarding boulder properties. The properties that are actually detectable are in fact only the location of boulders in the soil layer and the penetrated length from drilling measurements. Those results come from a dynamic penetration test known as soil–rock sounding, which is currently the only investigation method consistently executed in Sweden to detect boulders in soil. No further information on boulders properties are available from the campaign of investigations used for conventional construction projects.

The purpose of the paper is therefore to develop and validate a probabilistic model based on Poisson point process of the erratic presence of boulders in one dimension, using only the limited information of boulder properties available from site investigation. The model aims to estimate the number of boulders that can be encountered in a layer of glacial till during pile driving. Furthermore, the paper shows the potential contribution of the model for the prediction of PPR and for a cost-effective pile design. The advantages and limitations of the model are discussed and the results of a series of performed soil–rock soundings for a small construction project in Stockholm are shown here as an example of the model application.

2. Probabilistic modeling of boulder encounter

2.1. One dimensional homogeneous Poisson point process

The spatial distribution of boulders and their irregular geometric properties have been discussed in several studies for different applications. The latest work on probabilistic modeling for an offshore wind farm in UK is from Luo et al. (2023), predicting the rate of boulder-induced refusal for installed monopiles of 7.5 m in diameter. The boulder size were inferred by drilling data and the expected total number of boulders was generated by a Poisson point process in a 3D boulder field. Tang and Quek (1986) modelled the fraction of boulder volume with a lognormal distribution from a large database of boulders intercepted by borings in a sedimentary deposit in Singapore. Ditlevsen (1997, 2006) studied the problem of encountering boulders for the East tunnel project in the Great Belt region, estimating the distributions of locations and dimensions of boulders for several cliff beach locations with Poisson point process. Note that the existing probabilistic models require large quantities of data, which most of the time involves both geotechnical and geophysical investigations for large infrastructure or offshore construction projects. The models require also inferring 3D-properties of boulders from several theoretical assumptions, enhancing the dependence of the presence of boulders to other random variables.

We suggest approaching the problem of piles hitting boulders within the layer of glacial till in one dimension, implementing homogeneous Poisson point process to forecast the event of boulder encounter during driving of one pile. We identify the presence of boulders in a defined soil layer as the principal uncertainty of this problem. In particular, the number of boulders k along a 1D-line through the layer of glacial till is acknowledged as discrete random variable, as they can only be defined by finite number of values. Fig. 1 shows a picture of the boulders in the soil in Sweden and our simplification of the problem in one dimension. Considering the available information on boulder size (Stendahl et al. 2009), we consider it highly unlikely that the boulders in glacial till are large enough to simultaneously impact two or more piles. Especially in the Stockholm area, the boulders should be at least 1.5 m wide to hit two consecutive piles (based on pile diameters and minimum spacing of 1 m between two piles). Consequently, each pile can independently encounter boulders while driving, simplifying the study of the problem to one dimension. In addition, the dimensions of the cross-sectional area for a driven pile are usually less than 300 mm (Commission on Pile Research 2023), which is also very small compared to the length of the pile that will penetrate the soil layer, which can be of the order of 10 m to 20 m.

We let the Poisson probability mass function for discrete random variables,

$$P(k, \lambda L) = \frac{\lambda L^k}{k!} e^{-\lambda L}, \quad (1)$$

define the probability of encountering k-boulders in a soil layer with thickness L. The parameter λ is defined as the mean occurrence rate of boulders per unit interval of thickness of the soil layer. This allows us to predict the number of boulders along the driving direction of the pile within a layer of the glacial till with uniform thickness.

The Poisson point process is based on several assumptions, whose implications to this specific problem are outlined below:

1. The boulders are randomly expected at any depth within the layer of glacial till; consequently, the pile may encounter boulders randomly within the layer;
2. The occurrences of boulder encounters are statistically independent: the presence of a boulder at a certain depth within the soil layer does not imply the presence of another boulder at the subsequent depth;
3. The probability of boulder encounters is proportional to the thickness of the soil layer: without glacial till, there are no boulders.
4. Given a boulder that is encountered at a certain depth within the soil layer, the chance of a second encounter occurring at the same depth is assumed to be zero.

While assumptions (1) and (3) are justified for this specific problem, assumption (2) does not account for the possible scenario of clusters, for which boulders and other small debris may have been deposited in groups, depending on type and deposition process of tills (Evans 2013). Boulders clusters are not included in this study. In addition, assumption (4) neglects that two or more boulders can be encountered at the same depth in the glacial till for the same pile driving, which is reasonable. Note that the model does not account for boulder size, which means that two boulders can be encountered very close to each other in the model even if it is not physically possible given their size. We recognize this as a limitation, as further discussed in Section 4.

In order to calculate λ for the probability of boulder encounter $P(k;\lambda L)$ in Eq. (1), following the procedure explained in Feller (1976), we define N as the total number of tests of soil–rock soundings, which are performed to detect boulders. We further define N_k as the number of boreholes where exactly k-boulders are observed:

$$N = N_0 + N_1 + N_2 + \cdots = \sum_k N_k \tag{2}$$

The total number of boulders T observed in all N-investigations is then:

$$T = 1\cdot N_1 + 2\cdot N_2 + \cdots = \sum_k k\cdot N_k \tag{3}$$

According to the weak law of large numbers, the average of a sufficiently large sample is likely to be close to the expected value. Considering the large uncertainty around the presence of boulder within the soil layer, a large number of tests required to characterize the boulder in detail cannot be acquired in practice (Baecher and Christian 2003). In addition, considering that the Swedish construction industry follow the requirement for field investigation as specified in Eurocode 7 (CEN 2007), we assume that the field data for boulders used for this model are sufficiently large. Hence, the average number of observations of k-boulders N_k/N tends to be close to the probability $P(k;\lambda L)$:

$$N_k \approx N\cdot P(k;\lambda L) \tag{4}$$

By substituting Eq. (4) in Eq. (3), we calculate parameter λ as the ratio of the total number of detected boulders to the total number of performed investigations:

$$\begin{aligned} &T \approx N\cdot[P(1;\lambda L) + 2\cdot P(2;\lambda L) + \cdots] = \\ &= Ne^{-\lambda L}\lambda L\left[1 + \frac{\lambda L}{1} + \frac{\lambda L^2}{2} + \cdots\right] = \\ &= N\cdot\lambda L \end{aligned} \tag{5}$$

$$\lambda L \approx T/N \tag{6}$$

This shows the relation of the parameter λ with N soil–rock soundings, connecting theory with field observations. In particular, from these soundings we can infer k as the number of boulders detected per borehole (or per test), which we define as the number of boulder encounter. The total thickness L_{tot} and the average thickness L thickness of glacial till are also inferred by the results of soil–rock soundings. Eqs. (1) – (6) are the mathematical formulation of the physical problem of predicting boulders in one dimension within a layer of glacial till with uniform thickness.

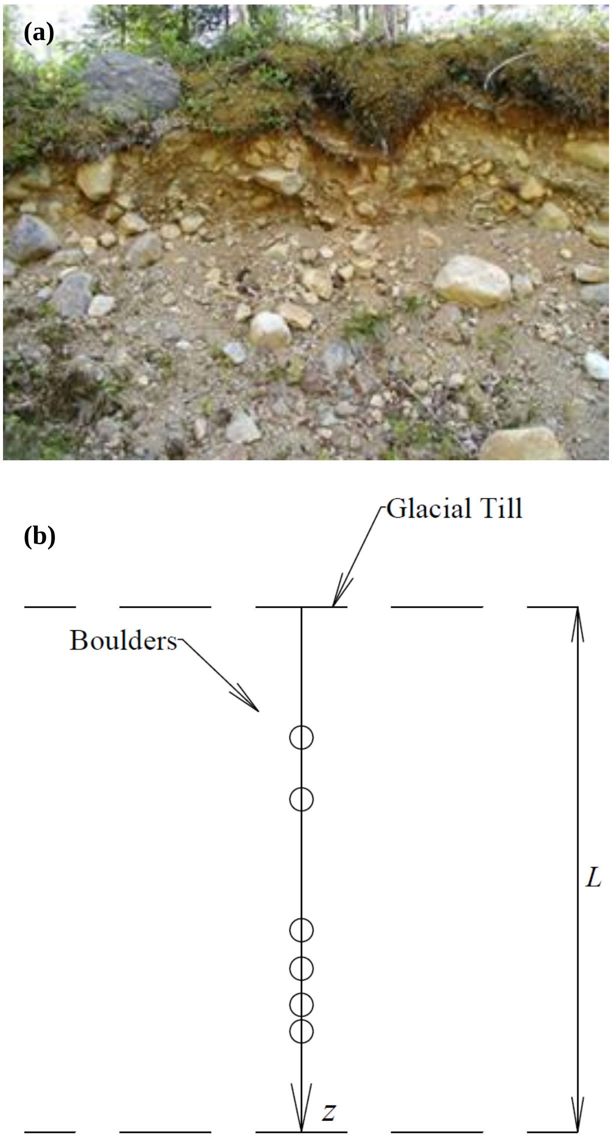

Figure 1. (a) Boulders in glacial till in the region of Hälsingland in Sweden (source: Geological Survey of Sweden (SGU), https://www.sgu.se, published with permission). (b) One dimensional representation of boulders in a layer of glacial till along the pile driving direction *z*.

2.2. Boulder data for a construction project in northern Stockholm

A collection of data of boulders acquired from a small construction project in the northern part of Stockholm is used in this study to validate the proposed probabilistic model. The boulder data consists specifically in the detection of number of boulders, location and penetrated boulder length along the borehole within the layer of glacial till. Several campaigns of investigation were performed between 2017 and 2020 to cover an area of approximately 8500 m^2. The investigations included 101 boreholes, with 33 specifically being soil–rock soundings. Only the results of the latter is included in this study, as this technique is the only source of information to detect boulders. Although there is no formally established standard of how to perform soil–rock soundings, a recommended procedure is described by the Swedish Geotechnical Society (2012).

The equipment consists of a drilling hydraulic rig equipped with a steel rod designed to drill inside the bedrock. This is mainly used to detect the depth of the bedrock and the thickness of various soil layers but it can also detect boulders into the soil along the borehole. Depending on the sounding classes, several drilling parameters can be recorded, such as drilling resistance, rate of penetration, rate of revolution, hammer pressure and rotational pressure. An example of the results from this testing method is shown in Fig. 2.

For this project, the number of boulders detected during investigation are summarized in Fig. 3. Boulders were detected in 30% of soil–rock sounding boreholes within the investigation area. Fig. 4 shows the locations of boreholes where boulders were encountered and locations of those where no boulders were detected. The spatial distribution of boulders provides insight of their random scatter in the area between the investigation points. It also highlights the challenge in predicting the boulders presence in the whole area with only a limited number of tests. Considering the thickness of glacial till to be also significantly spatially variable, an average thickness $L = 8$ m, assessed from the soil–rock soundings, is used in this study.

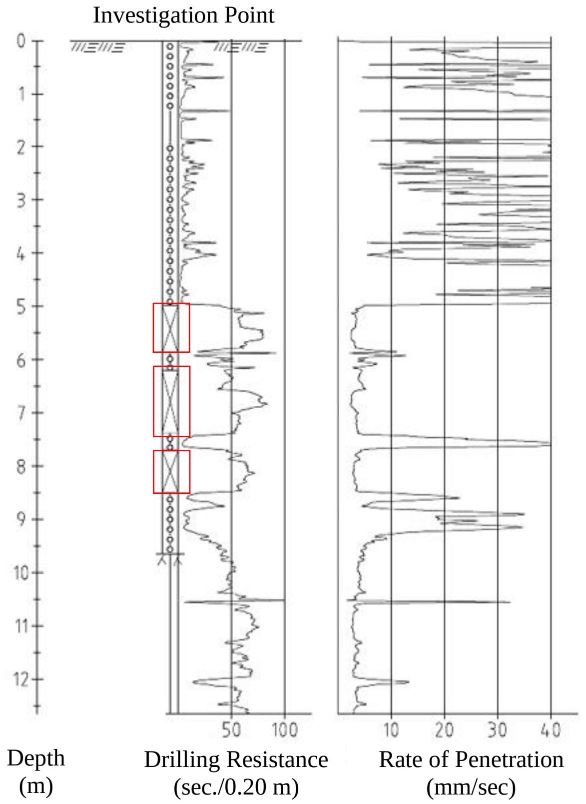

Figure 2. An example of results from soil–rock soundings, where detected boulders are marked in red.

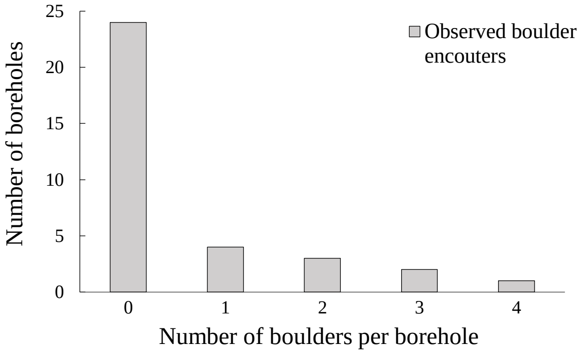

Figure 3. Graphical representation of number of boulders detected during site investigation.

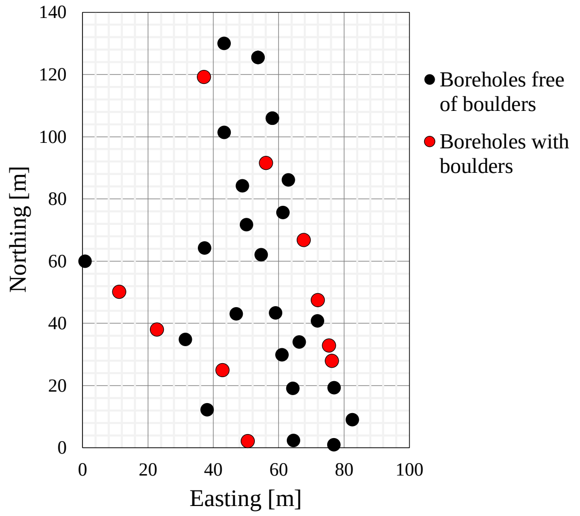

Figure 4. Location of boreholes with and without detected boulder within the investigation area.

2.3. Goodness-of-Fit test

In order to validate whether the provided data can be well represented by a Poisson point process, i.e. in other terms investigate whether the observations of boulders are completely random within the investigation area, we performed the chi-square goodness-to-fit test (Dodge 2008). The chi-square test compares the observed frequency of boulders per borehole from site investigations with the expected frequency of boulders per borehole from the theoretical Poisson distribution model. For this test, the frequency of boulders are divided in two categories: “no boulders” and “one or more boulders” encountered. The result is shown in Fig. 5.

The null hypothesis posits that the observed data for boulders follow a Poisson distribution. The level of significance α selected for this test was 1%. The same significance level has also been chosen before in checking the distribution of boulder diameters with a gamma probability distribution (Tang and Quek 1986).

The calculated value from observed and expected frequency of boulders per borehole (3.04) was found less than the critical value (6.63) for 1 degree of freedom, which means that the observations of number of boulders in a borehole in this project fit a Poisson distribution for a significance level of 1%. In other terms, the result supports the premise of randomness of the spatial distribution of boulders within the investigation area.

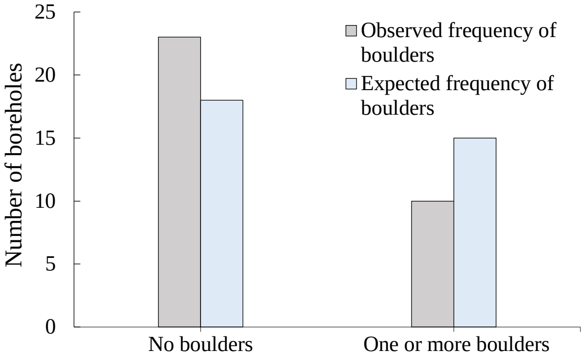

Figure 5. Bar chart comparing observed boulder encounters from site investigation with expected boulder encounters from the theoretical Poisson distribution.

Note that one of the requirements of the test is that the expected frequency for each category should be at least equal to 5 (Ang and Tang 2007). In case of smaller expected frequencies, the recommendation is to proceed with caution and, if possible, to combine different categories together. We fullfilled the requirement of the expected frequency by combine 4 categories together, following the practical suggestion for this test.

3. Decision-making in pile design based on the probability of boulder encounter

The design procedure for piles can consist of several initial steps to develop a preliminary design. One example of the design process for driven piles in soil with high boulder content was conceptualized by Cannizzaro et al. (2023). At this initial stage, the designer needs to take a set of decisions depending on the specific requirements of the project and on the observations of soil condition from geotechnical investigations. The designer should be able to identify the possible hazards during pile installation in order to select pile geometry, material and installation method for the preliminary design.

In this paper, we discuss the selection of the piles material for the pile driving procedure. Driven reinforced concrete piles can be more cost effective compared to driven steel piles, e. g. in terms of material cost, driving equipment and installation time. On the other hand, reinforced concrete piles are less robust and more prone to be severely damaged in case of encountering boulders. If many boulders are expected to be encountered at the project location, the probability of PPR for reinforced concrete piles can be significant, and consequently, several piles can be rejected during driving operations. Thus, the final cost of piling with reinforced concrete can be considerably higher compared to the cost of a design which involves steel piles from the outset.

As the presence of boulders in glacial till affects directly the design decisions, a reliable prediction of the boulders can provide guidance to a more cost-effective pile design in consideration of PPR. The one-dimensional model that we propose in this study can predict the probability of boulder encounters for driven piles in glacial till. We provide here a practical example of the model for the decision-making in pile design.

Using the data from the construction project introduced in Section 2.2, we calculate the Poisson probability distribution of boulder encounters for one pile during driving in glacial till. According to Eq. (6), with $N = 33$ soil–rock soundings, $T = 20$ detected boulders and the average thickness of glacial till being $L = 8$ m, it was found that $\lambda L = 0.6$. The mean occurrence rate of boulders per unit interval of thickness of glacial till was calculated to be $\lambda = 0.07$. Then, Eq. (1) was used to calculate the probability of boulder encounters $P(k;\lambda L)$, as shown in Fig. 6. We can deduce a 46 % chance that one pile will encounter at least one boulder during driving in 8 m of glacial till.

In the following, we assume that for the same project a number of $n = 10$ piles is required to be installed in the same area where the investigations were performed. To calculate the probability of boulder encounters for piles, a binomial probability distribution can be used. We are interested in the probability that a certain number of piles will encounter boulders. The following assumptions hold for this case:

1. There are only two possible outcomes for each pile driving operation: encounter boulders or not encounter boulders.
2. The probability of success is the same for each pile.
3. The outcomes for the piles are independent: each driven pile can encounter boulder independently of the others.

Using Eq. (1), we calculate the probability of not encountering boulders to be $P_0 = P(k = 0;\lambda L) = 0.54$ and the probability of encountering at least one boulder as $1 - P_0 = P(k\geq 1;\lambda L) = 0.46$. Using a binomial probability distribution, we define $B(x;n,1-P_0)$ as the probability that x number of piles (with x a finite number between 0 and 10 piles) will encounter boulders while driving through the layer of glacial till:

$$B(x;n,1-P_0) = \\ = \binom{n}{x}(1-P_0)^x(P_0)^{n-x} \qquad (7)$$

Hence, the probability that at least one pile will encounter boulders is 99 %. The probability of x driven piles to encounter one or more boulders is shown in Fig. 7.

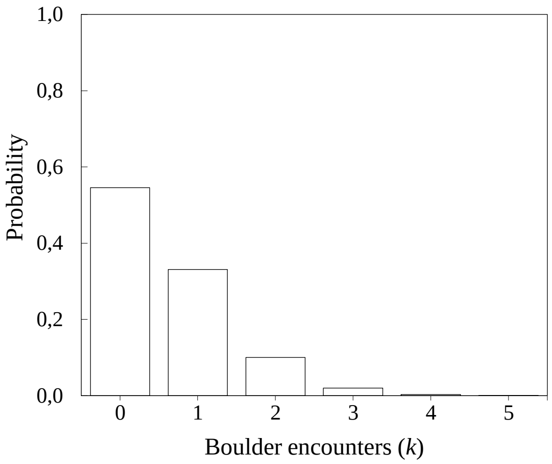

Figure 6. Probability distribution of having k boulder encounters for one pile during driving in glacial till.

We propose the following steps to evaluate the probability of PPR due to boulder encounter. In fact, encountering boulders during piling does not necessarily mean that the pile will be severely damaged, leading to PPR. To assess the probability of PPR due to boulder encounters, we need to take into consideration piles' geometric characteristics and material properties, boulders size and strength, as well as eccentricity of the encounter, which influence the dynamic interaction between piles and boulders. Refer to Holeyman et al. (2015), Stuyts et al. (2017) and Nietiedt et al. (2022) for the latest assessments of the dynamic interaction between piles and boulders for offshore projects, with particular focus on pile failure modes. For this study, we have considered the case of small square reinforced concrete piles. We also assume the following:

- The boulder is much stiffer than the pile.
- The pile will encounter centrally the boulder (neglecting any eccentricity between pile and boulder).

This means that encountering at least one boulder along the pile will lead to PPR. Hence, the information that we provide to the designer is that with 10 reinforced concrete piles to be installed in the area, there is a probability of 99 % that at least one pile will suffer structural damages leading to PPR. In addition, the designer should note a 70 % probability that 5 piles (out of 10) will undergo PPR. It is now the designer's task to estimate the total cost of PPR, which includes the cost of removing the damaged piles and substituting with new ones, in addition to the cost of a re-design for the entire pile group. This estimate can be compared against the cost of a more robust pile material for the entire pile group or a different installation procedure that reduces the probability of PPR. In this perspective, the probabilistic model that we propose can be used as a basis for an initial cost estimation for pile design and piling procedure. Furthermore, this can be the first step to assess the risk of PPR for different pile material.

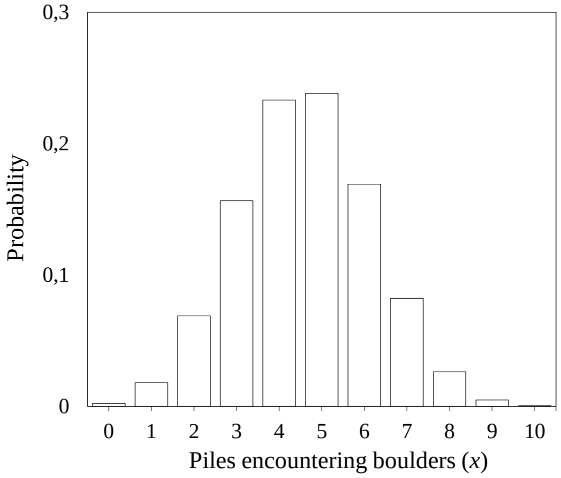

Figure 7. Binomial distribution for the probability of piles encountering boulders during driving in glacial till.

4. Discussions

4.1. Limitations of the one-dimensional probabilistic model for boulder encounter

In this paper, we proposed a probabilistic model in one dimension to predict the presence of boulders when piling in glacial till. Although the model does not incorporate two- and three-dimensional properties of boulders or piles and does not fully capture the boulder–pile dynamic interaction in the soil, we believe that the model is suitable for the problem that affects Swedish construction industry. The small pile cross-sectional area and the likely limited size of the boulders in glacial till let the problem be approached in 1D. Each pile is likely to encounter boulders independently when driving them into the soil, which simplifies the problem. The accuracy in the prediction of the boulder encounters will likely not improve significantly by approaching the problem in 3D.

We have identified the presence of boulders in glacial till as the principal uncertainty of this problem and used the model to address this one uncertainty. This means that the model does not require inferring any other properties of boulders to deduce their presence in the soil, using directly the information from soil–rock soundings. However, size, shape and orientation of the boulders, as well as eccentricity, are also recognized as uncertainties in the problem of PPR.

The limitation of neglecting boulder size can result in two boulders potentially being "encountered" very close to each other in the model. We have also assumed that the pile will only encounter boulders centrally, with no eccentricity between pile and boulder. This neglects to consider any possible alternative interactions between pile and boulder that do not result in permanent damages for the pile, such as relative movements and rotations of boulders. If any encounter of boulders in the model has the potential to cause permanent damages to the pile, the probability of PPR could be overestimated, which could result in a less economical pile design.

Another limitation of the model is the assumption of a layer of glacial till with uniform thickness, in which boulders are randomly present. The presence and thickness of the layer of glacial till have in fact high spatial variability. Incorporating different investigation methods could prove useful in modeling the thickness of the layer as a continuous random variable with a specific probability distribution. Because the probability of boulder encounters with a Poisson point process is directly proportional to the thickness of glacial till, the precision of measurements of the layer's thickness can improve the accuracy in the estimation of the probability of boulder encounters. Furthermore, piling does not necessarily involve the entire thickness of glacial till to the bedrock level. Glacial till can in fact be sufficiently firm at shallower depths to be a competent formation for a pile foundation, and this would affect the number of boulders that the pile can encounter.

As mentioned in Section 2, the number of boulders used for this model are inferred from soil–rock soundings. We note that the diameter of the rod of this investigation method is smaller than the size of a pile.

However, to simplify, we estimated directly the probability of boulder encounter boulders for piles from the number of boulders detected from investigations.

As the model was validated by performing the chi-square test only with the data available from a small construction project in the Stockholm area, we recognize the necessity to further validate the model with a bigger dataset than the one used in this study.

4.2. Comparison with the industry-recommended empirical approach

The current approach used by the Swedish construction industry to deal with the problem of PPR is mainly empirically grounded (Commission on Pile Research 2007). As discussed by Cannizzaro et al. (2023), the current approach directly employs the results of soil–rock soundings, without taking into consideration the compositional variability of glacial till and epistemic uncertainties in the presence of boulders within the glacial till. Although this approach can likely lead to a misinterpretation of the soil conditions, the Swedish construction industry still recommends its use in the design of driven piles. While the current approach is simple and convenient, it has significant limitations as it ignores the effect of the uncertainty of the presence of boulders. The current approach also neglects boulder size and pile dimensions as well as pile–boulder interaction. Furthermore, the lack of clear guidelines on how to interpret and use the results for decisions making can lead in a poorly suitable design of pile material and piling procedure in consideration to PPR.

If we apply the current empirical approach to the same set of data from soil–rock soundings presented earlier, the boulder density would be classified as “medium” and the probability of encountering boulders in a borehole as “very high”, using Table 1 and 2.

Table 1. Classification of the boulder density based on the number of boulders per investigated meter borehole (Commission on Pile Research, 2007).

Boulder density	Number of boulders per soil meter
Very low	0 – 0.015
Low	0.015 – 0.05
Medium	**0.05 – 0.15**
High	0.15 – 0.3
Very high	> 0.3

Table 2. Classification of the probability of encountering boulders based on the ratio of the number of boulders to the total number of performed boreholes (Commission on Pile Research, 2007).

Probability	Number of boulders per borehole[a]
Very low	< 0.02
Low	0.02 – 0.05
Medium	0.05 – 0.2
High	0.2 – 0.5
Very high	**> 0.5**

[a] Number of boulders per performed borehole, not per meter borehole.

As already mentioned, this classification does not provide any indication on how the designer should interpret these rather qualitative results. Although the probability in Table 2 is not a numerically calculated value, it appears to be similar in meaning to the probability of boulder encounter estimated with Eq. (1) and shown in Fig. 6. Moreover, the boulder density in Table 1 is similar to the parameter λ estimated for one-dimensional homogeneous Poisson point process with Eq. (6).

We believe this similarity can contribute to the acceptance of the proposed probabilistic model, as the empirical approach is well accepted by the industry. Our model is more rigorously grounded in scientific principles than the empirical approach, as it treats the prevailing source of uncertainty probabilistically. Additionally, the probabilistic model does not increase the complexity of the analysis, as it is a 1D model based on the same source of information. This makes the application of the proposed model appealing to designers, consultants and clients in the constructions industry.

5. Conclusions

This study discussed the probability of boulder encounter for a driven pile in glacial till that can lead to premature pile refusal (PPR). We proposed a new probabilistic model based on a Poisson point process and validated it using the data from a series of performed soil–rock soundings for a small construction project in the northern part of Stockholm.

The proposed method is a significant leap forward compared to the existing empirical approach used in the Swedish construction industry. The probabilistic model is more rigorously grounded in scientific principles than the current empirical approach. There are some identified limitations that are discussed in the paper. The boulder encounter is predicted in 1D within a soil layer with uniform thickness and relies on the results from one geotechnical investigation method. However, it is our belief that this model can be used as a solid basis for an initial cost estimation for pile material and piling procedure towards a more cost-effective and more suitable pile design in consideration to PPR.

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