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Characterization of Rock Fracturing for Vertical Boreability

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Abstract

Boreability can be defined as the ability of a bore to penetrate a rock mass. Understanding the factors influencing boreability is critical for enhanced project planning and reduce geotechnical risk in an offshore shaft boring environment. Large diameter drills are used for offshore shaft boring, which can be up to 7 m in diameter, and therefore more akin to tunnel boring machines due to the scale of the excavation and extent of ground interaction. With increases in bore diameter, there is a need to properly define and evaluate the effect of the degree of rock mass fracturing on machine performance for improved estimates of boreability. Discrete Fracture Network (DFN) simulation has been used as an innovative approach for stochastic realisation of rock mass fracturing by determination of the P_{32} volumetric fracture intensity in the context of boreability. P_{32} shows positive trend to specific penetration (SP), with maximum SP being achieved at moderate to high fracturing levels (20 - 25m^{-1}). However, in this case, P_{32} shows a similar positive trend to $P_{10,}$ but with peak SP appearing at higher intensity levels. Increased RQD values result in reduced SP, with peak SP reached at moderate fracturing levels, similar to P_{10}.

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Keywords: Boreability; Offshore Drilling; Discrete Fracture Network;

1. Introduction

Boreability is defined as the ability of a machine to penetrate a rock mass [1], and is commonly associated with Tunnel Boring Machines (TBM). The development of offshore shafts, Large Diameter Drills (LDD) are utilized, which feature similar tools or technology to that of oil well drilling with reverse circulation system for muck removal. The size and scale of ground interaction can be up to seven meters, making these type of LDD's more akin to tunnel

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boring machines due to their scale. Little research has been undertaken on the performance or boreability of LDD's when compared to evaluation of TBM behavior. Given that the underlying excavation process and ground interaction tools differ between LDD and TBM machines, TBM performance can only therefore be used as a proxy rather than direct comparison.

Research at the Camborne School of Mines is currently evaluating existing empirical boreability models for LDD's, and how they can be used to inform and help minimize geotechnical risk for offshore shaft developments, such as offshore windfarm monopole sockets. This paper presents some initial findings of how three rock core-derived fracture metrics correlate with recorded machine penetration rates for a LDD, for future use within a full boreability model.

2. Degree of fracturing

Boreability, as a variable, is related to the properties of the rock mass and machine specification [1]. Various models, from simple to multi – parametric models, have been produced for TBM's. Farrokh et al. [2] provides a good overview of the models available. Common to all of these models are some measure of rock mass fracturing. Wanner and Aerberli [3] found that fractures from shearing influenced the productivity of borers. Howarth [4] found that moderately fractured rock improved machine performance. Zhao et al. [5] found that an increase in fracture spacing (reduction in fracture frequency) lead to a reduction in productivity, with maximum productivity attributed to a relative joint strike of 60 degrees to the tunnel axis. Macias et al. [6], however, found a negative correlation with the rock mass fracturing factor (k_s).

In view of limited rock exposure in an offshore drilling or boring environment prediction of machine performance is typically based on evaluation of rock core and geophysics data. This limits estimates of the degree of fracturing of the rock mass and is constrained to measures such as the Rock Quality Designation and Fracture Frequency.

Traditionally, RQD is used as the standard for classifying the degree of fracturing of the rock mass [8], and is a key parameter in most stability-centric rock mass classification schemes such as the Geomechanics Rock Mass Rating [7] and the NGI Tunneling Quality (Q) Index [8], as well as inputs into existing boreability or TBM-related models [9, 10]. RQD is a relatively simple measure to determine, but its simplicity may lead to some disadvantages. These include the apparent rapid change in RQD when sub-parallel fractures are spaced in a range close to the cut off threshold [11], as well as the non-additive properties of RQD for combined databases [12]. The later issue becomes apparent when the axis of the excavation is different to that of the site investigation, such as with the utilization of the QTBM model developed by Barton [9].

Fracture Frequency is a measure of Fracture intensity and is defined as the number of fractures within a given interval. There are three main forms of fracture intensity, which differ by sample and measurement dimensionality. These different forms have been concatenated into the P_{ij} system by Dershowitz and Herda [13]. Within this system, P means 'persistence', with the following subscripts denoting sample dimension and measurement dimension respectively, as shown in table 1. Note that 'fracture intensities' are highlighted in red within table 1.

Table 1. Summary of Fracture Intensity Measures [13].

	Measurement Dimension (j)			
Sample Dimension (i)	Count (0)	Length (1)	Area (2)	Volume (3)
1D (borehole)	**P_{10}**	P_{11}	-	-
2D (mapping)	P_{20}	**P_{21}**	P_{22}	-
3D (geophysics)	-	-	**P_{32}**	P_{33}

Given the form of data available for this study, only P_{10} and P_{32} are used in the subsequent analysis. Fracture intensity in its simplest form is defined as the number of fractures per meter, a one-dimensional measure, which is historically referred to as Fracture Frequency, or P_{10} under the P_{ij} system, and has the dimensions of:

$$[P_{10}] = [m^{-1}] \tag{1}$$

This measure, as with RQD, has the disadvantage in that its directional dependence is based on the angle of the fractures relative to the sampling line [13]. To avoid referencing to any specific set or orientation, a three-dimensional fracture frequency can be used, named P_{32} under the P_{ij} system. P_{32} is defined as the fracture area per given rock volume, with the following dimensions:

$$[P_{32}] = \frac{[m^2]}{[m^3]} = [m^{-1}] \tag{2}$$

P_{32} has been widely used for rock mass characterization studies [14] and noted by Wanner and Aeberli [3] as having a significant positive effect on the performance on tunneling machines. However, one of the issues with P_{32} within this context is that it cannot be directly measured from core, and has to be determined from either P_{10} or P_{21} measurements by an analytical solution or by simulation, such as with a Discrete Fracture Network model (DFN) [14]. DFN is a stochastic model or representation of a fracture network. This approach takes basic fracture properties, such as location, orientation, size and intensity and treats them as random variables with inferred probability distributions. The advantage of this method is the retention of fracture properties throughout the entire process [15]. FracMan, developed by Golders FracMan Technology Group [16], is a proprietary software package for the creation of DFN's for subsequent rock mass characterization and hydrogeological modelling. FracMan has been used as part of this research for determination of P_{32}.

3. Case study overview

The case study data was kindly provided by Fugro Geoservices Limited (FGSL), formally operating under '*Fugro Seacore*'. The case study focuses on the establishment of a 63 m deep, 5.85 m diameter shaft as part of the Flamenville Nuclear power plant upgrade in 2008 [17]. The shaft was bored using a newly designed rig, the Teredo 90 (T90). The site investigation phase was conducted by three site investigation boreholes (BH1 to BH3), collared on a triangular pattern over the proposed shaft location.

The project area was situated offshore to the west of the Flamenville Granite, within the Sioville Syncline. The syncline has been classed as a plunging inclined fold with an ENE-WSW axial trend, verging towards the SE [18]. The lithological units comprise of a recrystallized Hornfel from a fine-grained carbonate protolith, presumed to be a limestone. Rock samples were taken for Uniaxial Compressive Strength testing, with strengths ranging between 20–150 MPa, and densities between 2.77 to 2.88 Tm^{-3}.

Fracture data was derived from a borehole acoustic televiewer (BHTV) survey. Analysis of this data showed that four distinct fracture domains, showing relatively consistent fracture intensity, can be applied (Fig. 1). The domains appear to correlate well between boreholes, with domain boundaries decreasing in depth from BH1 to BH3. The collared locations and the relative depths of domain boundaries indicate or suggest a south-easterly dipping structural control, synonymous with the regional syncline. These domains form the framework for fracture analysis, and subsequent DFN generation.

Stereographic analysis of the BHTV data within each fracture domain was carried out to identify fracture sets (Fig. 2). Three joint sets were common for each domain. The most dominant set is a low angle set dipping to the south-east, interpreted as bedding structures. In addition, a conjugate set was also identified, comprising a steeply dipping set dipping to the N-E / S-W and N-W / S-E respectively. Additional minor sets were found within each fracture domain in varying proportions.

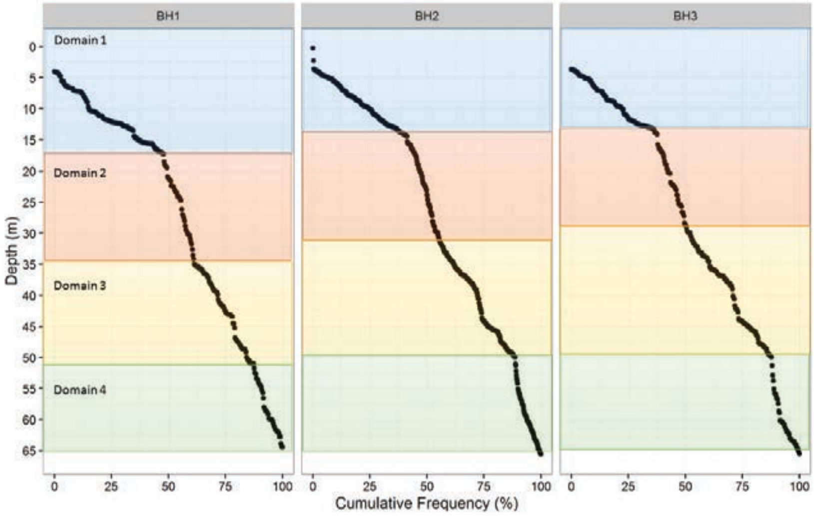

Fig. 1. Constant Fracture Intensity Domain (CFI) identified for each borehole. Domains are coloured for clarity.

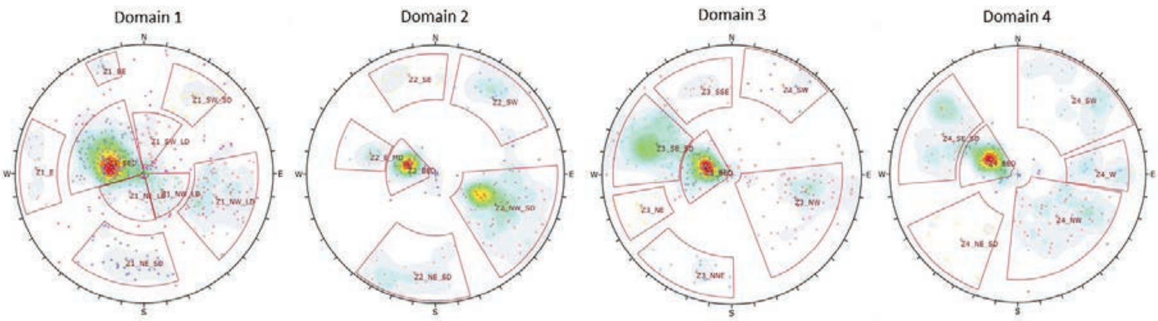

Fig. 2. Fracture Set Analysis for each Fracture Domain.

3.1. RQD and P_{10} determination

Determination of the degree of fracturing within the proposed shaft is derived from the BHTV data over 1 m intervals, with intervals bounded to the integer depths for ease of analysis. Both RQD and P_{10} were determined by averaging the values from each SI hole. Fig. 3a shows the average RQD as a function of depth. Four distinct regions of RQD values were identified, with high and relatively low RQD values respectively. These regions appear at different depths within the three SI holes. While not as well defined as in Fig. 1, there is evidence of a south-easterly dipping control on RQD values. P_{10} values were determined in a similar fashion to RQD. Fig. 3b shows how the P_{10} values vary according to depth. As with the RQD determinations, a total of four domains are apparent within the data. An outlier is present within region 12, showing consistent P_{10} values within each of the SI holes, in excess of 25.

3.2. P_{32} determination

P_{32} values were determined by discrete fracture network simulation using the code FracMan [16]. Fracture intensities are used to control the amount of the fractures to generate within the model. Since this model generates multiple joint sets, the P_{10} was weighted by the proportion of fractures attributed to each set. As P_{10} values vary for a single set between SI holes, the average P_{10} value was used to limit fracture generation. Fracture orientation characteristics were taken from the stereographic analysis. Fracture locations are determined using the Modified Baecher model [19]. Fracture size relates to the persistence of the generated fractures. Since rock mass information is constrained to rock core, it was not possible to directly observe persistence. However, observations of the near shore rock outcrop showed that fracturing within the rock mass can be estimated from a negative exponential distribution with a mean persistence of 10 m. Whilst this cannot be directly correlated to the project area, the data are considered indicative or representative of fracture size [17].

To sample the stochastically generated DFN for P_{32}, cylindrical sampling regions were established with a diameter of 5.85 m, and depth of 1m. These sampling regions were bounded to the integer depths to allow comparison to borehole-derived RQD and P_{10}. A total of 50 DFN iterations were completed, with P_{32} determined for each iteration in order to capture the variation in discrete fracture generation. Fig. 3c shows the resultant mean P_{32} distribution from the DFN models generated.

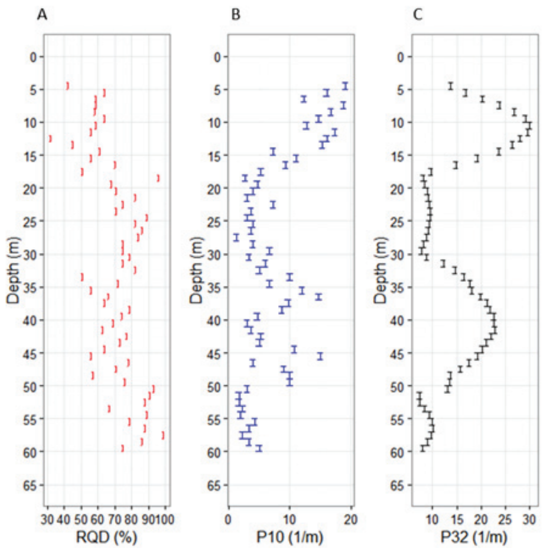

Fig. 3. (a) RQD, (b) P_{10} and (c) P_{32} determinations within the shaft.

3.3. Comparison of rock quality indicators to Penetration Rate

Specific Penetration (SP) has been used to provide the basis for boring performance. This is determined as the penetration per revolution divided by the total force provided by each cutter on the rock face. This provides a basis for future comparison to different LDD machines and site data [20].

To show the comparison of the different fracture measures on SP, a scatter matrix has been created (Fig. 4). The fracture domains (1 to 4) for each data point is indicated to give context of relative depth. An additional domain, marked as 'T', indicates the data point is located within a transition zone. These zones arise due to the intersection of a vertical shaft with dipping fracture domains, resulting in zones of mixed fracture domains, potentially altering SP. A Locally Weighted Scatterplot Smoothing (LOWESS) line has been added to each plot for observational ease.

The bottom row of matrix shown in Fig. 4. Shows the correlations between SP and the various fracture measures. RQD shows a negative trend to SP, with a wide range of SP for mid to low RQD values, in keeping with the TBM observations of Howarth [4]. RQD in excess of 90% show a consistently lower values of SP, where domains 2 and 4 dominate. P_{10} shows an approximate positive linear trend with SP, with highest variance located between 6 – 8 m^{-1}, indicating a similar relationship to RQD. P_{32} shows a similar linear trend than P_{10}. However, while P_{10} (and RQD) both indicate peak SP at moderate fracturing levels, P_{32} shows peak SP to be at a higher end of fracturing between 20 – 25 m^{-1}. This elevated fracture intensity highlights the increased fracture intensity from sub-vertical fractures, which can potentially be under-represented by P_{10}. P_{32} also shows an interesting feature of tighter domain groupings relative to the other fracture measures. Whether this is due to the hard domain boundaries used, still remains unclear.

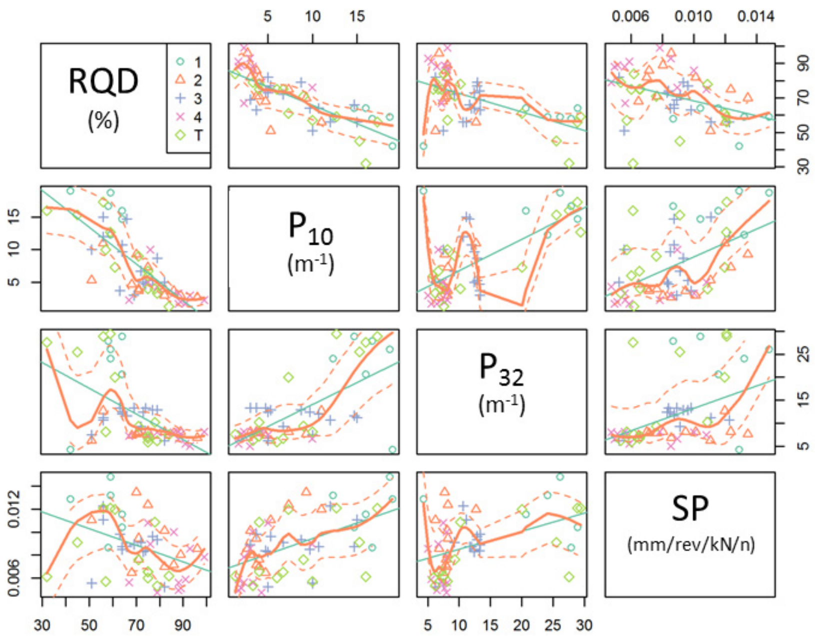

Fig. 4: Scatter matrix of different fracture measures against specific penetration rate for each fracture domain.

Results suggest that, in most instances, an increase in fracturing leads to an increase in SP. All fracture measures appear to have a point which can be classed as the local SP maxima, with decreasing productivities being observed either side, agreeing with previous observations of tunnel boring machine performance [3, 5]. Zhao et al [5] noted that fracturing at 60° relative to the shaft axis improves performance. Domains 1 and 3 contain the most intense amount of sub-horizontal fracturing, forming an acute angle between 60° and 80° relative to the bore axis. This can help explain the apparent increase in SP.

Conclusions

Using data from the Flamenville case study, three different fracture measures; RQD, P_{10} and P_{32} have been compared to machine performance using Specific Penetration (SP) for a large diameter bored shaft. Discrete Fracture Network (DFN) simulation has been used as an innovative approach for stochastic realisation of rock mass fracturing by determination of the P_{32} volumetric fracture intensity in the context of boreability. However, in this instance, mean P_{32} shows a close association with P_{10}, potentially due to the dominating fracture set being sub-perpendicular to the shaft and SI bore holes. All fracture measures indicate that moderate fracturing (50-60% RQD, 6 - 7 m^{-1} P_{10}, 20-25 m^{-1} P_{32}) improve SP. Incorporating the stochastic properties of P_{32} is currently underway, and may improve the usefulness of P_{32} within the context.

Further work is being undertaken to adopt the rock mass characterization approach to incorporate further case studies with varying rock mass parameters and machine performance parameters. This will provide a basis for improved understanding of factors controlling boreability and provide a basis for improved predictive capability of machine performance in large diameter offshore drilling operations.

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