Interpretation of Danish Chalk Parameters Applicable to Foundation Design

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ABSTRACT
The performance of chalk formations in the installations of different types of structure foundations has been investigated and discussed in different research studies and papers. Several symposiums and publications for many years have helped in increasing the knowledge and the understanding of this rock material. However, while the benefits of using the chalk as a competent foundation stratum are known, the selection of design parameters, due to the difficulties in testing and sampling, remains still a main concern and often associated with many uncertainties. This paper is an attempt in presenting practical guidelines in selecting design parameters of some of Danish chalks and gives guidance in the application of these parameters for foundation design / modelling. Direct interpretations of rock parameters, based on geotechnical boreholes, are carried out and different methods based on international and local recent studies have been used in assessing the rock mass parameters for the design / installation of piles / sheet-piles in chalk. A special attention is given to the conversion of the Hoek-Brown classification parameters into Mohr-Coulomb rock mass parameters. The impact of the used methods in the design bearing capacity of the pile foundations is analysed and discussed. Conventional and Plaxis finite element analyses are utilized applying converted Mohr Coulomb soil parameters and direct Hoek Brown soil model for calculating the pile / sheet pile vertical bearing capacity. Conclusions are drawn by comparing the results from the different methods, emphasizing the importance of site investigation methods, accurate interpretation and classification and full understanding of the soil-foundation interaction.

Keywords: Chalk, Hoek-Brown model, Mohr-Coulomb model, bearing capacity, sheetpile

1 INTRODUCTION

The use of the chalk as an engineering material has been studied and discussed since 1965, when the Institution of Civil Engineers (ICE) organized the symposium Chalk in Earthworks and Foundations. Since then, the performance of chalk formations in the installations of different types of structure foundations has been investigated and discussed in different research studies and papers. Several symposiums and publications for many years have helped in increasing the knowledge and the understanding of this rock material. However, while the benefits of using the chalk as a competent foundation stratum are known, the selection of design parameters, due to the difficulties in testing and sampling, remains still a main concern and often associated with many uncertainties.

The chalk structure geology is composed by a fine grained limestone with low magnesian carbonate and high moisture content. Due to its dual porosity (fine pores in the intact material and larger pores along the fractures) the chalk as an engineering material behaves in different ways.

In this paper, some practical guidelines in selecting design parameters of some Danish chalk and guidance in the application of these parameters for foundation design/ modelling, are presented.

2 SOIL INVESTIGATION / DATA

Typical samples of chalk formation carried out by Geo within the Copenhagen area are given in Fig.1 to 4. The results and samples carried out from this borehole (BH-1) will be used in this paper to interpret the chalk parameters.

The virgin soil conditions within the area consist of a top layer of clay till, with a thickness that varies from (8-12) m, overlaying limestone formation (chalk) to larger depths. Some filling with sand has been found on top of the borehole with a thickness of 1.3 m. This layer it is believed to come due to construction activities within the area.

In Table 1 are shown the depths and descriptions of the layers found in BH-1.

Table 1 BH-1

Depth		Layer Description
From	To	
[m]	[m]	[-]
0.0	1.3	Fill material (Sand)
1.3	12.9	Clay till
12.9	19.5	Chalk (Limestone) Sample no.30 (14.10-15.05) m – Figure 1 Sample no.31 (15.05-16.55) m – Figure 2 Sample no.32 (16.55-18.05) m – Figure 3 Sample no.33 (18.05-19.55) m – Figure 4

In total 4 core samples have been carried out for the chalk formation (limestone). The obtained core recovery varies from (67-77) %. The limestone appears with a high degree of fractures (S4 – S5), which correspond to a strongly fractured limestone with distance between fractures less than 6 cm. The Rock Quality Design (RQD) varies between (0-21) %. The degree of induration varies from (H2-H4) indicating a slightly to strongly indurated limestone. The depth interval of the cores are given in Table 1 and the photos of the core samples with the measured recovery and RQD are given in Figures (1 - 4).

Figure 1 Sample no.30, Chalk, RQD =21, TCR=74 %

Figure 2 Sample no. 31, Chalk, RQD =10, TCR=67 %

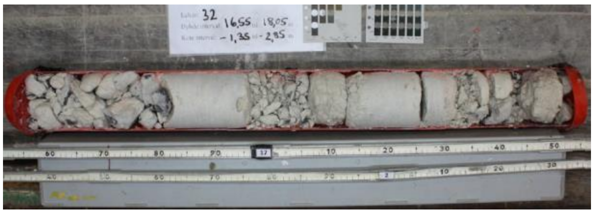

Figure 3 Sample no. 32, Chalk, RQD =20, TCR=67 %

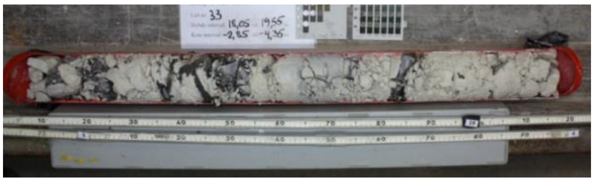

Figure 4 Sample no.33, Chalk, RQD =0, TCR=77 %

3 ESTIMATION OF HOEK-BROWN CLASSIFICATION PARAMETERS

The Hoek-Brown failure criterion was originally developed for estimating the strength of hard rock masses. Because of the lack of suitable alternatives, the criterion has been applied to a variety of rock masses including very poor quality rocks, which could almost be classed as engineering soils. For the derivation of the effective strength parameters from Hoek-Brown rupture criterion, the following classification parameters are calculated (Hoek, 2002).

- Uniaxial compressive strength of the intact mass (q_{uc})
- Geological Strength Index (GSI)
- Material constant for the intact rock (m_i)
- Disturbance factor (D)

3.1 Calculation of the uniaxial compressive strength of the intact mass (q_{uc})

Within the borehole area, no available compressive tests on rock samples were available. However, some Point Load (PL) tests have been carried out in some limestone samples at BH-1. Within the area, Geo has carried out previous geotechnical investigations including UCS and PL tests for the chalk formation. In absence of compressive tests, the point load test index has been used to correlate the UCS. In Fig. 5 and 6, the results of the PL test and UCS have been plotted against the measured bulk density.

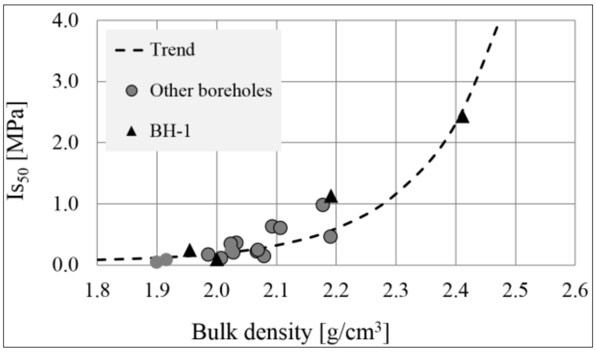

Figure 5 Bulk density vs Is_{50}

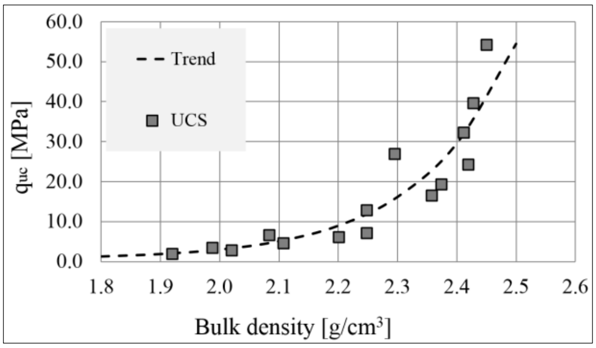

Figure 6 Bulk density vs q_{uc}

From these graphs, the degree of induration was estimated as H=2 for bulk density smaller than 2.1 g/cm^3 and H=3 for bulk density between (2.1 - 2.25) g/cm^3. The correlation between the point load strength index and UCS show a ratio q_{uc}/ Is_{50} between (15 - 20). Taking into account the results of the available data and by considering the previous studies and experience with the Danish chalk in the area, the q_{uc} for the intact rock was estimated as given in Table 2.

Table 2 Estimation of q_{uc}

Degree of Induration	q_{uc} [MPa]	
	Lower bound	Upper Bound
H2	1.0	3.0
H3	5.0	8.0

The values of the q_{uc} given in Table 2 are within the applicable limits for the limestone found in the Copenhagen area (Hansen and Foged, 2002). On the contrary, the strength index (Is_{50}) was found generally lower than the empirical values of the limestone in Copenhagen, which resulted in a higher ratio of q_{uc}/ Is_{50} of about (15 - 20). The averaged uniaxial compressive strength of the formation has been estimated as q_{uc} = 11.3 MPa (lower bound) and q_{uc} = 24.2 MPa (average). The averaged q_{uc} takes also into account the very thin layers with a high degree of induration (H4 and H5). For the top part of the limestone (maximum 2 m of depth), with an estimated degree of induration H2, the q_{uc} was estimated equal to 1 MPa (lower bound) and 3 MPa (average).

3.2 Calculation of the Geological Strength Index (GSI)

The calculation of the GSI has been carried using the correlation with Rock Mass Rating after Bieniawsky (RMR_{89}).

$$GSI = RMR_{89} - 5 \qquad (1)$$

The calculation procedure of the total RMR value by taking into account all the individual contributions of the factors is explained in details by Bieniawski (1989). The following values given in Table 3 have been assigned for the calculation of RMR.

Table 3 RMR and GSI calculation; lower (LB) and upper (UB) bound rating

Factor	Rating	
	LB	UB
q_{uc}	1	1
RQD	3	8
Spacing of discontinuities	5	8
Condition of discontinuities	25	30
Groundwater	7	7
Joint orientation	0	0
RMR total	41	54
GSI	**36**	**49**

The calculated values of GSI are in good agreement with the instructions given by Marinos and Hoek (2004).

3.3 Calculation of the material constant (m_i)

References of the material constant (m_i) are given by Marinos and Hoek (2004). The recommended range given suggests values m_i=7 ± 2. The m_i assigned for this project has been chosen as 6 for the lower bound and 9 as best estimate.

3.4 Calculation of the disturbance factor (D)

Since the limestone structure is not disturbed, a value of D=0 has been assigned.

3.5 Hoek-Brown classification parameters

In Table 4 are summarized the best estimate Hoek-Brown classification parameters.

Table 4 Hoek-Brown Best Estimate Parameters

Hoek-Brown Classification Parameters	Units	Best Estimate Values
q_{uc} (below the sheet pile tip)	[MPa]	11.3
q_{uc} (above the sheet pile tip)	[MPa]	1.5
$\sigma'_{3,max}$	[kPa]	1500
E_m	[MPa]	1418
GSI	[-]	35
m_i	[-]	9
D	[-]	0

The Young's modulus (E) was calculated using the formula given in equation (2) (Hoek, 2002).

$$E_m = \left(1 - \frac{D}{2}\right) * \left(\frac{q_{uc}}{100}\right)^{0.5} * 10^{\left(\frac{GSI-10}{40}\right)} \qquad (2)$$

4 CONVERSION OF HOEK-BROWN CLASSIFICATION PARAMETERS INTO MOHR-COULOMB PARAMETERS

The conventional calculations of the pile/ sheet pile bearing capacity as well as many other geotechnical engineering analyses (conventional and finite element) require Mohr-Coulomb parameters (cohesion and friction angle) as input, even though actual strength envelopes are often non-linear.

4.1 Calculation of equivalent Mohr-Coulomb parameters using RockData 5.003v software

An important feature of RockData software (Rockscience, RockData 5.003v) is the calculation of equivalent Mohr-Coulomb parameters for non-linear failure envelopes. The equivalent Mohr-Coulomb parameters are automatically calculated by determining a linear envelope, which provides a "best-fit" over a given stress range of a non-linear envelope. The results of the Mohr-Coulomb fit (cohesion and friction angle) are displayed in the data legend and on the failure envelope plots. For a given set of input parameters (q_{uc}, GSI, m_i and D), RockData calculates the parameters of the generalized Hoek-Brown failure criterion (m_b, s and a). The results of the analysis are given in Table 5.

Table 5 RockData results

RockData results	Best Estimate
E_{rm} [MPa]	161
Hoek-Brown parameters	
m_b	0.883
s	0.0007302
a	0.516
Mohr-Coulomb parameters	
φ' [°]	30.1
c' [kPa]	279

Where E_{rm} is the deformation modulus of the rock mass.

4.2 Calculation of equivalent Mohr-Coulomb parameters using the Palmstrøm Jv index and GSI.

The method proposed by Hansen and Foged (2002) and Foged and Stabell (2011) uses the Hoek-Brown failure criterion in combination with the geological strength index (GSI) and with the Palmstrøm Jv index. By using this method, a more realistic rock mass modelling of limestone has been established in Malmö and Copenhagen area. The method used to derive rock mass strength and deformation properties from element tests includes the density, induration, fracturing and weathering, evaluated taking in consideration sample disturbance from face logs and acoustic televiewer logging. In Fig. 7 and 8 are given the derived correlations between GSI - Jv and Jv – (Friction angle and Cohesion) (Foged, 2008). The calculated Mohr-Coulomb parameters are given in Table 6.

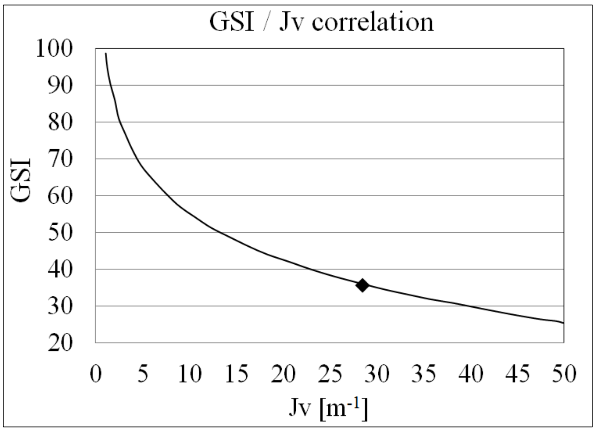

Figure 7 GSI – Jv correlation

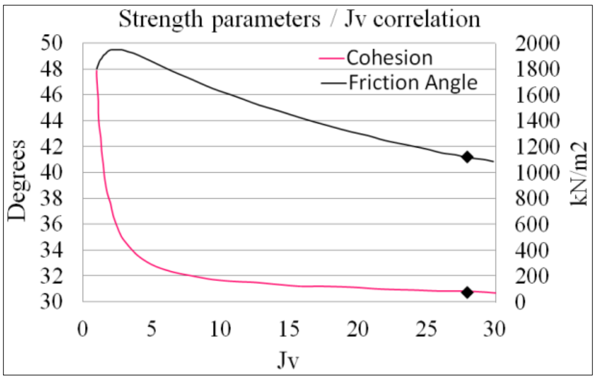

Figure 8 Mohr-Coulomb strength parameters versus Jv

Table 6 Equivalent Mohr-Coulomb parameters using the Palmstrøm Jv index

Hoek-Brown parameters	Best Estimate
GSI	35
Palmstrøm Jv index	
Jv [m^{-1}]	28
Mohr-Coulomb parameters	
φ' [°]	41
c' [kPa]	75

5 DESIGN OF BEARING CAPACITY - STRUCTURES SUPPORTED IN CHALK FORMATION

The derivation and interpretation of the rock mass (chalk) parameters (explained in the previous sections) is one of the most important step in order to design the structures that will be supported on this formation. All the conventional and finite element calculations for design of bearing capacity of piles/ sheet piles, footing or other structures require especially the converted equivalent Mohr-Coulomb parameters. Depending on the project and on the specific situation, the chalk formation may serve as a good foundation stratum for the installation of steel piles (circular, H-piles or end-bearing piles), sheet piles or shallow footing.

In this paper, an example of the calculation of the axial bearing capacity of sheet piles installed in chalk will be given. The use of sheet piles to support substantial vertical loads is a trend in today's installations and has been mentioned in previous publications since 1991 (McShane, 1991).

5.1 Conventional calculations of axial bearing capacity of sheet piles installed in chalk.

The calculation of the vertical load capacity of the sheet piles will be a combination of the mobilised shaft (side bearing capacity) and end-bearing resistance (tip resistance). In order to assess the contribution of each of the factors, both the side and the cross sectional area of the sheet pile must be assessed. For a chosen sheetpile section AZ 42-700N, the effective width of the sheet pile was estimated as B' =0.07 *h = 0.035 m (Iversen, Augustesen and Nielsen (2010)), where 'h' is the height of the sheet pile section.

The characteristic tip bearing capacity (R_{bk}) of the sheetpile is given from equation (3).

$$R_{bk} = q_k * B' \tag{3}$$

Where:

$$q_k = (c'N_c + p'N_q + 0.5\gamma B N_g s_g)/\xi \tag{4}$$

The term 0.5*γ*B*N_g*s_g is small compared with c*Nc and is neglected (Tomlinson, 2001). N_c, N_q are the bearing capacity factors according to Tomlinson (2001).

The design tip bearing capacity (R_{bd}) is given from equation (5).

$$R_{bd} = R_{bk}/(\gamma * K_{FI}) = R_{bk}/(1.3 * 1.1) \tag{5}$$

The characteristic shaft side bearing capacity (R_{mk}) is given from equation (6) according to Kulhawy and Phoon (1993).

$$R_{mk} = (\tau * L) * 2 \tag{6}$$

$$\tau = 1 * [0.1 * (q_{uc}/2)]^{0.5} \tag{7}$$

The design shaft side bearing capacity (R_{md}) is given from equation (8).

$$R_{md} = \frac{R_{mk}}{\xi * \gamma * K_{FI}} = \frac{R_{mk}}{1.5 * 1.3 * 1.1} \tag{8}$$

where:
L is the embedment of the sheetpile in the chalk layer.

Since the main focus of this paper is the assessment of chalk design parameters applicable to foundation design, the vertical bearing capacity of the sheet piles crossing the clay layer will not be discussed in this paper. The vertical bearing capacity of the sheet piles installed into the top weathered chalk with a considered embedment of about 2 m has been calculated for both derived equivalent Mohr-Coulomb parameters (using RockData software and Palmstrøm Jv index, respectively). The results are given in Table 7.

Table 7 Conventional calculations results – sheet piles installed in chalk

Design Bearing Capacity [kN/m]	RockData parameters (BE)	Palmstrøm Jv index (BE)
R_{bd} (tip)	83	81
R_{md} (shaft)	551	551
Total	634	632

There are no difference between the shaft resistances in the conventional calculations between the two methods. The most important factor affecting the side capacity (equation 7) is the q_{uc}, which is not affected by the Mohr-Coulomb parameters and is the same in both sets of parameters. The tip bearing capacity between the two methods are found to be similar because the terms c*N_c and p'*N_q compensate each other (for RockData parameters Nc=14, Nq=9.5 and for the parameters derived using Palmstrøm Jv index Nc =26, Nq=24).

5.2 2D Finite Element (FE) Analysis of sheetpiles installed in chalk

In section 5.1, the axial bearing capacity was calculated using conventional analysis and by taking into account both sets of equivalent Mohr-Coulomb parameters. In continuation of this, Plaxis 2D finite element analysis has been performed in order to analyse the vertical bearing capacity by use of numerical modelling. The model used in Plaxis 2D is shown in Fig.9. In order to take into account both tip and shaft resistance, the sheet pile is modelled as solid wall element with a thickness of 35 mm. A plate element with same section properties as the sheet pile has been inserted inside the solid element in order to derive the internal forces. The sheet pile has been considered embedded about 2.1 m into the chalk. Plaxis 2D plain strain analysis has been performed.

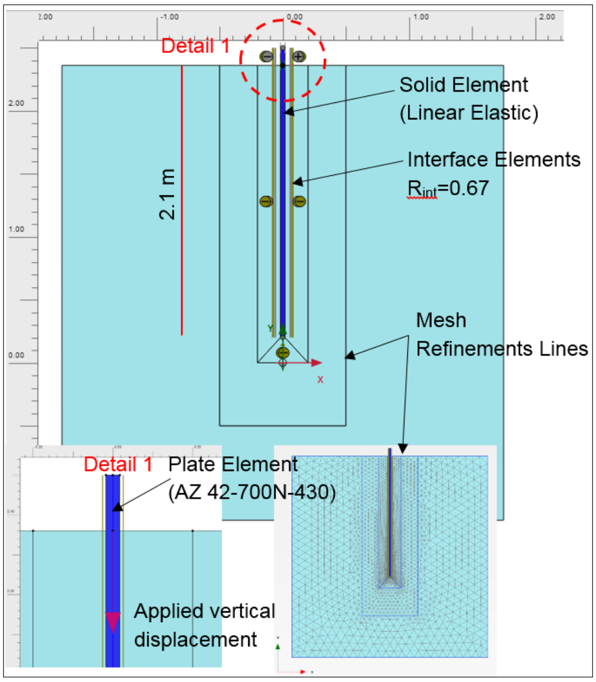

Figure 9 Plaxis 2D FE Model

The size of the model has been chosen in order to avoid any boundary conditions effect. The 15 nodes finite element analysis used in Plaxis 2D are known to give accurate results for the analysis of the foundation vertical capacity. Mesh sensitivity analysis has been performed in order to define the required mesh refinements, especially at the vicinity of the sheet pile. In order to take into account the effect of limestone disturbance during installations, interface elements are used in both sides by reducing the strength by 33% (R_{int}=0.67). The sheet pile is pushed down by applying a vertical force and the measured reaction as function of penetration represents the axial load capacity. By keeping the same model geometry and only changing the soil parameters, the following analyses have been conducted:

- Mohr-Coulomb parameters (φ' and c') determined by Hoek-Brown classification parameters and converted using RockData software (Table 5)
- Mohr-Coulomb parameters (φ' and c') determined using Palmstrøm's Jv index (Table 6)

As an alternative to the above models, another model has been analysed using directly Hoek-Brown parameters (best estimate and upper bound parameters) available in Plaxis 2D. The results from Plaxis 2D are summarized in Table 8.

Table 8 Results from Plaxis 2D FE –Design vertical capacity of sheet piles installed in chalk [kN/m]

MC model (Rock Data parameters)	MC model (Palmstrøm's Jv parameters)	HB model (best estimate/ upper bound parameters)
R_{cd}=807	R_{cd}=412	R_{cd}=(198/410)

In Fig.10 is shown a plot of the total displacements from the Mohr-Coulomb model with Palmstrøm's Jv parameters.

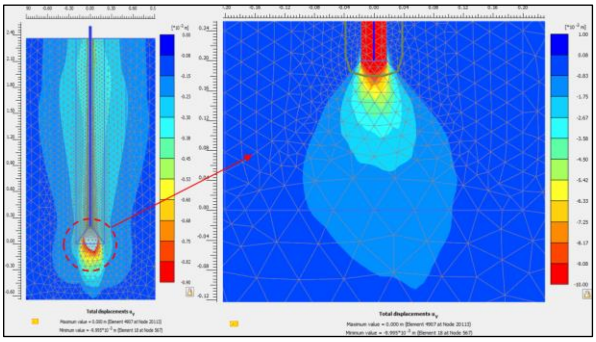

Figure 10 Total displacements u_y (model with Palmstrøm's Jv parameters)

5.3 Conclusions

In this paper, practical guidelines in selecting design parameters of some Danish chalk are given. A direct interpretation of the geotechnical borehole has been carried out. The selection of Hoek-Brown parameters for the available samples as well as calculations of the equivalent Mohr-Coulomb parameters have been explained and analysed in details. Two methods have been presented with regards to the calculation of the Mohr-Coulomb parameters for design purposes. As an example illustration for the application of the derived parameters, the vertical capacity of sheet piles installed in chalk has been analysed conventionally and by use of finite element analysis (Plaxis 2D). The results show that the equivalent Mohr-Coulomb parameters derived using the Palmstrøm's J_v index method look more realistic with regards to assessment of the sheet piles vertical capacity. The results from FE analysis using directly Hoek-Brown parameters show a vertical capacity to the range of the MC model derived by use of Palmstrøm's J_v index method. The equivalent MC parameters derived using RockData (based on Hoek-Brown criterion) are found to overestimate the capacity. The results of this study are in line with the conclusions derived by Foged (2008), with regards to the establishment of a more realistic model of the limestone. However, there are still many uncertainties related with the assessment of the design parameters of the limestone (chalk) and involving engineering subjective estimation of the drilling disturbances, lack of investigations and laboratory tests etc. A more extensive and comprehensive research is needed to reduce the uncertainties of the chalk formations used as foundation stratum.

6 REFERENCES

Bieniawski, Z. T. (1989): Rock Mass Rating System.

Foged, N. (2008): Rock Mass Characterization in Limestone, Ingeniørgeologisk Fjeldklassifikation, Foredrag i Dansk Geoteknisk Forening 2008-04-24.

Foged, N., Stabell, S. & Foged, B. (2011): Rock mass characterization for tunnels in limestone in Copenhagen and Malmö area, Proceedings of the 15th European Conference on Soil mechanics and Geotechnical Engineering.

Hoek, Evert et. Al. (2002), Hoek-Brown Failure Criterion – 2002 Edition.

Kryger Hansen, H. & Foged, N. (2002): Kalkens bjergmekaniske egenskaber, DGF-Bulletin 19.

Kulhawy, F. H. and Phoon, K. K. (1993): Drilled shaft side resistance in clay soil to rock. Proc. Conf. on Design and performance of Found.: Piles and Piers in Soil and Soft Rock. Geotechnical Special Publication No. 38, ASCE, 172-183.

Marinos. P & Hoek. E (2000), GSI: A geologically Friendly Tool for Rock Mass Strength Estimation.

McShane, G (1991), Steel sheet piling used in the combined role of bearing piles and earth retaining members, Proceedings of the 4th International Conference on Piling and Deep Foundations, STRESA, Italy, 7-12 April 1991.

Palmstrøm, A. (2005): Measurements of and correlation between block size and rock quality designation (RQD). Tunnel and Underground Space technology, 20: 363-377, 2005.

Plaxis 2D AE Version 2014.00. Finite Element Code for Soil and Rock Analysis. Delft University of Technology & Plaxis b.v. The Netherlands.

Rock Data 5.003 v (2014), Rockscience software.

Tomlinson, M. J. (2001): Foundation and Construction, 7th edition, Printice Hall.

Zang, L. (2004): Drilled Shafts in Rock, A.A. Balkema Publishers.