SPUDCAN PENETRATION INTO ROCK

J. Irvine*, P. Stephenson and C. Jaeck
Cathie Group

** corresponding author: Jamie.irvine@cathiegroup.com*

ABSTRACT
Recent experience has shown that a significant number of construction projects are being planned for areas with rock at shallow depth. There is currently limited guidance regarding the penetration of spudcans into weak rock meaning penetration range and risks may not be well understood.

The aim of this paper is to propose a new approach for estimating penetration resistance based upon rock strength (Uniaxial Compressive Strength) and weathering/fracture profile (Geological Strength Index) and a comparison with available field penetration data. A better understanding of the penetration resistance in weak rock has the potential to better understand potential risks including high point loads on the spudcan, rack phase difference and high extraction loads.

KEY WORDS: Spudcan penetration, rock

INTRODUCTION

Offshore renewable energy developments are expanding in size and are being planned in deeper waters with more challenging ground conditions than their predecessors. The authors have worked on a number of projects where weak rock is anticipated to be present near to the seabed level including in France, northwest Scotland, Japan, Spain, Korea and more. Shallow rock is often also a common feature at wave and tidal development areas and for port and harbours.

There is currently limited guidance regarding the penetration of spudcans into weak rock meaning penetration range is uncertain and risks may not be well understood. The aim of this paper is to propose a methodology to better predict penetrations in weak rock and to propose a framework to understand and mitigate potential risk.

EXISTING PRACTICES

ISO 19905-1 (2016) [1] recognizes that ‘hard sloping strata’, rock pinnacles, reefs, etc can pose a risk to spudcan due to the potential for partial spudcan penetration and resultant eccentric loading on the spudcan which can lead to extraction and removal difficulties.

The codes ISO 19905-1 (2016) [1] and SNAME (2008) [2] recommend equations for bearing capacity in sand and clay and provide background references for considering cemented carbonate sands. However, no specific guidance is provided for the assessment of bearing resistance of rock.

The lack of established guidance means that rock is often modelled as a cohesionless soil with a high friction angle (>40deg) or a cohesive soil with a high undrained shear strength (often using su = 0.5*rock Uniaxial Compressive Strength (UCS)). However, rock masses are typically heterogeneous media composed of rock material and naturally occurring discontinuities such as joints, fractures and bedding planes. Modelling rock as a cohesionless material will tend to underestimate bearing capacity (penetration resistance) as it doesn’t account for the intact rock strength. However, modelling the rock as a cohesive material could tend to overestimate the bearing capacity (penetration resistance) especially in weathered rock as it doesn’t allow for the discontinuities which reduce the rock mass strength and stiffness.

ROCK CHARACTERISATION

The key characteristics which can influence the behaviour of the rock mass are considered to be:

- Rock type, grain size, mineral composition and moisture content.
- Intact rock strength usually measured as uniaxial compressive strength.
- Rock weathering profile:
    - Rock mass strength and condition including rock discontinuity (joints, fractures, bedding planes) distribution, frequency and orientation.
    - Condition of joints in the rock mass including surface roughness and the nature of any infill material.

There are a number of semi quantatitive frameworks that are used to provide an estimation of rock mass behaviour, one of which is the Geological Strength Index (GSI) [3]. This framework has been used as a key parameter within this paper and is described in further detail in the section below.

It is noted that the strength and condition of weak rock masses can vary significantly, which can result in difficulties selecting appropriate lower and upper bound strength parameters. A pragmatic approach to parameter selection is often required to allow the realistic assessment of the risks associated with jacking operations in such ground conditions.

Hoek and Brown (1997) [3] introduced the Geological Strength Index (GSI) to describe both hard and weak rock masses. Experienced field engineers and geologists generally show a liking for simple, fast, yet reliable classification systems which are based on visual inspection of geological conditions. Hoek and Brown proposed such a practical classification for estimating GSI based on visual inspection alone. In this classification, rock mass structure and joint surface condition are assessed against five qualitative classifications which were combined to estimate a GSI index value between 0-100, with poor quality heavily weathered/fractured rock having very low values and better quality largely intact rock masses having values up to 85-90.

Geological Strength Index (GSI) [3][4][5] logging should be undertaken by qualified and experienced geologists or engineering geologists on the basis of rock mass observations. However, frequently this data is not available, therefore, it may be necessary to estimate GSI based upon ground investigation data. Hoek et al (2002) provides a method for this based upon the Rock Quality Designation (RQD) and Joint Surface Conditions (Jcon89) measured visually from core samples.as shown in Figure 1.

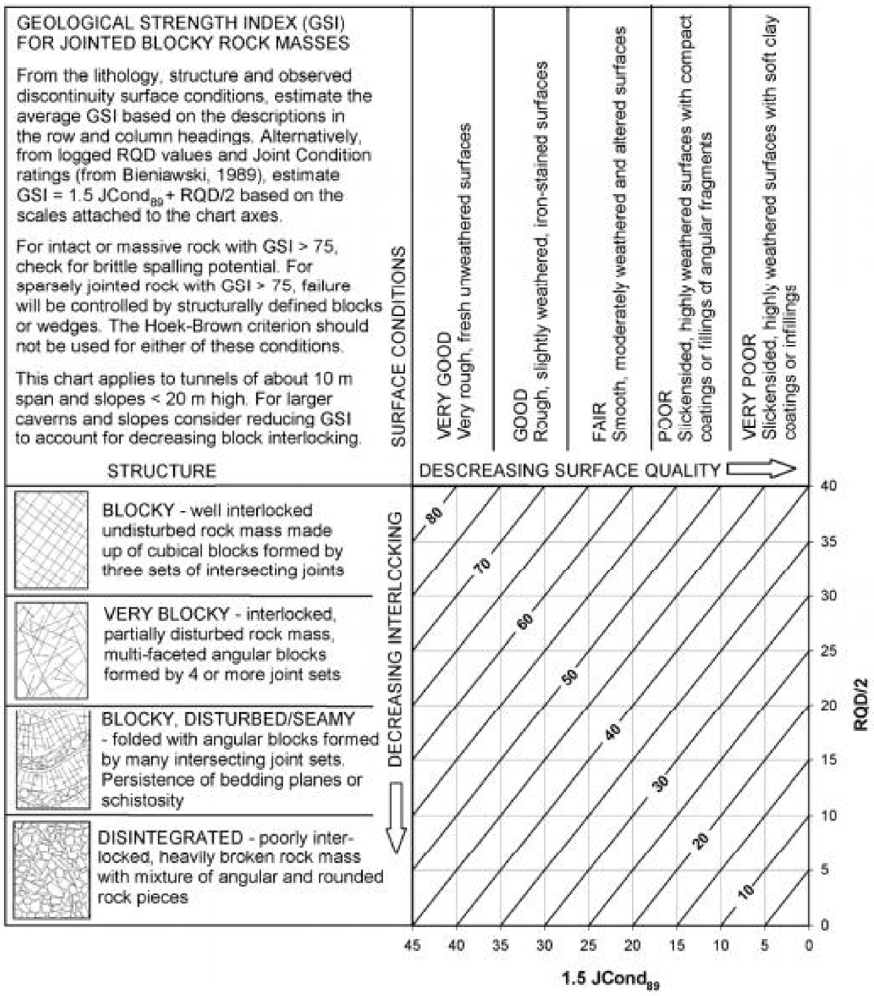
Rock Mass Strength Characteristic

The Hoek & Brown methodology [3][4][5] can be used to estimate the effective strength (cohesion) and friction angle for a rock mass based upon the following key parameters:-

- Rock type (and associated Hoek Brown Intact Rock Parameter m_i),
- UCS and GSI
- Level of disturbance (defined by parameter D)
- Stress level.

For details of the full formulations of this assessment refer to Hoek & Brown methodology [3][4][5]

Figure 1: GSI Chart [Extract Ref]

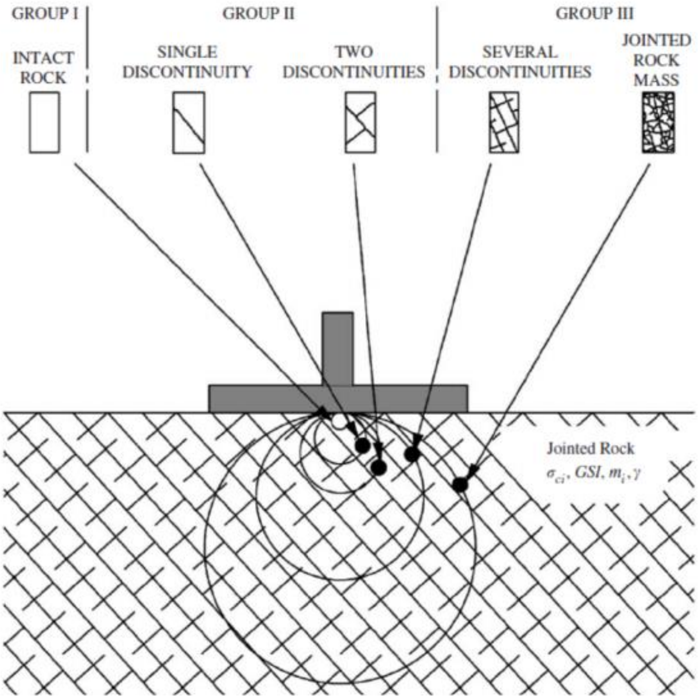


BEARING CAPACITY OF SHALLOW FOUNDATIONS IN ROCK

Merifield et al. (2006) [7] investigated the bearing capacity of shallow foundations in Hoek-Brown rock masses through numerical analysis. The problem of a spudcan penetrating in rock can be solved as a bearing capacity problem where penetration stops if the vertical load equals the bearing capacity. This is analogous to jack-up spudcan penetration theory SNAME, 2008 [2] and ISO 19905-1, 2016 [1], particularly for undrained clays, however, Merifield proposes reduced bearing capacity factors which allow for the pre-existing failure planes such as joints or discontinuities.

The ultimate bearing pressure depends on the UCS, GSI, rock submerged unit weight and the Hoek-Brown Intact Rock Parameter (m_i).

Figure 2: Vertical bearing capacity on jointed rock masses (Merifield et al., 2006)



The ultimate bearing pressure can be derived from UCS and Nσ as shown in Equation 1.

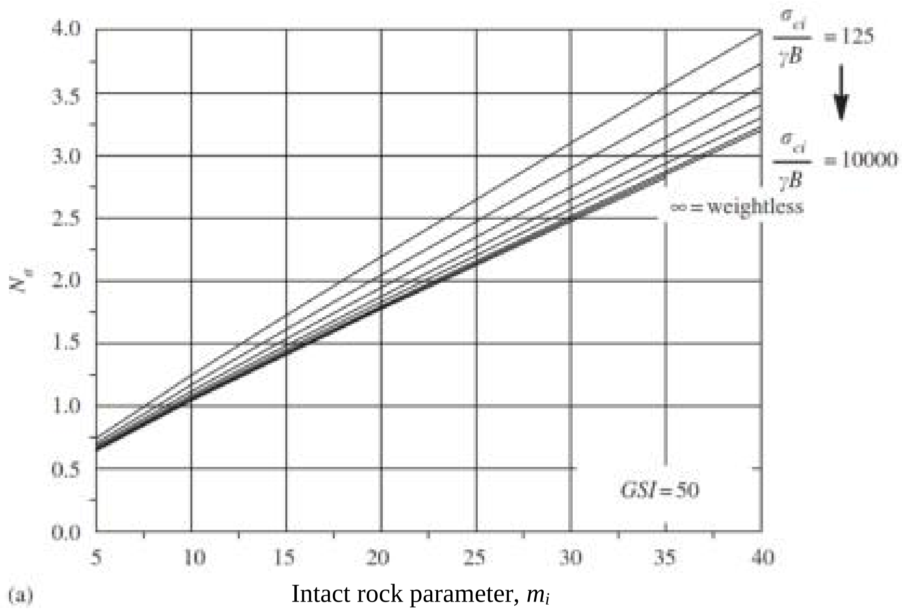
$$q_u = \sigma_c N_\sigma \qquad \text{Equation 1}$$

where:

q_u	=	Ultimate bearing pressure;
σ_c	=	Unconfined compressive strength (UCS);
N_σ	=	Bearing capacity factor from a series of graphs (example below).

Merifield et al. (2006) derived bearing capacity factors (Nσ) for various combinations of the above parameters as shown below.

Figure 3: Merifield et al. (2006) – Example bearing capacity factors (for GSI=50)



For spudcan foundations, the ultimate vertical capacity can be calculated using the cross-section area at mudline. As this area often increases with embedment due to the shape of a spudcan, the vertical bearing capacity will also increase.

SPUDCAN PENETRATION INTO ROCK

Three possible methods have been used for assessing spudcan penetration into rock in this paper :-

- Use of standard ISO 19905-1, 2016 [1] methodology modelling the weak rock as a clay material with a undrained shear strength equal to 0.5*UCS.
- Use of the Merrifield et al (2006) [7] method to assess the ultimate bearing capacity in the weak rock at regular depth intervals to account for increasing spudcan area.
- The calculation of effective cohesion from Hoek & Brown methodology [3] and the use of standard ISO 19905-1, 2016 [1] cohesive (clay) soil methods. This is noted to be conservative at higher stress levels.

This is discussed further in the following example case studies.

EXAMPLE PENETRATION CASE STUDIES

Case 1 – Extremely weak to weak mudstone

A nearshore development where bedrock was encountered near seabed. The bedrock was described as:

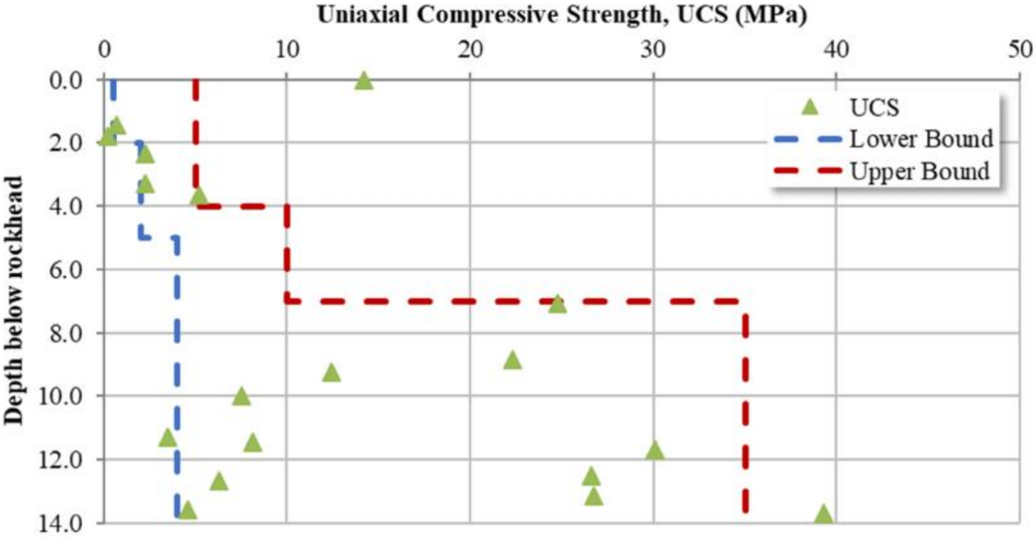
Extremely weak to weak, locally medium strong, fissile, indistinctly and thinly laminated, weathered becoming fresh to slightly weathered with depth, calcareous MUDSTONE. Fractures are extremely closely to closely spaced, horizontal, planar and smooth locally infilled with clay. Occasionally interbedded with medium strong to strong LIMESTONE.

Uniaxial Compressive Strength (UCS) values at shallow depth (<5m) ranging from 0.5 to 5MPa, see Figure 4. No Geological Strength Index (GSI) data was available, however, the Rock Quality Designation (RQD) was noted to range from 10% to 60% at shallow depth. The Joint Surface quality (JCond) was considered to range from Poor to Very Poor based upon the available descriptions, this would indicate a GSI ranging from 10 to 40. A summary of the lower bound and upper bound assumptions about rock mass strength are given in Table 1

Table 1 – Case Study 1 Lower and Upper Bound Rock Mass Strength Assumptions

Parameter		UCS	GSI	Rock mass strength, Su	Intact rock parameter, m_i
Lower Bound	0 to 2m	0.5MPa	10	87kP	10
	2 to 5m	2MPa	20	113kPa	
Upper Bound	0 to 5m	5MPa	40	171kPa	10

Figure 4: Case 1 - UCS Data

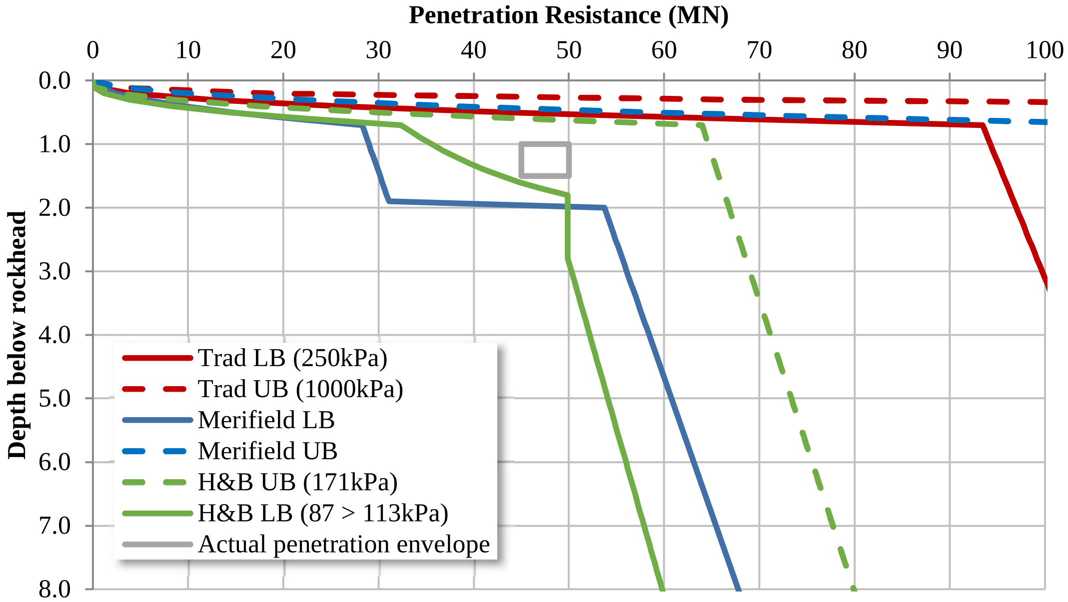


The spudcans projected area was ~60m^2 with a preload of ~50MN. The leg penetration assessments were undertaken using the 3 methods discussed above and the results are shown in

Figure **5**. These indicated the following:

- The traditional use of an undrained shear strength based upon 0.5*UCS tends to significant underestimate spudcan penetrations.
- The use of the rock mass shear strength derived using Hoek & Brown criteria with the conventional ISO methodologies (for clay capacity, and layering effects) gives a close match.
- The use of the Merifield method gives a slightly wider envelope than the Hoek & Brown assessment and the simplified rock strength model does not account for potential layer interactions (i.e. mobilizing strength of underlying ‘hard’ rock layers). No disturbance to the rockmass below the spudcan was allowed for in the calculations.

Figure 5: Case 1 – LPA Results



Case Study 2 – Weak to medium strong Limestone

A nearshore development where bedrock was encountered near seabed. The bedrock was described as:
Weak to medium strong LIMESTONE

Uniaxial Compressive Strength (UCS) values at shallow depth range from 5 to 25MPa. Again no Geological Strength Index (GSI) data was available, therefore RQD and JCond were used to estimate the GSI which ranged from 20 to 60. A summary of the lower bound and upper bound assumptions about rock mass strength are given in Table 2.

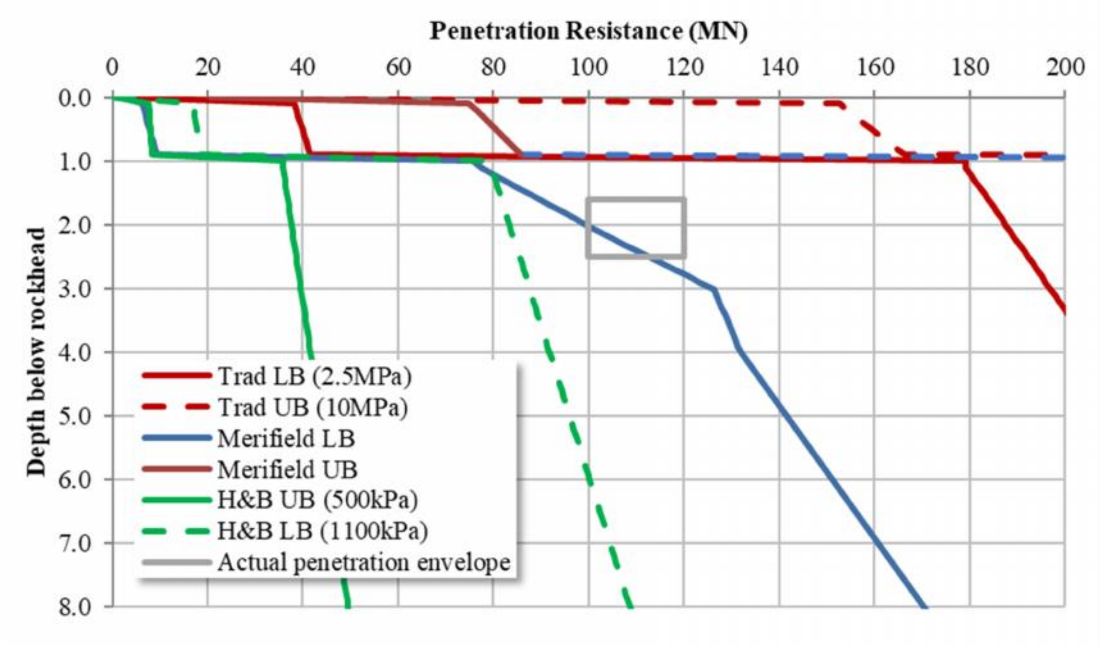
Table 2 – Case Study 2 Lower and Upper Bound Rock Mass Strength Assumptions

Parameter	**UCS**	**GSI**	**Rock mass strength, Su**	**Intact rock parameter, m_i**
Lower Bound	5MPa	20	500kPa	10
Upper Bound	20MPa	60	1100kPa	10

The spudcans projected area was ~12m^2 with a preload of ~120MN Leg penetration assessments were undertaken using the 3 methods discussed above and the results are shown in Figure 6. These indicated the following:

- The traditional use of an undrained shear strength based upon 0.5*UCS tends to significant underestimate spudcan penetrations
- The use of the rock mass shear strength derived using Hoek & Brown criteria with the conventional ISO methodologies tended to over predict penetrations.
- The use of the Merifield method gave the closest match, however, still slightly under predicted penetrations

Figure 6: Case 2 – LPA Results

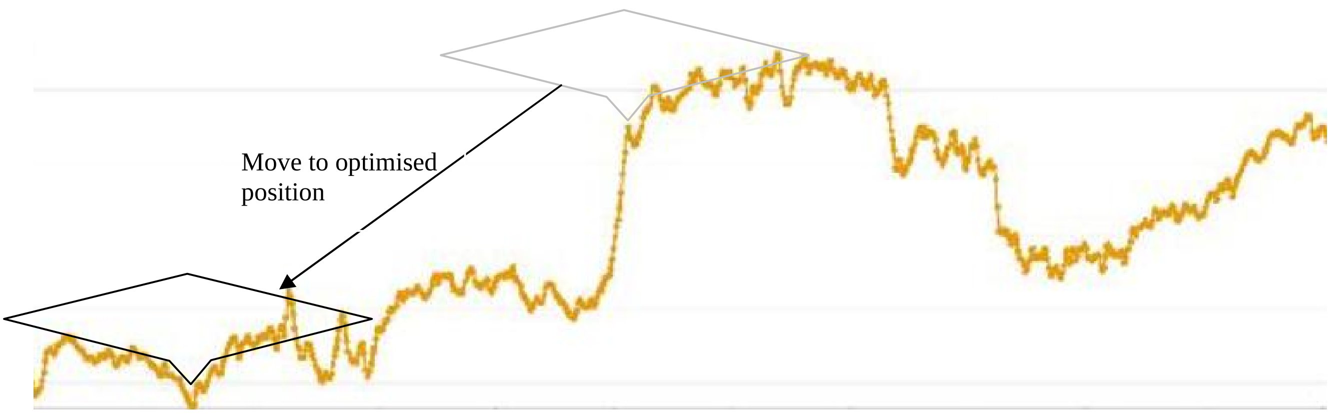


JACKING RISK ASSESSMENT AND MITIGATION MEASURES

Localised bathymetric highs, slopes and/or boulders could result in reduced spudcan contact, see Figure 7, localized point loading or eccentric loading on the spudcan. It is recommended that high resolution bathymetry (or sub-bottom for shallow rockhead) is combined with an understanding of the anticipated penetration depths to allow the jacking location to be microsited to avoid potential issues.

The ’breaking point’ of localized highs identified by the data can be assessed to understand the potential risk to the spudcan and allow appropriate risk mitigation to be allowed for. For instance small, local weak pinnacles may break under the spudcan leading to low risk. However, larger, high strength pinnacles may pose a risk to the structural integrity of the spudcan resulting in the requirement to install gravel beds at seabed level to provide a level platform for spudcans.

Figure 7: Indicative bathymetry cross section



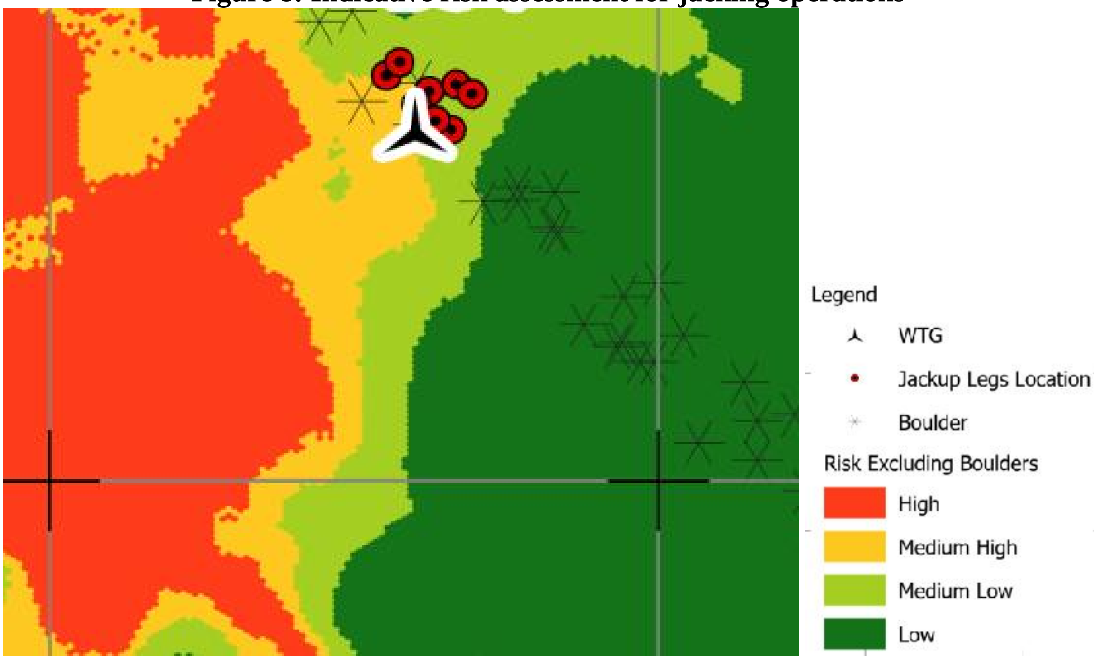
The understanding of the bearing capacity of the rock can also be used to inform the design of spudcan modifications such as rock tips to ensure reasonable penetrations and fixity to reduce sliding risk and/or base reinforcements to reduce risk of damaging the spudcan.

Regions with exposed rock also frequently have a significant number of boulders. These are of concern as they can result in high point loads on the spudcan. Boulders can also be mobile under significant storm events and may require surveys shortly prior to jacking to confirm locations are clear.

An often neglected risk is that of high extraction forces which can occur in rocks such as mudstone and chalk which have significant discontinuities and fissuring. These can be 'closed' during penetration of the spudcans, increasing the effective rock mass strength and reducing the permeability, this in turn can result in spudcans generating significant 'reverse end bearing' (suction) during extraction from the seabed. It is therefore recommended that this is considered during the risk assessment phase.

Using Geographical Information System (GIS) tools it is possible to map risks such as depth of rock, strength of rock, intrusions, boulders, etc across a large area. These features can then be assigned a score and GIS software can 'add' the risk scores and create a 'risk map' as illustrated below for the area surrounding a Wind Turbine Generator (WTG). This scoring could then be used during micro siting of jack up locations for installation activities to help mitigate installation risks.

Figure 8: Indicative risk assessment for jacking operations



CONCLUSIONS AND RECOMMENDATIONS

Rock at seabed is becoming an increasing common issue for offshore renewable energy developments and nearshore ports and harbour developments. However, guidance on how to undertake Leg Penetration Assessments (LPAs) and risk assessments is limited. Therefore, three methods were compared for two indicative case studies with the following results:

- The 'traditional' assumption of cohesive strength of 0.5*UCS with conventional ISO 19905-1, 2016 penetration resistance methods tended to under predict penetrations

- The use of rock mass strength based upon relationships proposed by Hoek et al (2002) gave reasonable predictions for extremely weak to very weak mudstones but tended to over predict penetrations for stronger rocks
- The Merifield (2006) method gave reasonable predictions for both cases considered.

Additional research including further back analysis is required to confirm the above but both the use of Hoek et al (2002) rock mass strength values with conventional ISO methods and the use of Merifield (2006) bearing capacity methods are considered to provide the most suitable assessment of potential leg penetrations in weak rock.

Several risks including eccentric loading, sliding and extraction issues were identified and mitigation methods suggested. The main mitigation being to properly understand the rock including seabed 'roughness' depth to intact rock, rock mass behaviour, particularly rock mass characterization information (such as GSI). Therefore, properly specified geophysical and geotechnical survey is considered highly important.

REFERENCES

[1] ISO 19905-1:2016; Petroleum and Natural Gas Industries – Site-specific Assessment of Mobile Offshore Units, Part 1: Jack-ups.

[2] SNAME (Society of Naval Architects and Marine Engineers), Guidelines for Site Specific Assessment of Mobile Jack-Up Units, Technical and Research Bulletin 5-5A, Rev.3, August 2008.

[3] Hoek, E., Brown, E.T., 1997. Practical estimates of rock mass strength. Int. J. Rock Mech. Min. Sci. 34, 1165–1186. – GSI reference.

[4] Hoek E., Carranza-Torres C. and Corkum B. (2002). Hoek-Brown criterion – 2002 edition. Proc. NARMS-TAC Conference, Toronto, 2002, 1; 267-273.

[5] Hoek, E and Diederichs, M.S. (2006), Empirical estimation of rock mass modulus. International Journal of Rock Mechanics and Mining Sciences, 43, 203–215

[6] Hoek et al, Quantification of the Geological Strength Index chart, 47th US Rock Mechanics / Geomechanics Symposium, 2013.

[7] Merifield, R.S., Lyamin, A.V., Sloan, S.W., 2006. Limit analysis solutions for the bearing capacity of rock masses using the generalised Hoek–Brown criterion. International Journal of Rock Mechanics.