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Assessment of boulder content by stochastic modelling and inverse analysis

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ABSTRACT: A key feature of pile drivability studies is the risk of pile loss caused by structural failure of the pile. A frequent cause of pile loss in the Scandinavian context is the existence of boulders in the soil strata. These boulders prevent the pile from penetrating into the soil as well as increase the risk of impairing its structural integrity. A systematic assessment of the risk of pile loss encompasses an estimation of the boulder content based on the site investigation data. The boulder content can be expressed as a point estimate, and the volumetric boulder content is defined as an interval estimate for the whole soil strata. Based on the information from the site investigation, an inverse analysis can be carried out. Herein, a numerical model for the sample generation is described. A computerized site investigation with the Nordic soil-rock drilling method is executed with the Monte Carlo method in which the boulders are randomly generated. An interval estimation of the boulder content is then formulated based on the number of site investigations. The method can subsequently inform if further site investigation is needed to reduce the confidence interval of the estimate. Further, suggestions for practical use in pile drivability studies are explored.

Keywords: Boulder; pile refusal; probabilistic method; Monte Carlo method; inverse analysis

1 INTRODUCTION

Pile foundations are in many countries the most common method to transfer loads from the surface to competent soil layers, (Fleming et al., 2008). Most scientific texts on piles are concerned with the bearing capacity of the finished pile foundations, e.g. Poulos and Davis (1980). The specifications for the construction of the pile itself, including selection of the driving equipment and the maximum driving stress, has historically been included both in the pile design and the construction execution depending on the type of construction contract, (Akintoye, 1994). The choice of piling method is frequently chosen by the contractor, both for design-and-build and for build construction contracts (Tomlinson and Woodward, 2007).

Pile loss, including the structural damage to the pile itself, causes delays in the construction procedure as well as associated cost, (Stuyts et al., 2017). This includes the structural failure of the pile and the possibility to reach a specified depth in the soil, the latter which has a large influence on the horizontal bearing capacity of the pile (Tomlinson and Woodward, 2007). Pile loss during pile driving can be caused both by stiff ground, but also from boulders intermixed in the soil, (Stevens et al., 2019). This issue has been considered both in offshore and onshore piling, and during the introduction of piled foundations in the North Sea significant time delays occurred because of premature pile refusal during construction (Fox et al., 1970; McClelland et al., 1971). Frequently gravity structures were used in the areas, but with the introduction of offshore wind turbines, pile refusal was once again considered one of the biggest risks during the construction phase, (Niestedt et al., 2022), leading to an increased interest in the issue in offshore conditions. In the onshore Scandinavian context the pile design is frequently influenced by the possibility of pile loss which the countermeasures including a large diameter pile or less utilization of the pile bearing capacity to reduce the risk of pile loss.

Mechanical damage to piles during driving has been considered in various numerical model, e.g. Holeyman et al., (2015), Niestedt et al., (2022) and Stevens et al., (2019). These models included steel tubular piles in which the boulders were included in the soil mass and estimated the stresses in the piles during the driving. These models are very useful to assess the risk of pile refusal if the boulder content is known.

Traditionally, the boulder content in soil for the choice of the pile type, piling method and assessment of pile drivability has been estimated with very simplified methods. The statistical properties of the site investigation data have consequently not been included, and the design process has lacked a thorough scientific basis. Instead, the design has mostly comprised local experience for the pile design. This has several disadvantages, especially when new pile types are considered in the design. A further study would

Figure 1. An example of structural failure in a concrete pile

therefore be helpful. However, a significant part of the pile drivability assessment consists of examining the site investigation data and estimating the probability of encountering boulder during the pile driving. This must be carried out with a probabilistic framework, since the soil borings constitute information points which are interpolated in the soil mass, instead of treating the soil as a continuum. Probabilistic methodology to describe the properties of the soil strata has been demonstrated in other contexts, e.g. Phoon et al., (2022) and Zentar et al., (2001) for general geotechnical conditions. A statistical framework for large diameter driven offshore piles is demonstrated in Musso et al., (2019) and Stuyts et al., (2017). In this context soil corings are used to estimate the distribution of boulders in the soil mass. This methodology is very promising but needs to be adapted to local site investigation methods.

In this paper, the requirements for a systematic assessment of boulder content in the soil are described based on the work of Alinejad (2020). The estimation of the volumetric boulder content (*VBC)* of moraine soil is studied in detail. The volumetric boulder content is the volumetric ratio of boulders in the soil, in which the rest of the soil mass is assumed to be a continuum placed around the boulders. A model is developed to find the statistical relationship between the site investigation results, the number of tests and the estimate of the volumetric boulder content (*VBC)* in the soil layer. This statistical relationship can subsequently be used to assess if further site investigation tests are needed, as well as representing the basis for the pile design.

2 BOULDER DETECTION BY SOIL-ROCK DRILLING

Site investigations are an essential part of geotechnical design, providing both design parameters and the specifications for a particular design, (Littlejohn et al., 1994). For the analysis of the geotechnical structure, an appropriate description of the geotechnical system needs to be obtained, (Oskay and Zengal, 2011). In the Scandinavian geological area the soil strata consists of very firm Precambrian rock covered with Holocene moraine and frequently very soft clay.

Standard site investigation methods such as the cone penetration test (CPT) cannot penetrate into the firm rock and the moraine, and for the drilling through the complete soil strata, the soil-rock drilling method is commonly used. The method consists of a rotating and hammering 64 mm drillbit that is drilled through the soil to the bedrock. The method allows a complete penetration record of the whole soil strata from very soft clays to firm rock, which is not possible to assess with other site investigation methods, e.g. the cone penetration test (CPT). It therefore provides point-specific information regarding the boulder content in soil strata, where the boulders are penetrated with the drillbit, resulting in a different penetration resistance in comparison to gravel or moraine. Figure 2 shows a real moraine layer from an excavation, displaying the boulders and the surrounding soil.

Figure 2. An excavation into a moraine layer, showing the boulders and the surrounding soil.

An example of typical site-investigation results from soil-rock drilling is illustrated in Figure 3. The highlighted rectangle represents the boulder penetrated by this method. The drilling operator observes the boulders and records the information in the site investigation. One of the numerical parameters that can be obtained from the site investigation result is the "penetration depth" which represents the length drilled into the boulder during soil-rock drilling, marked in Figure 3. On the right-hand axis of the Figure 3 the penetration velocity in seconds per 0.2 m penetration is displayed. During the penetration of the boulder the time required to penetrate the boulder is significantly higher than for the surrounding soil. Further down the soil penetrates the rock and a larger slowly increasing penetration resistance is shown in the Figure 3.

For the geotechnical engineering, the challenge is to assess the boulder content from the site investigation records, as well as deciding whether more site investigation is needed. In the current practice, experience frequently guides the design, and a systematic method would be helpful in practice. In this paper, a method has consequently been elaborated based on a random generation of boulders and the inverse analysis of the site investigation.

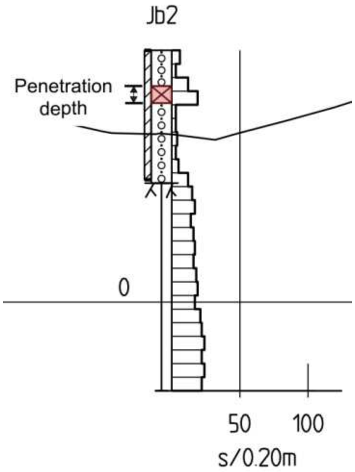

Figure 3. An example of soil-rock drilling with illustration of boulder (highlighted in red) and the penetration depth.

3 BOULDER CONTENT DETERMINATION BASED ON SOIL-ROCK DRILLING

A probabilistic inverse analysis framework is adapted to the description of the boulders in the soil, following the general approach of Ledesma et al. (1996) and Phoon et al. (2022). The stochastic framework is initiated by generating a 3D domain containing boulders and simulation of soil-rock drilling in order to describe the geotechnical system as a simplified model, a specific adaption of the methodology in Oskay and Zengal (2011). This model is then used to determine the boulder content from the records of soil-rock drilling. For this purpose, a methodology is formulated in two steps, forward and inverse analyses as shown in Figure 4. The method allows the generation of a system with a predetermined *VBC* and realistic properties, in which the actual site investigation method can be simulated and the influence of the number of tests assessed in the synthetic model.

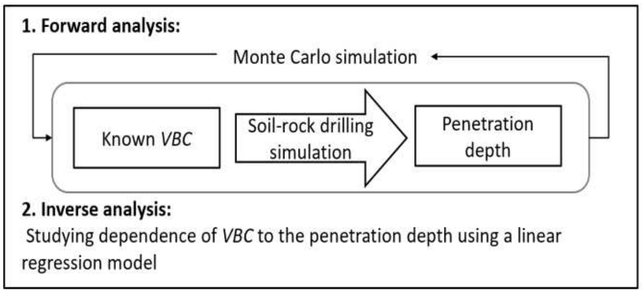

Figure 4. Illustration of the methodology

3.1 Methodology

Both the generation of the boulders and the synthetic site investigation are carried out with the Monte Carlo simulation, (MCS) which relies on the generation of random objects or processes by means of a computer (Kroese, et al., 2014). Here, the random generation of boulders is performed by integration of MCS into the analysis.

In the first step, the synthetic records of soil-rock drilling are generated from the simulation of this drilling method for predetermined volumetric boulder content (*VBC*). The real moraine soil strata shown in Figure 2 consists of materials from clay to large boulders, but this is assumed to be realistic description since most material around the boulders is quite small. MCS is incorporated to this analysis to enable the random generation of boulders based on the given boulder content and size distribution determined for the domain. In the second step, a linear regression model is fitted to the data to address the correlation of volumetric boulder content to Soil-rock drillings' records from the synthetic site investigation.

3.2 Forward analysis: simulation of domain containing boulders

Initially, the synthetic soil layer is set up. A 3D domain of a single layer of soil with size of 25 m × 25 m × 5 m is generated. The boulder content in this domain is controlled by predetermined *VBC*, which is generated in the MCS. Boulders within the domain are modelled by ellipsoids with axes parallel to the global coordinate axes. An example of boulders' distribution in the 3D domain is illustrated in Figure 5.

A stochastic generation of boulders follow a specific statistical distribution. Field measurements of boulders in moraine have shown that the distribution of boulders' dimension in a graded soil strata can be assumed to follow the exponential distribution (Ditlevsen, 2006).

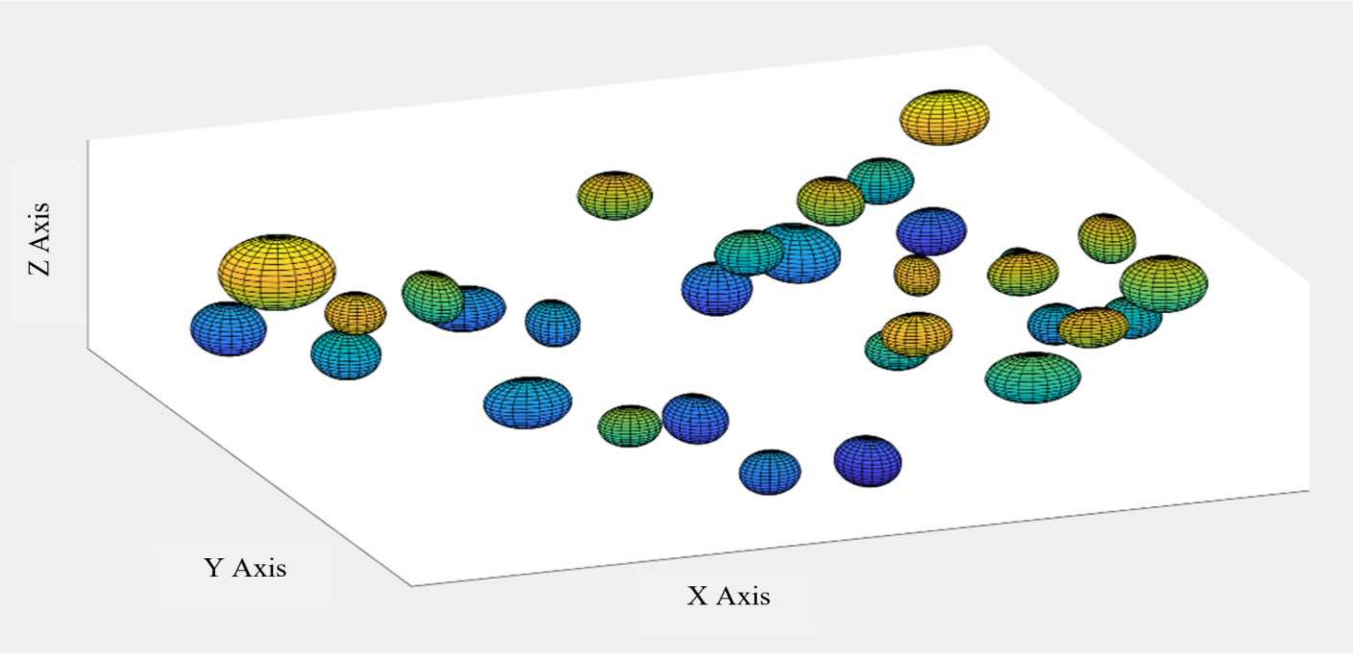

Figure 5. An example of distributed boulders in the domain. (The colourful ellipsoids represent boulders)

For the numerical modelling of the dimension's distribution of boulders in the Z-axis, the exponential distribution is consequently assumed. According to SS-EN ISO 14688-1 standard, the rock fragments larger than 200 mm are categorized as boulders. Therefore, the rate parameter for the exponential distribution is assumed to be 0.2. The ratio between the boulder diameter in X- and Y- axes (d_x and d_y) with boulder diameter in the Z-axis (d_z) are presumed to follow a normal distribution with a distributed mean of 1.5 and standard deviation 0.25, based on inspection of photographic documentation of moraine layers (Moraine symposium, 1969). This implies that the height is smaller than the length of the boulder and is founded on the geological history of the moraine, where the boulders were deposited in a stable position (the length exceeding the height) during the melting of the glacial ice. The generated d_x and d_y below 0.2 m are discarded and regenerated. The boulder's centroid is distributed uniformly in the domain. The sizes in the X, Y are uncorrelated, resulting in the shapes of the boulder in Figure 5. Summary of used distributions are given in Table 1.

Table 1: Summary of used distributions in the model

Model parameters	Distributions' type
d_x/ d_z	Normal
d_y/ d_z	Normal
d_z	Exponential
Centroid of boulders	Uniform

3.3 Forward analysis: simulation of the soil-rock drilling method

To assess the recorded boulders from a standard soil-rock drilling tests, a synthetic site investigation was carried out after the generation of the boulders. Soil-rock drillings are simulated by vertical lines where their length is equal to depth of the domain, which is realistic since the whole soil strata is normally covered in the test. The softer soil layers where are normally part of the tests are not included since the boulders are deposited in the moraine layer. Since boulders are randomly distributed in the domain, there is no necessity to have randomly located boreholes. Therefore, a 4 by 4 grid is chosen to model the boreholes' location in the domain. This grid size provides minimum 5 meter spacing on the X-Y plane where it is a realistic implementation of minimum spacing of performed soil-rock soundings for projects in Scandinavia. The intersections between ellipsoids and lines are determined to calculate the penetration depth.

3.4 Forward analysis: collection of site investigation data

In the forward analysis of the simulation, for predetermined *VBC*s and the number of drillings, the site investigation simulation is performed and their results, namely the penetration depth, are obtained. Further, a parameter here named penetration length ratio (r_b) is defined based on the result as given by Equation (1).

$$r_b = \frac{\sum Penetration\ depth}{Total\ length\ of\ Soil{-}rock\ drilling} \qquad (1)$$

The MCS model is terminated after 20,000 iterations as the chosen convergence criterion (first moment of the results) is fulfilled. Note that the resolution of soil-rock drilling is assumed to be about 150 mm. Therefore, the simulation is adjusted accordingly and penetration depth below 150 mm are removed from the results.

3.5 *Inverse analysis: linear regression*

In the subsequent step, the probabilistic dependence of VBC to r_b is addressed. This gives the main result of the model in which a statistic relation between the site investigation and the volumetric boulder content can be obtained. The relationship between these parameters is modelled using a linear regression model with least squares, shown in e.g. Watson (1967). This relationship can be expressed by Equation (2) which represents a line that best fits the data.

$$yi = \beta_0 + \beta_1 \times xi \qquad (2)$$

where yi are random variables that refers to VBC, xi is the set of observations that refers to r_b, β_0 and β_1 are partial regression coefficients that represent the intercept and slope of fitted line.

The least squares approach is used to obtain the partial regression coefficients (β_0 and β_1) and the standard error. When regression coefficients for various numbers of soil-rock drilling are known, VBC estimator ($\widehat{VBC}$) can be written as given in Equation (3).

$$\widehat{\mathrm{VBC}} = \beta_0 + \beta_1 \times r_b \pm margin\ of\ error \qquad (3)$$

The margin of error depends on level of confidence and sample size and is calculated by Equation (4).

$$Margin\ of\ error = t_{\alpha/2,n-2} \times SE \qquad (4)$$

where $t_{\alpha/2,n-2}$ is critical value from student distribution, α is significance level, n is sample size and SE stands for standard error.

Assuming a confidence interval of 95% and using 20,000 samples, the critical value (t) is given as 1.645. The VBC estimator parameters given in Equation (3) for various numbers of soil-rock drilling are presented in Table 2. In practical design, the VBC can then be estimated from a standard site-investigation with only an analysis of the penetration length, the number of tests and by help of Equation (3) and Table 2.

Notes the significant reduction in margin of error if a larger number of tests are carried out. The linear regression coefficients show the importance of including the extent of the site investigation in the pile drivability assessment. With very few tests, the information inferred from the boulder penetration length is very uncertain since the observer does not know how representative the borehole is of the whole domain. As the number of the tests increases, the estimate is becoming more reliable, and the information retrieved from the r_b parameter becomes more representative for the whole soil layer and with a large number of tests you approach a more direct relation between the r_b and the real VBC of the soil. The geotechnical designer will need to determine the necessary number of tests to reduce the uncertainty while reducing the cost of the site investigation.

Table 2.VBC estimators' parameters for various numbers of soil-rock drilling

Number of drillings	$\boldsymbol{\beta_0}$	$\boldsymbol{\beta_1}$	**Margin of error**
1	4.3	25.5	±4.2
2	3.5	41.5	±3.7
3	3.0	52.0	±3.4
4	2.6	60.3	±3.2
5	2.3	66.1	±3.0
6	2.1	71.1	±2.8
7	1.9	75.2	±2.7
8	1.7	78.0	±2.6
9	1.6	80.7	±2.5
10	1.5	82.7	±2.4

4 CONCLUSIONS

Pile drivability studies are frequently carried out to assess the risk of pile refusal and constitute a significant portion of practical pile design. An examination of the site investigation information is needed for the pile drivability study, and the suitability of site investigation techniques should be considered. For the Scandinavian soil conditions, the soil-rock drilling method provides a continuous record of the soil strata, including the penetration depth of the boulder. In the current paper, a statistical relationship between the VBC of the soil and the site investigation data has been developed. A Monte-Carlo model is used to generate known boulder distributions, and a forward model samples the synthetic site investigation results. An inverse simulation of the site investigation is then presented to find the correlation between the site investigation results and the VBC. This provides a realistic model of the soil mass with the boulders, which corresponds well with an authentic moraine soil strata where the boulders were encompassed in the surrounding glacial ice. An estimation of the volumetric boulder content was outlined, encompassing the regression coefficients and the confidence interval depending on the number of soil-rock drilling tests.

In practical design, a site investigation is carried out and the data for calculating r_b are collected, from which the VBC is estimated based on the number of performed tests according to Equation (3) and parameters reviewed in Table 2. The scope of the site investigation can be enlarged based on the initial results, and the piling method can be also adapted.

It is assumed that the soil strata is homogeneous, and for larger areas, the local VBC should be determined by dividing the volume into smaller parts. The statistical model elaborated in Stuyts et al. (2017) requires a direct detection of the boulder from core samples. The novel use of the soil-rock drilling records permits a more economic method to estimate the boulder content which does not require soil sampling and where a large geological domain can be assessed readily from standard site investigation tests.

Currently, pile drivability studies do not encompass the statistical information from the site investigation. The statistical model displayed in this paper presents a modest step into a more systematic approach, since the results and the extent of the site investigation campaign are included. Hence, further site investigations tests can be added to reduce the uncertainty regarding the *VBC*, and pile drivability studies can be based on a more scientific foundation.

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