

# Driving Monopiles into Glacial Till

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## Abstract

Large diameter monopiles is a foundation solution often used in connection with design of offshore Wind Turbines Generators (WTG) placed in shallow water. This paper presents the installation experience achieved from two wind farm projects, respectively Utgrunden Wind farm located offshore Sweden and Samsø Wind farm located offshore Denmark.

The purpose of the paper is to also provide the reader with knowledge regarding the driveability predictions in the type of soils encountered on the site. Predictive pile driveability analysis results (blow count v depth) are compared with results from back analyses of as-measured pile driving records.

## Introduction

The paper describes the process of hammering large diameter monopiles into glacial till, starting from project preparation and in the end execution of the hammering itself. It highlights the difficulties encountered, related to the large diameter and weight of the monopiles and the difficulties related to the hammering of the piles into the glacial till.

## Pre investigation and design

Extensive soil investigation campaigns were executed at the site two wind farm sites. For Utgrunden, the soil investigation performed by the client consists of CPT's and core drillings on the pile locations. For Samsø, the in situ soil investigation campaign consists of: one vibrocore, one cone penetration test, one core drilling and three jet probings at every pile location. The vibrocores and CPT's were executed in the pile centre, whereas the core drillings and jet probings were executed at angles of 90° on the circumference of the pile diameter. The location of the latter was planned with purpose to provide as much as possible information on the possibility of encountering boulders on the driving path of the pile. No boulders were encountered on the location of the piles, although diving inspection shows boulders between 200mm and 800mm on the seabed at some locations nearby the pile locations. The design of the monopiles and

the hammer requirements were established from the above mentioned data.

## Preparing the piling

Typically a number of issues need to be tackled in such projects:

- 1) Handling and especially upending of the piles
- 2) Piling corrections and piling frame
- 3) Handling of the hammer
- 4) Contingency measures.

### 1) Handling and upending of the piles

The problem encountered for this type of very long and heavy monopiles lies in the upending. The combination of these two factors usually leads to the fact that no single crane can combine the lifting capacity and outreach to upend such piles. At Utgrunden, the monopiles were upended with the jack-up crane combined with a tailing crane on the transport barge. At Samsø the upending problem was overcome by a floating shearlegs combined with a specially designed rotating upending frame. The rigging of the piles for both projects was done with spreader bars, guaranteeing an easy upending but sometimes causing problems in removing the spreader bar.

### 2) Piling corrections and piling frame

Typical tolerances for piling projects for offshore windfarms are : +/- 1m in the horizontal location, +/- 0.1m in the vertical and between 0.5° and 1° for the inclination of the pile. The "soft" tolerance in the horizontal plane can normally easily be achieved with a single level piling gate. In small piling jobs, e.g. for jetties, this is usually not achievable. In such cases a double level piling gate needs to be used. Piling tolerances are set by combining a number of aspects. The governing factor is the tolerance on the lower flange of the turbines. In most cases this is 0.1°. Counting back from this, combining it with the maximum correction that can be made with a transition piece or shims, the tolerance for the inclination of the piles is set. Engineering calculations then show whether this maximum tolerance is acceptable for the piles. In both

Utgrunden and Samsø, flange tolerance is  $0.1^\circ$ . Maximum corrections were respectively  $1^\circ$  and  $0.5^\circ$ . This led to the respective tolerances of  $1^\circ$  and  $0.5^\circ$ .

### 3) Handling of the hammer

The hammer and adaptor have a combined weight of approximately 94 Tonnes for 3m diameter and 130 Tonnes for 4.5m diameter. These hammers were upended and lifted with respectively Liebherr LR1300 and Demag CC2400 cranes from on board a jack-up.

### 4) Contingency measures

The chance of having to apply corrective measures can never be ruled out completely in this type of projects. Two issues need to be dealt with: First the chance of having a pile hammered out of tolerance. Secondly, an early refusal can never be ruled out. This can be due to a number of reasons such as a large boulder or more than expected shear or point resistance. In case a pile is hammered out of the tolerances on verticality, a back calculation has to show whether the pile can be left in place, and an extra correction on the flange has to be made by means of shims or an extra flange ring.

In case a pile meets early refusal, in small piling projects, back calculation usually shows that the pile has sufficient vertical bearing capacity and the pile can be left in place and cut off at the required level. In windfarm piling projects, this is however seldom the case, since vertical bearing capacity is met much before the very important lateral resistance is met. The pile can only be left in place from around 1m from the theoretical penetration. In case the pile meets a refusal at an earlier stage, a number of measures have to be foreseen. The most common are the possibility to empty the pile to take away the inner friction. If this shows insufficient, means to drill out beneath the pile tip have to be foreseen.

### Project Execution

Both the Utgrunden and Samsø piling jobs were executed without significant problems. The tolerances were met, with maximum vertical inclination of the piles of  $0.4^\circ$ .

In Utgrunden, for the 3 m diameter piles, a maximum driving energy of 400kNm and in Samsø, for the 4.5m diameter piles a maximum driving energy of 550kNm was used. In Utgrunden, a particular phenomenon occurred. During the piling, the piles turned between  $10^\circ$  and  $70^\circ$  during the hammering, all in the same clockwise direction. This was not causing any technical problems, since the piles did not have any attachments which were direction sensitive. In Samsø the phenomenon didn't occur.

This turning of the piles needs to be taken into account for projects where orientation sensitive attachments such as flanges, ladder brackets etc. are already attached to the piles. For both projects a back calculation was made for the soil characteristics to verify the assumptions.

### Pile Driveability Assessment

A pile driveability assessment was carried out for both Utgrunden and Samsø. The pile driveability assessment involves three stages:

- Evaluation of soil resistance to driving (SRD)
- Wave equation analysis
- Estimate of blowcount versus pile penetration

### Evaluation of Soil Resistance to Driving

Soil resistance to driving has been evaluated using the empirical method proposed by Stevens et al. (1982) and Semple and Gemeinhardt (1981) depending on the soil conditions found.

Semple and Gemeinhardt method is based on case studies evaluating pile driveability in clay, relating clay unit friction to the clay stress history in terms of OCR. Stevens et. al. method is based on case studies evaluating pile driveability for hard clay, very dense sand and rock. The computed SRD was checked and compared with other independent methods.

### Driving Shoe

The piles are constructed with an internal driving shoe. The purpose of the driving shoe is to assist piles to penetrate through hard layers or reduce driving resistance (internal shaft resistance) and make the piles drive easier. For a pile with a driving shoe, the internal shaft resistance is taken as 25 percent of the outside skin friction in determining end bearing, according to Semple and Gemeinhardt (1982).

### Wave Equation Analysis

Wave equation analyses were performed using computer program GRL WEAP v. 2002, which employs a finite difference approach to solve the wave equation as proposed by Smith (1962).

The dynamic soil parameters used in the wave equation analysis are respectively point and side quake,  $Q_p$  and  $Q_s$ , and the point and side damping,  $J_p$  and  $J_s$ . The dynamic soil parameters used are consistent with the two methods used to evaluate the soil resistance to driving.

Thus to be consistent with the Semple and Gemeinhardt procedure the wave equation analysis carried out using this method should be performed using the following pile-soil model parameters. Side/toe quake equal 2.54mm, side damping equal 0.65s/m and toe damping equal 0.15s/m.

The quake and damping parameters recommended by Roussel (1979) were used when the wave equation analysis were assessed according to Steven et. al. (1982) method.

Table 1: Dynamic soil parameters analysis (after Roussel, 1979)

	Quake (mm)		Damping Factors (s/m)	
	Side, $Q_s$	Point, $O_p$	Side, $J_s$	Point, $J_p$
<b>CLAY</b>				
Soft	5.08	5.08	0.26	0.66
Firm	3.81	3.81	0.23	0.50
Stiff	2.54	2.54	0.20	0.50
Very stiff	2.54	2.54	0.16	0.50
Hard	2.54	2.54	0.10	0.50
<b>SAND</b>	2.54	2.54	0.26	0.50

#### Hammer Details

For the driving of each pile the hydraulic hammer Mench MHUT 500 is considered. Model parameters (i.e. masses, spring stiffnesses and restitution coefficients) representing the physical characteristics of the hammers (i.e. rated energy, ram weight, anvil weight, cushion properties) are presented in Table 2.

Table 2: Hammer model parameters

Parameters	Hammer
	Mench MHUT 500
Type	Hydraulic
Ram weight (kN)	294
Rated energy (kNm)	550
Hammer efficiency	85
Anvil weight (kN)	118
Cushion material	-
Cushion stiffness (kn/mm)	-
Coefficient of restitution	-

The hammer is modeled with an accompanying adapter, which is modeled as the top part of the pile assuming a slack element between pile and adapter. According to Mench, the presence of an adapter can result in approximately 15 percent efficiency loss resulting in a maximum driving efficiency of approximately 85 percent.

#### Predictive Blow Count

Blow count predictions were made using the lower and upper bound SRD envelopes based on the computed SRD profiles and the wave equation results.

#### Pile Installation Considerations

The piles may encounter refusal in the clays either due to high driving resistance, normally experienced in strong clays, or from "set-up" if pauses in the driving are significant. Hard driving may also be experienced if the pile encounters cobble layers and boulders. This could lead to premature pile refusal. Therefore a contingency plan was developed to account these situations.

Pile buckling could be caused by local defects such as dents, unevenness or out of roundness. Most often those defects occur at the pile tip due to improper or rough handling. The pile should be handled with care in order to reduce that risk.

#### Back Analysis of Pile Driving Records

Back analysis of pile driving field (blow count v depth, energy v depth) data is required when:

- Pile(s) refuse before design depth
- Pile(s) driving was considerable easier than expected (low soil resistance encountered)

The purpose of the back analysis is to reassess the design soil parameter for the specific location with the purpose to verify e.g. the lateral pile response. The purpose of the back analysis presented in this paper is also to improve the driveability predictions in the type of soils encountered on the site.

#### Utgrunden Wind Farm – Case Study

Utgrunden wind farm consist of seven 1.5MW wind turbine offshore Utgrunden (Sweden). The wind turbines are constructed on an underwater ridge, which is believed to be an esker (gravelly end moraine) ridge deposit laid down during glacial retreat. Esker deposits originate within or beneath the ice, either from the continuous deposition at the mouth of a sub-glacial stream as the ice retreated, or from infilling of the tunnels of these streams before recession. Eskers are therefore usually very varied in grading, without layer structures and often contain patches or lenses of more clayey glacial till. Piles encountering a lens or layer of more clayey material will tend to drive more easily than through medium dense or dense gravelly sands. The borehole logs, CPT profiles, SPT data and grading curves showed different soil conditions at each WTG location. Based on the geotechnical data the worst soil conditions for the driveability analysis were assessed to be a dense to very dense sandy gravel profile. The internal angle of friction was assumed 40° and the submerged unit weight 10kN/m<sup>3</sup>. The geotechnical report refers to the presence of cobbles and boulders, which might create difficulties in pile penetration.

The design driveability soil profile does not account for the possible presence of cobbles or boulders.

The outside diameter of the monopiles is 3.0m with a 45mm wall thickness. A pile length of 33.7m was assumed. The target depth for all locations is 19m below seabed.

Soil resistance to driving was evaluated using Stevens et al. (1982) method. Figure 5 provides the assessed SRD assuming the pile is coring. The predicted blow count versus depth was assessed for the MHUT 500 hammer working at 70% and 85% efficiency. Figure 6 shows the pile driving simulations carried out for various efficiencies of the MHUT 500 hammer.

As-measured blowcounts versus depth and hammer efficiency versus depth for all 7 WTG locations were recorded. Overall the driving records showed similar profiles except for pile location 1, where the driving resistance was considerable lower than the other piles. Pile self penetration was recorded to approximately 1.0m to 2.0m.

Back figured soil resistance to driving is compared with predicted SRD in Figure 7 and Figure 8. Generally, the back figured SRD fitted well with the predicted SRD as shown in Figure 7. However, for WTG location 1 the back figured SRD does not agree well with the predicted SRD, as expected due to the low driving resistance as mentioned above.

A reasonable good fit is obtained between the back figured SRD curves and the calculated SRD curves assuming a soil profile, which includes a clay layer from 9m to 19m below seabed, Figure 9. The undrained shear strength was assessed to 150kPa. The internal angle of friction is assumed 40° for the top sand layer.

#### Samsø Wind Farm – Case Study

Samsø wind farm consists of ten 2-3MW wind turbines located approximately 6.2km offshore the south of Samsø at Paludan Flak. The soil conditions found on the site show postglacial deposits, where the predominant soil is Clay Till. The fact that the soil conditions consist of glacial deposits makes it very difficult to produce a driveability design profile that is suitable for all locations. Thus the worst soil conditions for the driveability have been found to be a Clay Till layer with increasing strength with depth. Geotechnical parameters are shown in Figure 10 and Figure 11. High shear strength values in the order of 700kPa have been assumed for the last 5.5m in accordance with the findings in Borehole 1. There is a risk of encountering cobble layers and boulders, which might create difficulties in pile penetration or buckle the pile.

The outside diameter of the monopiles is 4.2m with a 45-65mm wall thickness. A pile length of 45.8m was assumed. The design depth is 25m below seabed.

Soil resistance to driving was evaluated using Simple and Gemeinhardt (1981) method. Figure 12 provides the assessed SRD assuming the pile is coring non-plugged. A case where the pile self penetrates 3.0m into the seabed is also displayed on Figure 12, as geotechnical site data at some of the WTG locations indicated that the top 2.0-3.0m seabed sediments were sand. Figure 13 provides the predicted blow count versus depth, assessed for the MHUT 500 hammer working at 70% and 85% efficiency.

Figure 14 to Figure 15 respectively shows as-measured blowcounts versus depth and hammer efficiency versus depth for all 10 WTG locations. Pile self penetration was recorded to approximately 3.0 to 6.0m. This agrees well with the borehole logs and CPT profiles, which indicate that the top seabed deposits at some of the WTG locations are loose to medium dense sand or very soft clay/peat. The driving records, Figure 12, generally show the same profile with increasing blowcount v depth, which is in line with the predictions for a coring non-plugged pile. The exceptions are at pile location 8 where slightly harder driving was experienced and at pile location 9 where pile refused at approximately 19.5m below seabed.

Pile driving simulations were carried out for various efficiencies of the MHUT 500 hammer, Figure 15. Back analysis of the pile driving field data illustrates that the back figured soil resistance is less than the predicted SRD, Figure 17. The field records indicated pile self penetration in the order of 3.0m to 6.0m and applying this to our predicted SRD analysis, Figure 18, a better fit between the predicted SRD and the back figured SRD is achieved. The comparison also clearly indicates that the soil profile results in the better fit.

Fitted SRD compared with back figured SRD is shown in Figure 19. The plot shows the best fit achieved, which was for a soil profile developed partly from upper bound undrained shear strength values estimated from CPT profile 2. The soil profile is shown on Figure 20.

#### Conclusions

The design, fabrication and installation of the wind turbine generators offshore Utgrunden and Samsø were successfully completed. The large diameter monopiles were successfully driven into the glacial till, achieving target depths at nearly all WTG sites. Back analysis of pile driving records data was carried out for the WTG sites where target depth was not achieved. Based on the developed soil profiles the

lateral capacity was verified and assessed to be sufficient.

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**Figure 1: Jack-up Wind and Barge Bolle VIII with monopiles (Utgrunden)**



**Figure 2: Shearlegs Samson with monopile and Jack-up Vagant (Samsø)**



Figure 3: Hammer MHU 500 and piling adaptor diameter 4.5 m (Samsø)



Figure 4: Jack-up Vagant and monopile in piling frame with hammer MHU 500 (Samsø)

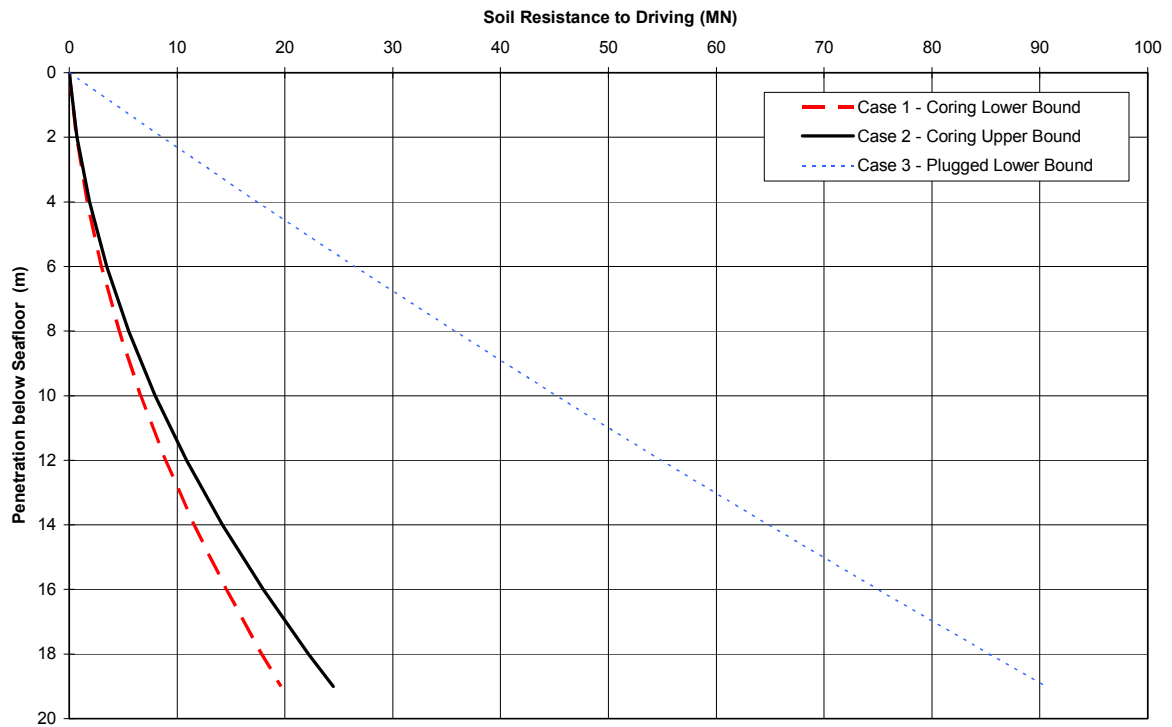


Figure 5: Predictive soil resistance to driving - Utgrunden

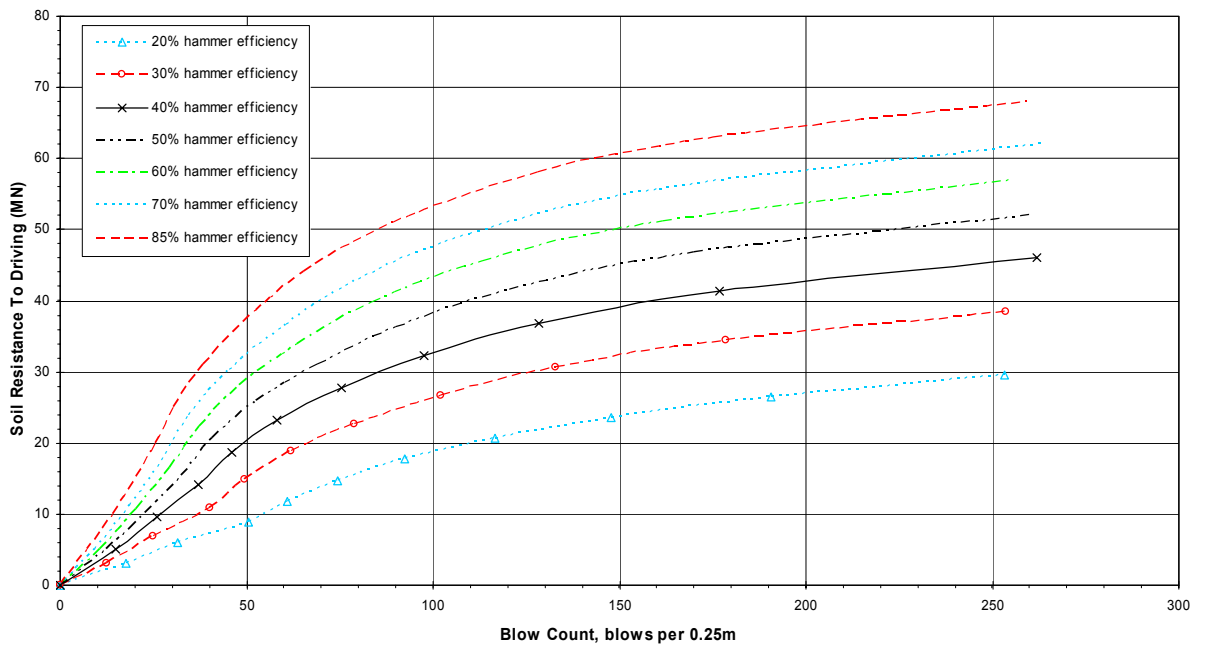


Figure 6: Wave equation analyses results assuming pile is coring - Utgrunden

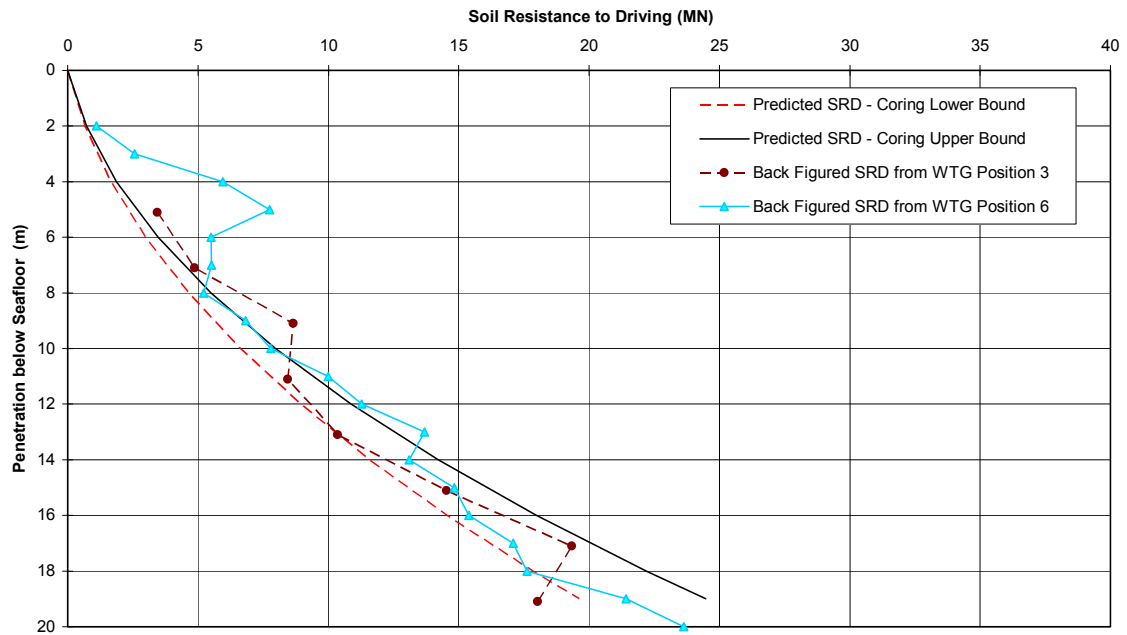


Figure 7: Predicted SRD compared with back figured SRD - Utgrunden

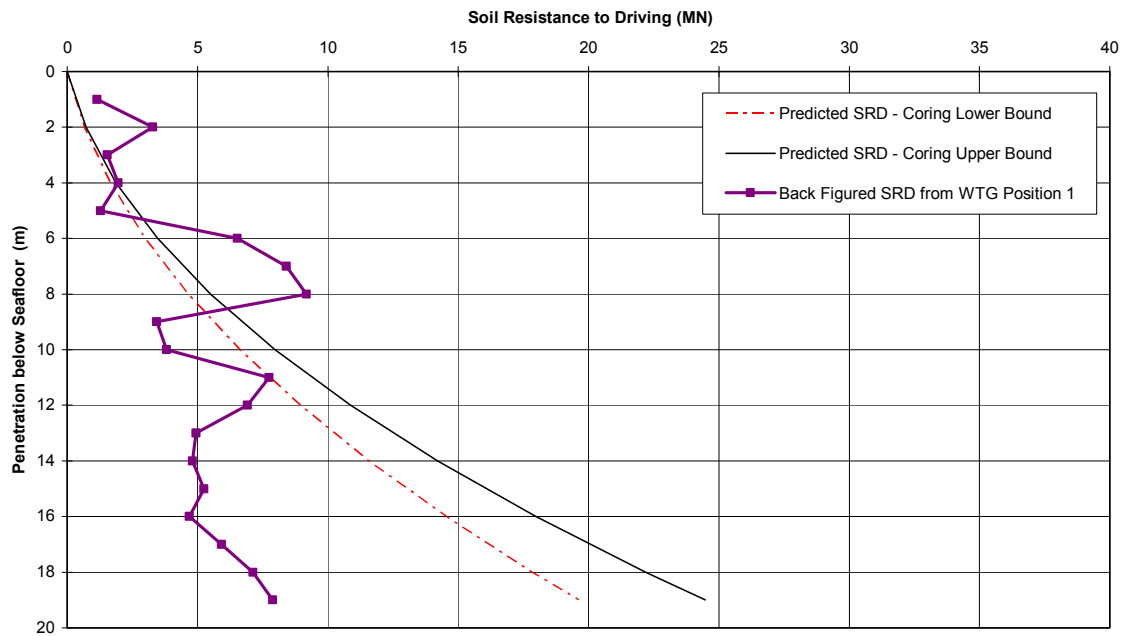


Figure 8: Predicted SRD compared with back figured SRD - Utgrunden

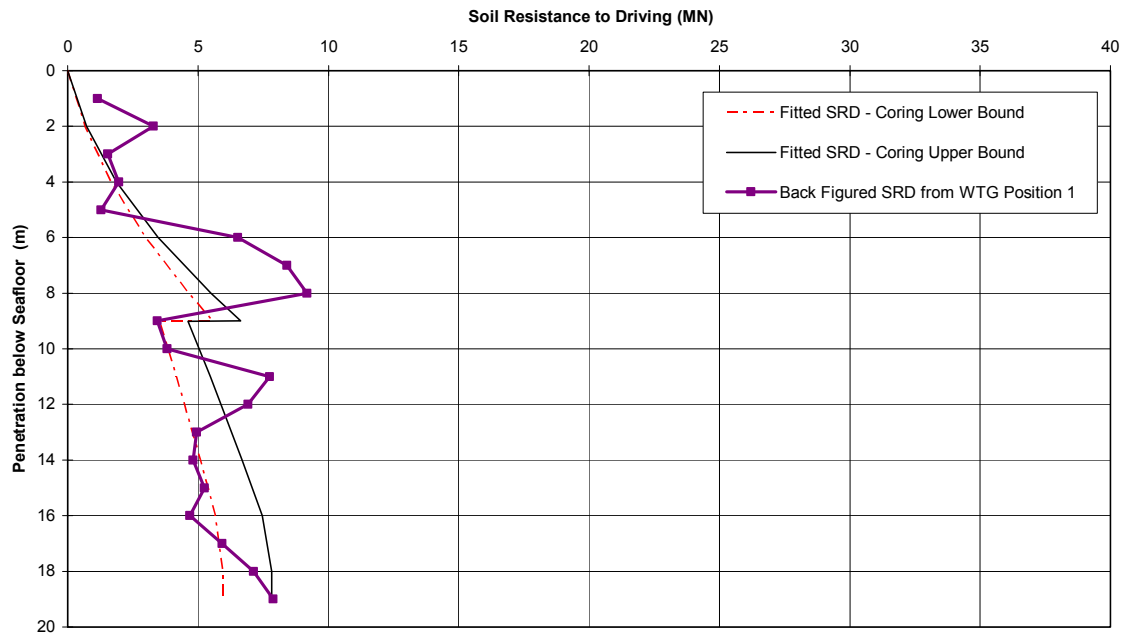


Figure 9: Fitted SRD compared with back figured SRD – Utgrunden (WTG location 1)

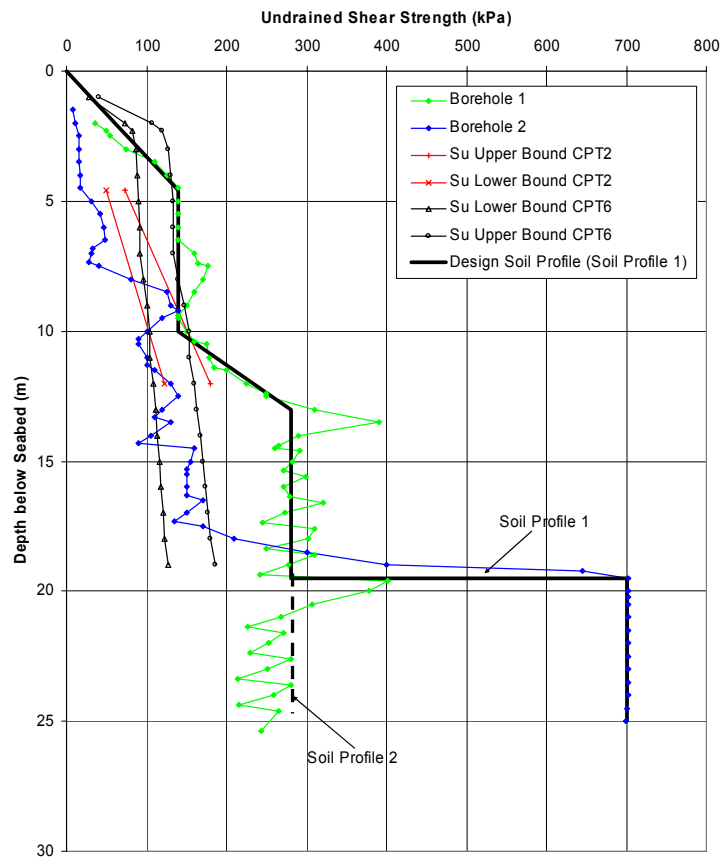


Figure 10: Interpreted shear strength and design soil profile - Samsø

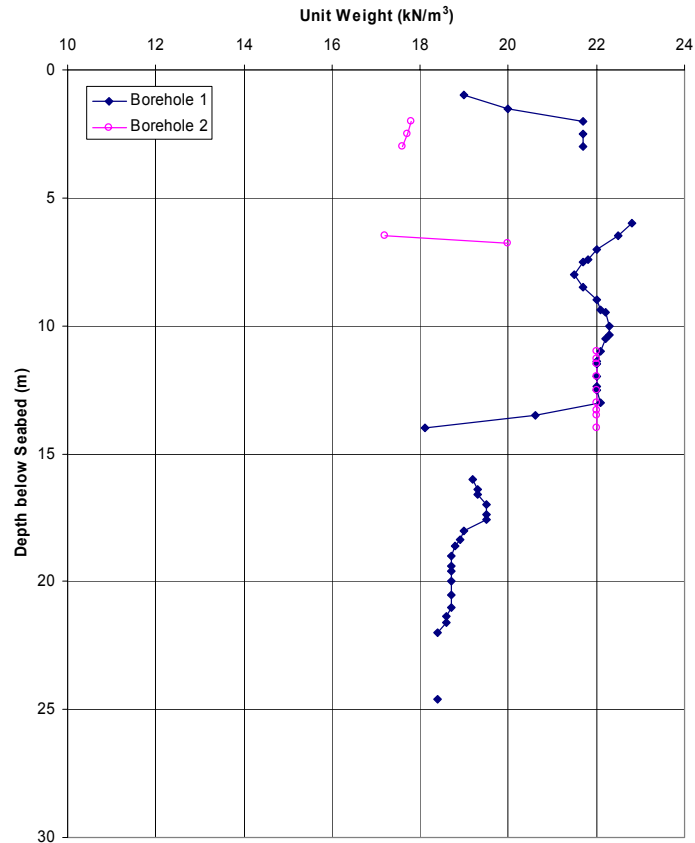


Figure 11: Unit weight – Samsø

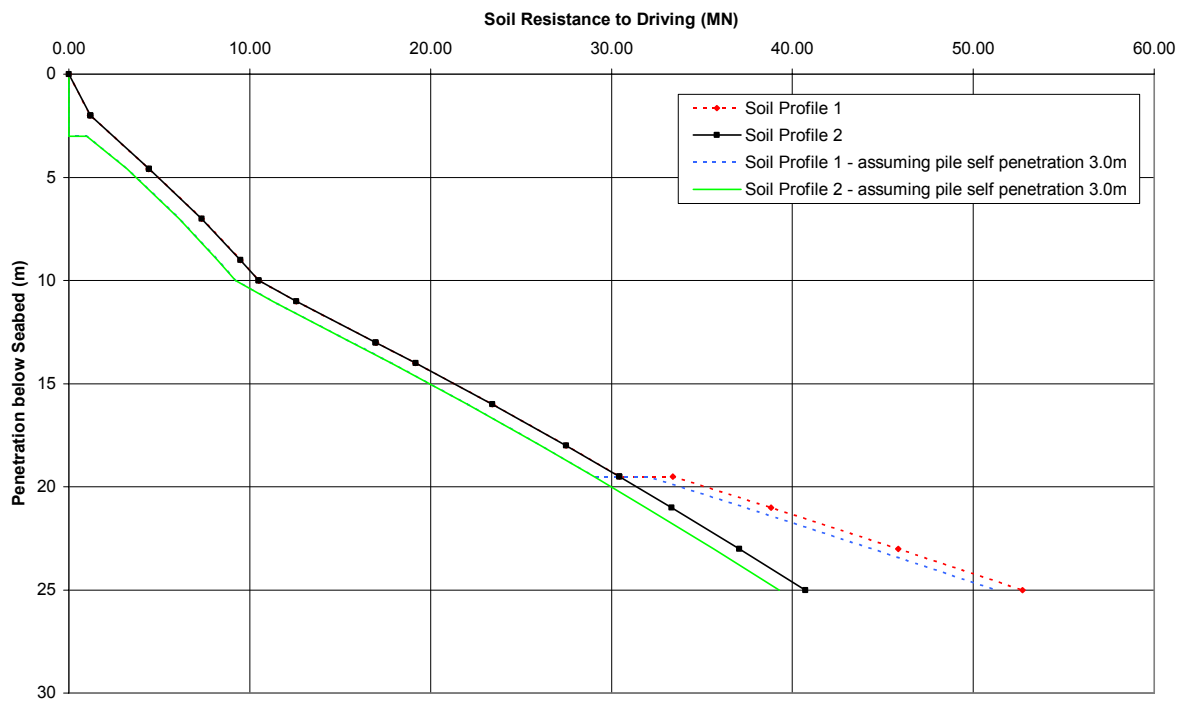


Figure 12: Predictive soil resistance to driving – Samsø

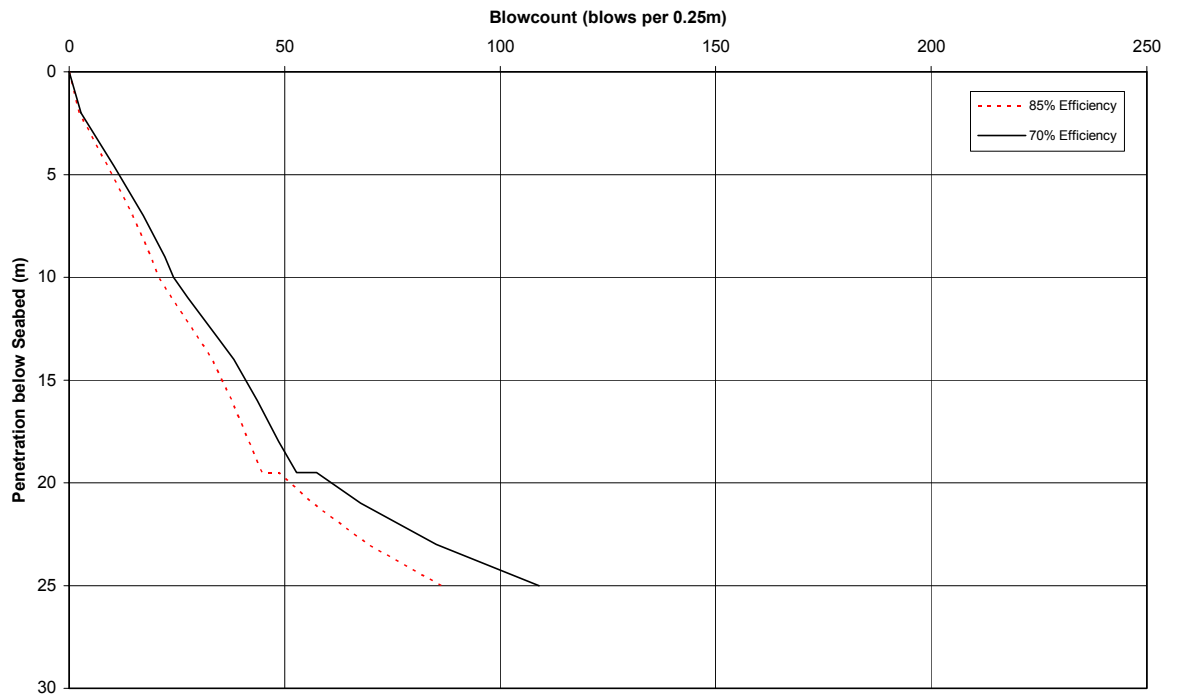


Figure 13: Predicted blow count - Samsø

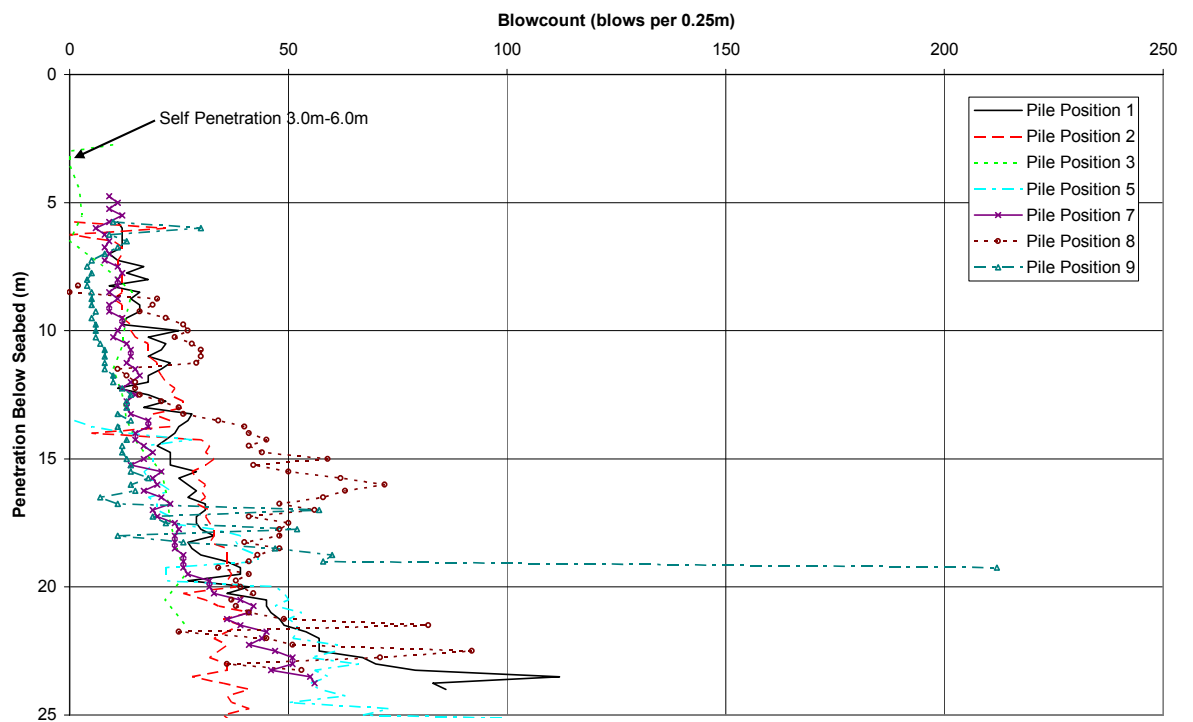


Figure 14: As-measured blow count v depth - Samsø

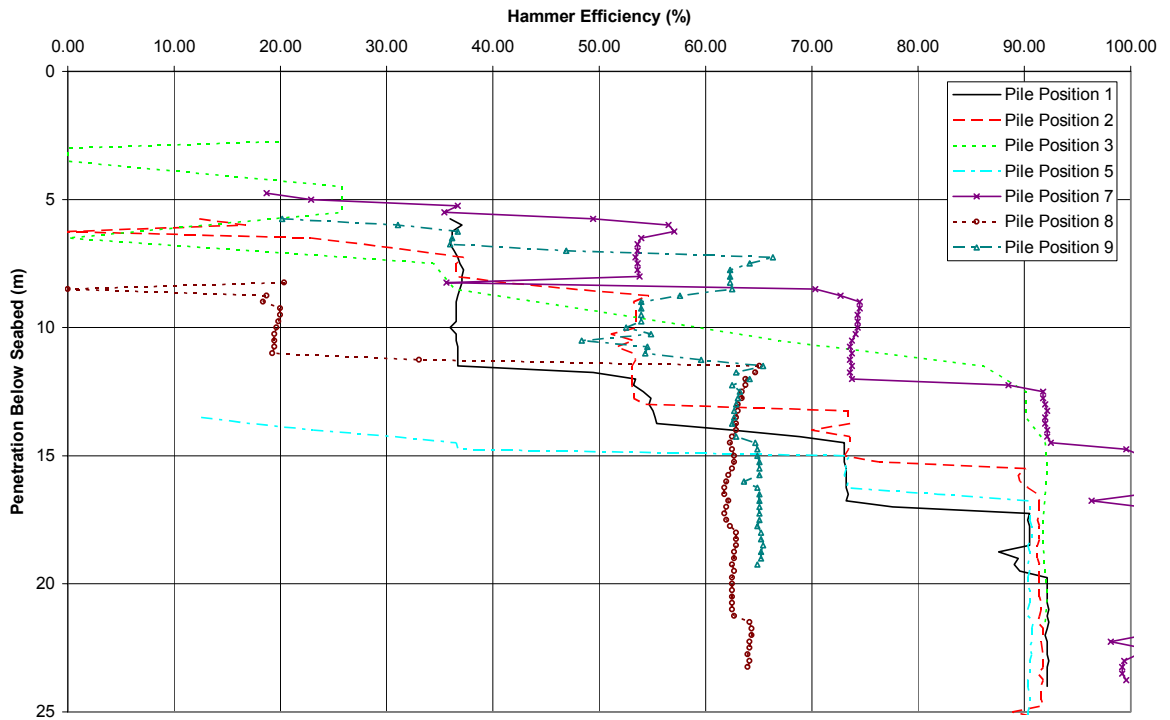


Figure 15: As-measured hammer efficiency v depth - Samsø

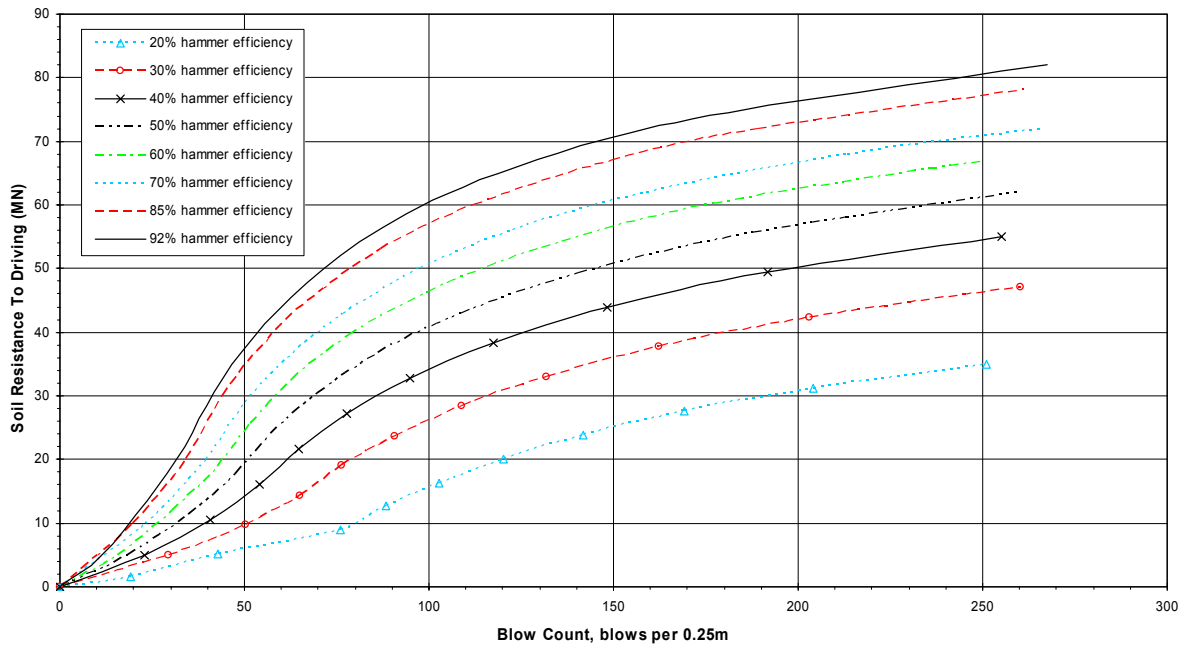


Figure 16: Wave equation analyses results assuming pile is coring - Samsø

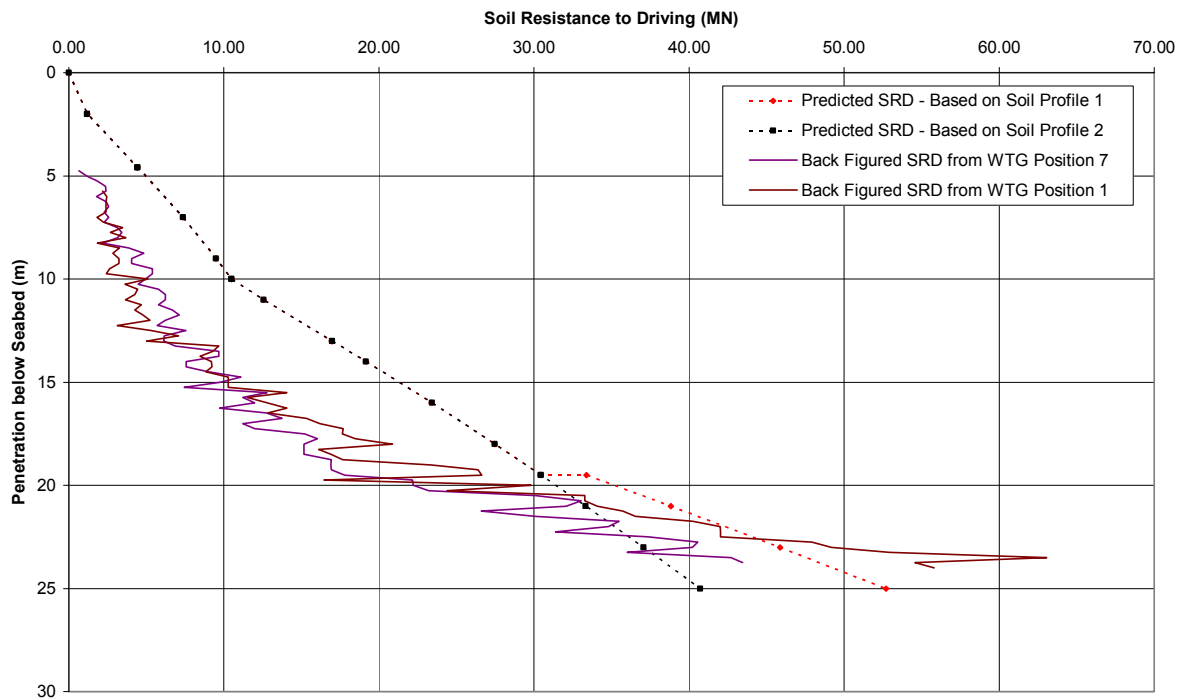


Figure 17: Predicted SRD compared with back figured SRD - Samsø

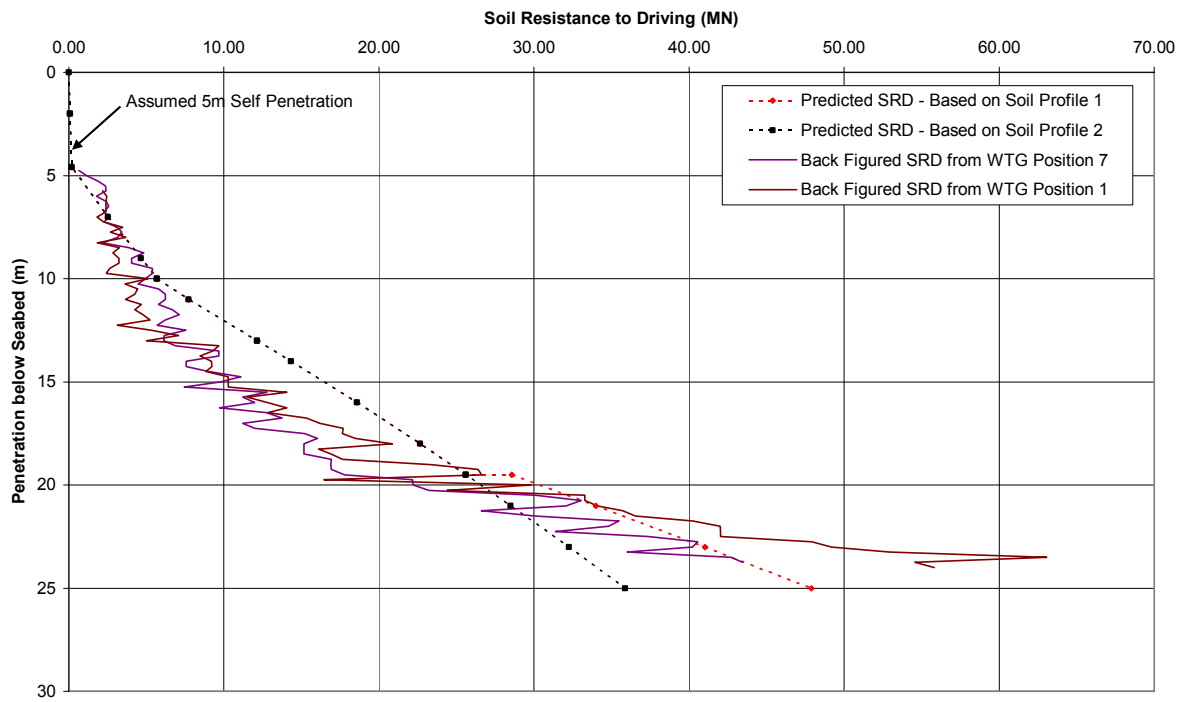


Figure 18: Fitted SRD compared with back figured SRD - Samsø

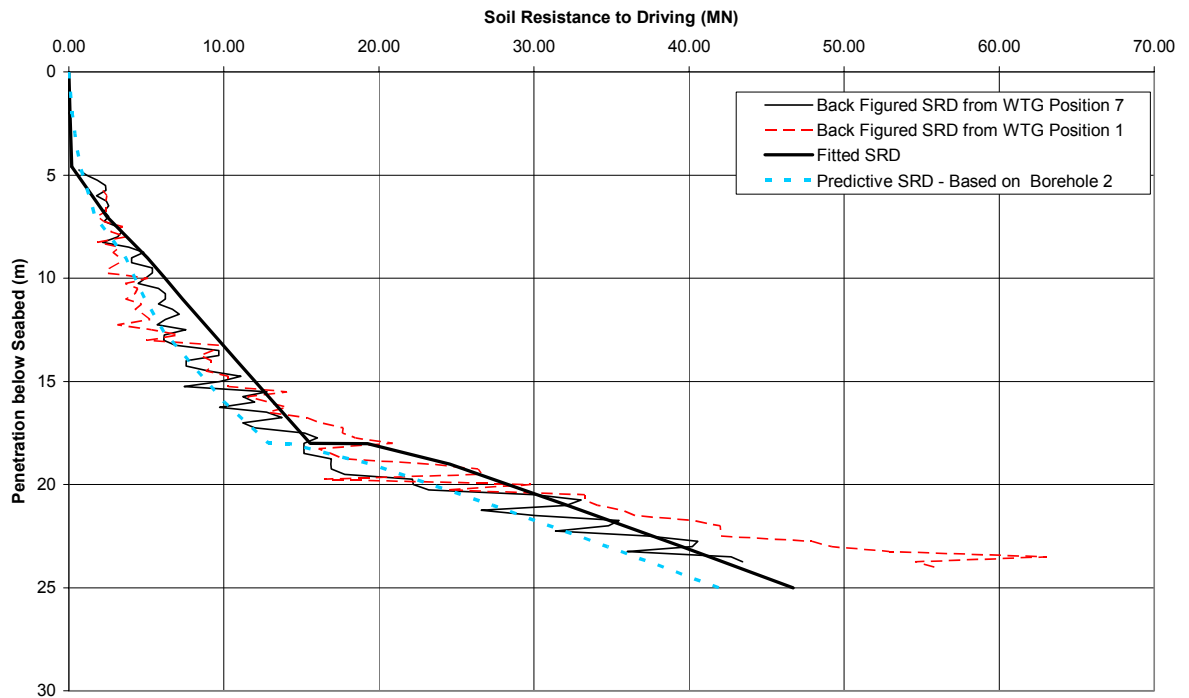


Figure 19: Fitted SRD compared with back figured SRD – Samsø

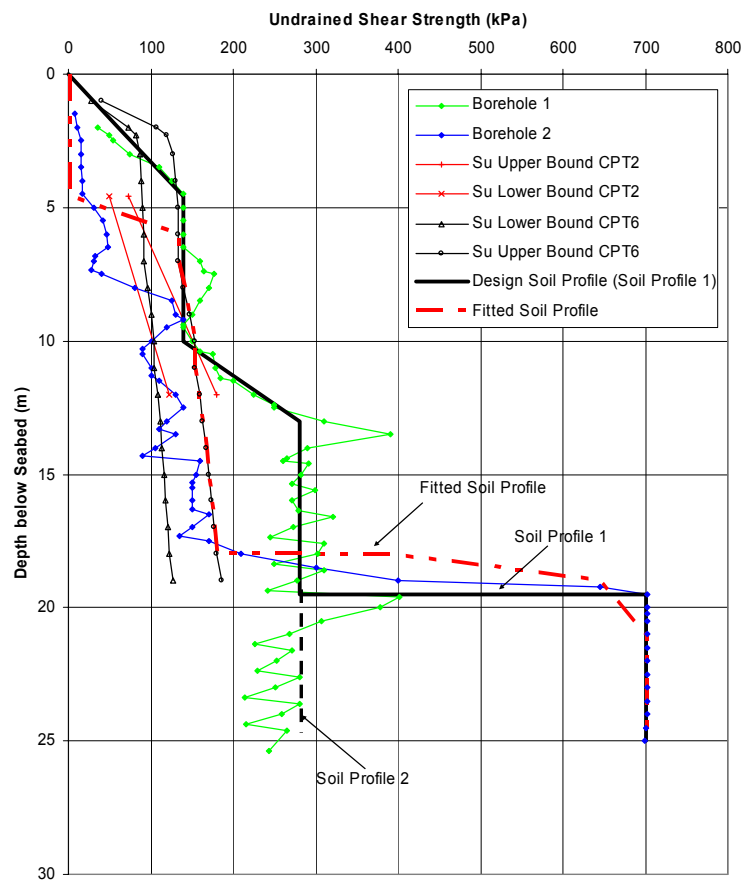


Figure 20: Fitted soil profile compared with interpreted shear strength and design soil profile – Samsø