



GUIDANCE NOTES ON

GEOTECHNICAL PERFORMANCE OF SPUDCAN FOUNDATIONS

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Foreword

For the last decade, ABS has been involved in numerous joint industry projects on jackup spudcan foundations. ABS has outlined this knowledge herein to provide guidance covering the design and installation of jackup spudcan foundations addressing the following topics:

- Site assessment
- Spudcan penetration prediction in a single layer of soil, such as clay or sandy soil
- Punch-through prediction and mitigation
- Foundation stability assessment
- Foundation fixity
- Spudcan-jacket pile interaction
- Spudcan footprint interaction

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SECTION 1 Introduction

1 General Comments

For the last decade, ABS has been involved in numerous joint industry and government sponsored projects on jackup spudcan foundations. The current state of the art in spudcan design and installation represents worldwide contributions by a large number of investigators from government agencies, marine warranty survey groups, classification societies, contractors, shipyards, universities and petroleum companies.

ABS has gathered this body of knowledge to provide a guideline on geotechnical performance of spudcan foundations, including site assessment, spudcan penetration prediction, punch-through problem, foundation stability assessment, foundation fixity, spudcan-jacket pile interaction and spudcan footprint interaction.

3 Scope and Application

The Guidance Notes apply to the geotechnical design, installation and operation of jack up spudcan foundations. These recommendations are to be used in conjunction with Part 3 of the *ABS Rules for Building and Classing Mobile Offshore Drilling Units (MODU Rules)*. As MODU Classification is not site-specific in nature, the Owner specifies conditions for which the unit is to be installed.

Guidance for site assessment of jackup operability is given in Section 2, followed by spudcan penetration prediction in single layer soil, such as clay and sand in Section 3. In strong over soft soil where punch-through failure is a major concern on design of jackup spudcan foundation, the recommended prediction methods to calculate spudcan bearing capacity in layered soils are introduced in Section 4, as well as the mitigation method for reducing punch-through failure. Three steps are suggested in the order of increasing complexity and reducing conservatism for the overall foundation stability assessment in Section 5. The procedure for calculating foundation fixity is presented in Section 6. If the proximity of the spudcan to the pile is less than one spudcan diameter, detailed analysis is recommended to estimate the severity of spudcan-pile interaction problems as given in Section 7. The footprint characteristics and its influence on spudcan-footprint interaction are presented in Section 8 as well as possible effective mitigation methods in various field conditions.

These Guidance Notes are applicable to self-elevating units which undertake drilling, construction, support, wind turbine installation or other offshore activities.

5 Terms and Definitions

Backfill: Soil material used to refill the cavity above the spudcan due to spudcan penetration.

Backflow: Soil flows from bottom of spudcan back into the cavity on the exposed top of the spudcan.

Breakout Force: The maximum uplift force during spudcan extraction.

Cavity Depth: The depth of an open cavity forms above the spudcan after penetration.

Consolidation: The process in which soil reduction in volume takes place by expulsion of water under long term static loads.

Footprint: After a jackup unit is removed from a site, depressions are left in the seabed where the spudcans were located. The soil in way of the footprints has modified physical profiles of the seabed and soil properties.

Foundation Fixity: Also called spudcan-soil rotational stiffness, is the rotational restraint offered by the soil supporting the foundation.

Mobile Jackup Platform: A self-elevating unit with movable legs capable of raising its hull above the surface of the sea.

Perforation Drilling: A technique performed to perforate the stiff layer with drill holes and remove the soil as one of the mitigation methods to reduce the punch-through failure.

Prescriptive Preloading: During preloading, the hull is kept at, in or close to water level, with each individual leg preloaded by sequential filling and discharge of selected preload ballast tanks.

Punch-Through Failure: Unexpected sudden and rapid penetration of the spudcan through soil occurs when strong soil is over soft soil and is a major risk for the stability and equilibrium of the jackup structure.

Rack Phase Difference (RPD): The difference in elevations between the chords of any one leg.

Reaming: A technique that involves forcing a leg into position by incremental vertical reciprocation to penetrate the spudcan into the soil at the required position. Reaming is one of the mitigation methods for reducing spudcan footprint interaction.

Remoulded Undrained Shear Strength: The magnitude of the shear stress that a disturbed soil can sustain in an undrained condition.

Simultaneous Preloading: During preloading the hull is held with minimal draft or air gap and the preload is incrementally increased on all the legs simultaneously.

Soil Sampling: A suitably stored, small amount of soil for visual inspection and laboratory testing for the determination of the soil unit geological provenance, characteristics and geotechnical engineering design parameters.

Spudcan: A large inverted cone that is roughly circular in-plan with a shallow conical underside and a sharp protruding spigot. It is mounted at the base of a jackup's leg, and is primarily considered to provide sliding and bearing resistance to the jackup rig when deployed into the sea bed.

Stomping: A process where a spudcan is initially emplaced away from the center of an old footprint and then the spudcan is used to displace soil towards the old footprint at desired positions to widen the disturbed region. In soft to stiff clay, stomping is very effective in mitigating spudcan footprint interaction.

Triaxial Test: A common laboratory testing method widely used for obtaining shear strength parameters for a variety of soil types under drained or undrained condition.

7 Symbols and Abbreviations

7.1 Symbols

A	=	spudcan maximum cross sectional area
A_a	=	area ratio
A_e	=	spudcan effective bearing area based on cross-section taken at uppermost part of bearing area in contact with soil
A_s	=	spudcan laterally projected embedded area
c_{ul}	=	undrained cohesive shear strength at spudcan tip
c_{u0}	=	undrained cohesive shear strength at lowest maximum bearing area
c_v	=	coefficient of consolidation of clay
D	=	maximum spudcan diameter below mudline
D_{eff}	=	equivalent spudcan diameter at mudline
D_f	=	diameter of the spudcan which forms the footprint
e	=	opening ratio

E_u	=	Young's modulus of clay in undrained condition
F_H	=	leg horizontal reaction associated with F_V
F_M	=	leg moment reaction associated with F_V
F_{mob}	=	mobilization factor to reduce the calculated bearing capacity of spudcan foundation
f_r	=	reduction factor
F_V	=	leg vertical reaction
G	=	soil shear modulus
h_c	=	soil back flow depth
h_{layer}	=	sand layer thickness
H_{L0}	=	horizontal foundation capacity
h_{plug}	=	height of sand plug
h_t	=	height of spudcan widest diameter
I	=	second moment of area
I_D	=	relative density
I_{RD}	=	relative dilatancy
k_0	=	coefficient of earth pressure at-rest
K_1	=	vertical stiffness
K_2	=	horizontal stiffness
K_3	=	rotational stiffness
K_s	=	punching shear coefficient
m	=	3 for failure under triaxial or general loading conditions and 5 under plane-strain conditions
M_{L0}	=	moment capacity of foundation
N_c	=	bearing capacity factor at shallow spudcan penetration prior to any backflow
N_{kt}	=	cone factor
N_γ, N_q	=	bearing capacity factors
p'	=	mean effective stress
p_r	=	100 kPa (0.010197 kgf/mm ² , 14.5 lbf/in ²)
q_c	=	cone resistance
q_{net}	=	net cone resistance, which is the measured cone resistance being corrected for the pore pressure effects and the total in-situ vertical stress
$Q_{crushing}$	=	particle crushing strength on a natural log scale
Q_v	=	ultimate vertical bearing capacity of the spudcan foundation
R	=	radius of the circular footing
R_d	=	radial distance from spudcan center to footprint center
r	=	shear strength ratio

r_f	=	failure ratio
S_{ua}	=	undrained shear strength averaged from $(h - h_l)$ to $(h + h_{plug})$
S_{ubs}	=	shear strength intercept at the clay layer's surface in strong overlying soft soil
$S_{u_footprint}$	=	footprint undrained shear strength
S_{uH}	=	shear strength at the back flow depth h_c
S_{um}	=	shear strength intercept at the layer's surface
$S_{u,plugbase}$	=	undrained shear strength corresponding to the level of the sand plug base
S_{utop}	=	undrained shear strength of the top strong clay
$S_{u_undisturbed}$	=	undisturbed undrained shear strength
S_{u0}	=	undrained shear strength at the lowest depth of the maximum plan area of spudcan
$\overline{S_u}$	=	mean value of undrained shear strength
t	=	consolidation time
V	=	volume of the conical spudcan below mudline when $z = y_m$
V_c	=	volume of the conical spudcan below mudline
V_{L0}	=	maximum vertical foundation load during preloading
V_{soil}	=	volume of the backfill soil that rests on the spudcan
z	=	soil depth
$\bar{z}$	=	mean values of soil depth
γ'	=	submerged soil unit weight
ν	=	Poisson's ratio
ξ_{sq}, ξ_{hy}	=	empirical shape factors
ξ_{hq}	=	empirical depth factor
ρ	=	shear strength gradient with soil depth
σ	=	standard deviation
σ'_v	=	effective stress at the level of the sand plug base
σ'_{v0}	=	effective overburden stress
τ_1	=	adjusted time factor for soil consolidation during the operational period
τ_2	=	adjusted time factor for soil consolidation during the elapsed time after a footprint is formed
ϕ'	=	friction angle
ϕ_{cv}	=	critical state friction angle

7.3 Abbreviations

CAUC	Anisotropically consolidated undrained triaxial compression test
CAUE	Anisotropically consolidated undrained triaxial extension test
CID	Isotropically consolidated drained test
CoV	Coefficient of variation
DS	Direct shear test
DSS	Direct simple shear test
MinV	Miniature vane
MODU	Mobile offshore drilling unit
MV	Motor vane
PP	Pocket penetrometer
RPD	Rack phase difference
SI	Site investigation
TV	Torvane
UU	Unconsolidated undrained triaxial tests



SECTION 2 Site Assessment

1 General

A clear understanding of the seabed and sub-seabed conditions is critical for the site specific assessment of a jackup's suitability during installation, elevated operations and leg extraction. The jackup foundation site assessment procedure usually comprises:

- Acquisition of regional and local geological and geotechnical data (to include previous jackup foundation performance if available)
- Geological data review to develop the ground model
- Geophysical site survey to refine the ground model
- Geotechnical Site Investigation (SI) to further refine the ground model
- Generation of geotechnical design profiles with engineering parameters
- Performance of jackup foundation site-specific assessment using the design profiles.

The Geophysical Site Survey report should describe the interpreted ground model; include an explanation of the geological setting, depositional environment and history together with descriptions of any potential geohazards which could influence jackup operations.

Intrusive geotechnical SIs are conducted in order to ground-truth the geophysical data and to obtain the required geotechnical index and strength measurements. The geotechnical SI allows confirmation or further refinement of the interpreted ground model. Adequate data are required to facilitate detailed engineering characterization of each soil layer and to provide understanding of the spatial variation of these parameters.

Preferably the geophysical and geotechnical components are planned together as integrated parts of the same investigation. The soil design profiles with associated engineering strength parameters are then developed for use in the predictive bearing capacity analyses. The actual scope of work developed will depend upon the vertical and lateral variability of the soil as well as the presence of any geohazards.

The main requirements of site investigation are to be in accordance with 3/6.3 of the *ABS Rules for Building and Classing Offshore Installations*.

3 Geotechnical Site Investigation

Ideally, the geotechnical SI should be conducted well in advance of the jackup deployment to the field in order to allow time for adequate data interpretation and site specific assessment. The scope of in-situ tests, soil sampling, soil index, strength and advanced laboratory test data required for analytical purposes will depend on the ground conditions. For a continuous layer of homogeneous soil, limited data acquisition will be necessary. However for highly variable and complex ground conditions where advanced foundation performance modeling is to be conducted, a considerably greater amount of information may be required. The SI scope of work should be planned according to the expected circumstances with the provision for amendment should the actual ground conditions differ from that expected during the investigation.

The geotechnical report should include borehole logs and soil laboratory test procedures and results. If piezocone or other in-situ penetrometer tests are performed, the test records should be documented together with descriptions of test procedures, tool calibration certificates, field offsets and processing information, as applicable. All reports should contain water depth data and geographic coordinates of the location with the measurement datum clearly stated.

5 Sampling and Field Testing

Sampling and in-situ testing tools can be deployed through a drill string supported by a drilling derrick mounted on a floating vessel, and these are referred to as “down hole operations”. For marine operations, the drilling system should be heave compensated to minimize sample disturbance resulting from vessel movement. Alternatively, in-situ testing and sampling operations can be conducted using remotely operated systems deployed at the mudline in the “seabed mode” which do not require heave compensation. These systems may provide improved depth control. However, due to their limited thrust, the borehole may not be able to advance to the required depth.

Details of the field investigation and subsequent testing program depend on soil variability, environmental design conditions, structure type and geometry, presence of geo-hazards, etc. At least one borehole with sampling and laboratory testing, or in-situ testing is provided at each platform location. If the foundation area shows significant variation, it may be necessary to perform more than one boring/in-situ testing to verify the irregular soil conditions.

Soil sampling provides material for visual inspection and laboratory testing for the determination of the soil’s geological provenance, characteristics and geotechnical engineering design parameters. Additionally, such parameters can be evaluated from in-situ field testing. Continuous in-situ test profiling may also be used to more accurately determine layer boundaries and material variation.

As the quality of the SI significantly affects the quality of the spudcan penetration prediction, sampling and field testing should be planned accordingly. Jackup SI may be conducted from the jackup itself where there is reliable knowledge of the ground conditions and local jackup operating experience, otherwise relying only on such cursory data should only be considered where it is certain that this data will be adequate for the intended purpose.

During soil sampling material disturbance should be minimized since the greater the soil disturbance the less representative the laboratory test results will be of the in-situ condition. Jackup spudcan penetration performance can be significantly influenced by minor variations in the soil properties and the acquisition of continuous vertical soil profiles is recommended. When continuous profiling is not possible, the aim should be to minimize the gap between data points. The target data gaps should not exceed 0.2 m, although it is noted that for some geotechnical systems this may be unachievable, in which case the maximum allowable gap may have to be increased to 0.5 m. Due consideration should be given to the consequence of data gaps in terms of their location and size, and how this may influence interpretation of the ground model and the necessity to acquire additional data.

Cone penetration tests provide measurements of tip penetration resistance, sleeve friction and pore pressure and are conducted either continuously in the seabed mode or in up to 4.5 m strokes in the down hole mode. Unlike soil sampling and testing data the continuous cone penetration test plots allow for the identification of stratigraphic boundaries and soil strength trends, and the data are usually compared with the laboratory strength test data. The cone penetration tests can be further extended to incorporate dissipation tests to estimate the consolidation coefficient of soils.

Where site specific borehole data are required for a jackup’s operating site assessment, the borehole or piezocone penetration target depth is the greater of either 30 m or $1.5 \times$ spudcan diameter beneath the calculated spudcan tip penetration depth at the maximum preload, with all relevant soil properties being sufficiently investigated. Where appropriate, the target depth may be extended deeper to account for future jackup installation operations where a different rig subjected to a higher preload level may be employed.

A full-flow penetrometer; such as the cylindrical T-bar and spherical ball penetrometer, offer some advantages over the conventional cone in accurate strength interpretation, measurement of remoulded strength and hence soil sensitivity in soft soils. They are not commonly employed in geotechnical SI for jackup assessment and the understanding of the penetration behaviors of these penetrometers is restricted to clay soil conditions.

In-situ vane tests provide only discrete measurements of the intact and remoulded undrained shear strength of clays, and thereby soil sensitivity. The vane testing procedure is important and the strength measured may be sensitive to drainage effects, material heterogeneity and in-situ stress anisotropy. Note that the in-situ vane tests may not be suitable for soil conditions which are heterogeneous due to the test nature of providing only discrete measurement. In comparison, the various penetrometer systems are more versatile than the vane testing systems, and as such, their use is favored.

7 Laboratory Testing

Soil samples are extruded from the sample tubes on the SI vessel, (in the same direction which they were taken to minimize disturbance by stress reversal), where they are carefully separated from drill cuttings and any heavily disturbed material. The samples are described, photographed and catalogued in accordance with recommended industry practice. Selected undisturbed samples are stored in sealed containers, which are usually wax-filled, to preserve the moisture content and limit further disturbance.

A range of different soil tests are available from simple laboratory index tests to advanced stress path tests conducted in specialist onshore soil testing laboratories. Typically offshore tests include moisture content and density determination, carbonate content, particle size distribution together with simple strength tests such as pocket penetrometer, torvane, laboratory vane, fall cone, unconsolidated undrained triaxial tests (UU). Index tests are conducted to assist with the soil type classification and also to provide preliminary parameters for initial jackup foundation assessment.

While these undrained soil strength tests are comparatively quick and relatively easily conducted in the offshore laboratory they measure shear strength by different failure mechanisms, and may provide significant strength data scatter and may not provide an accurate indication of sample quality. Some offshore soil laboratory tests, such as the fall cone and the motor vane, can be used to provide an indication of the soil sensitivity.

Advanced onshore soil laboratory testing is encouraged as these strength tests [e.g., anisotropically consolidated undrained triaxial compression test (CAUC), anisotropically consolidated undrained triaxial extension test (CAUE), direct simple shear (DSS) test] provide data for calibration of the in-situ penetrometer results. Oedometer tests provide information about the stiffness and drainage behavior of the soil. Simple offshore laboratory strength tests may provide adequate information for relatively simple soil conditions which lend themselves to modeling by simple bearing capacity formulations. However, for more complex soil conditions, simple soil test results with the application of simple models become less reliable and advanced soil testing is advisable. The relative reliability of various tests in measuring the undrained strength of clay is presented by [Ref.1] in Section 2, Table 1.

TABLE 1
Relative Reliability of Tests Measuring the Strength of Clay Soils

Test Type	Soil Profiling	Intact $S_u^{(1)}$			Remoulded $S_u^{(1)}$
		<40 kPa	41-80 kPa	>80 kPa	
Piezcone	1	2	2	2	4-5
T-bar & ball penetrometers	1 (with pore pressure measurement)	1-2	1-2	1-2	1-2
In-situ vane	---	1-2	1-2	1-2	3
UU ⁽²⁾	---	4-5	3-5	2-5	2-3
Motor vane ⁽²⁾	---	3-5	3-5	4-5	2-3
Torvane ⁽²⁾	---	3-5	3-5	4-5	---
Pocket penetrometers ⁽²⁾	---	4-5	4-5	4-5	---
CIU/CAU/DSS	---	1-2	1-2	1-2	2

Notes:

- Rating ~ 1 High reliability; 2 High to moderate reliability; 3 Moderate reliability; 4 Moderate to low reliability; 5 Low reliability.
- The test result reliability is dependent on the sample quality (or degree of sample disturbance) and soil homogeneity.

9 Soil Engineering Parameter Selection

Section 2, Table 2 lists the basic soil properties which should be obtained for jackup foundation assessment purposes for homogeneous clay or sand. For silty material, the properties defined for clay may be applicable but with consideration of partial drainage characteristics. For a highly variable and complex ground where advanced foundation performance modeling is to be conducted more soil properties may be obtained.

TABLE 2
Index Properties for Jackup Foundation Site Specific Assessment

<i>Soil Type</i>	<i>Strength Properties</i>	<i>Index Properties and Additional Parameters</i>
Clay	Undrained shear strength S_u Remoulded shear strength and soil sensitivity S_t	Water content Plastic limit Liquid limit Submerged unit weight of clay Coefficient of consolidation Over consolidated ratio
Sand	Critical state angle of friction Crushing strength	Particle size distribution curve Relative density Submerged unit weight of sand Over consolidated ratio

9.1 Identification of Soil Type and Layers

In order to determine the soil stratification, the desk study, geophysical site survey report and geotechnical testing results should be viewed in a holistic and integrated manner. As part of this process, variation of the subsoil conditions across the planned jackup spudcan locations should be assessed. Soil classification charts are empirical correlations which should be verified against the site geotechnical data (i.e., borehole logs and laboratory test data). For offshore conditions, pore pressure data may be generally considered more reliable than friction sleeve data for soil classification.

Continuous penetrometer profiling is suggested in order to provide a full profile for site characterization. Where intermittent piezocone, penetrometer and soil sampling is used in an alternating manner, data gaps are introduced and precise identification of layer boundaries may not be possible. Furthermore, where intermittent penetrometer profiling is used, portions of test data may be of reduced quality and reliability due to soil disturbance from the drilling and soil sampling operations. Discrepancies in the penetrometer resistance profiles between two sequential penetrometer test strokes may be difficult to resolve, and this may introduce uncertainty in the soil layer interpretation. If intermittent profiling is unavoidable, the interval between strokes should be kept as small as practicable and drilling disturbance should be minimized.

It is also suggested that penetrometer tests be conducted adjacent to continuous sampling borehole(s) with a separation on the order of 5 m to avoid interference. Also obtaining pore pressure can aid in the identification of soil type and layering.

The following paragraphs consider strength measurement in:

- Clay, where undrained conditions are assumed for both testing and spudcan penetration;
- Sand, where drained conditions are assumed for both testing and spudcan penetration.

9.3 Clay

The undrained shear strength, S_u , can be established from a number of commonly conducted strength tests as follows.

- In-situ testing: field penetrometers (cone), vane shear
- High quality laboratory testing: CAUC, CAUE, DSS
- Simple laboratory testing: unconsolidated undrained triaxial test (UU), miniature vane (MinV), motor vane (MV), torvane (TV), pocket penetrometer (PP)

The reliability of the interpreted strength parameters relies heavily on the quality of test and sample conditions. The simple laboratory tests typically should be conducted immediately after the samples are extruded in the laboratory. However, the test results may tend to show significant variability both within a given type of test and between different tests, and are ‘operator dependent’. Tests of this type may be sufficient where reasonable knowledge of the ground conditions and knowledge of successful jackup operations in the locality are available; the data may also be used to extend or interpolate between results from previous high quality laboratory tests. As samples are not reconsolidated prior to testing, the reliability of these tests suffers from unquantifiable sample quality.

The knowledge of remoulded shear strength and sensitivity is necessary for consideration of strain softening effects, particularly for highly sensitive clays. Strain softening reduces the average operational strength during spudcan penetration, thus increasing the penetration. Partial remoulding of the soil will also affect the magnitude of strength recovery or enhancement with time and this is relevant for spudcan breakout force assessment and bearing capacity evaluation for jackup revisits.

In-situ cyclic full-flow penetrometer tests (using T-bar or Ball) with 10 cycles of penetration and extraction, will generally show a well-defined remoulded penetration resistance. The ratio by which the penetration resistance decreases between initial and post-cyclic penetration resistance will be less than the actual sensitivity at the elemental test level, largely due to the partial remoulding that occurs during initial penetration. Such tests do, however, provide an appropriate measure of remoulded shear strength that is directly applicable to spudcan performance.

Where the sediments may be susceptible to significant strength loss during cyclic loading under environmental or seismic loading conditions, cyclic shearing tests should be undertaken in the laboratory in addition to monotonic tests. In the depth range of expected spudcan penetration, sufficient cyclic tests should be undertaken to establish a “cyclic fatigue” curve, showing how the normalized shear stress to cause a given magnitude of strain varies with the number of cycles. This information may then be used to assess an appropriate cyclic shear strength for use in quantifying the jackup’s performance during installation and under ultimate cyclic loading conditions.

9.5 Sand

The most common laboratory tests for determining effective strength parameters in sand are CID and DS tests, which represents triaxial and plane strain condition, respectively. Sample disturbance is inevitable when sampling cohesionless material from the seabed. The samples are reconstituted to their approximate in-situ state, with the relative density generally estimated from the cone resistance. Appropriate effective stresses are then applied before the shearing stage. During shearing, it is important to verify that the shearing rate applied is slow enough to prevent the development of excess pore pressure. Theoretically, under a given stress level, it is expected that the friction angle ϕ' from DS tests will be greater than that from CID tests.

To better account for the stress level effect on ϕ' , the design value may be estimated from the value of the relative density, I_D , and the critical state friction angle, ϕ_{cv} , using an appropriate strength-dilatancy relationship that takes account of the mean effective stress p' during bearing failure.

Since the value of critical state friction angle ϕ_{cv} lies within a small range, at least for silica sand, it is possible to estimate the in-situ directly from the cone resistance, q_c . The following expression has been applied widely to sandy sites in the North Sea by [Ref.2].

$$I_D = a_1 \ln \frac{q_c}{p_r} - a_2 \ln \frac{\sigma'_{v0}(1+2k_0)}{3p_r} - a_3$$

where

$$a_1 = 0.336$$

$$a_2 = 0.154$$

$$a_3 = 1.91$$

$$\sigma'_{v0} = \text{effective overburden stress, in kPa (kgf/mm}^2\text{, lbf/in}^2\text{)}$$

$$q_c = \text{cone resistance, in kPa (kgf/mm}^2\text{, lbf/in}^2\text{)}$$

$$p_r = 100 \text{ kPa (0.010197 kgf/mm}^2\text{, 14.5 lbf/in}^2\text{)}$$

$$k_0 = \text{coefficient of earth pressure at-rest, normally taken as 0.5 and 1.0 in order to generate upper and lower bounds of } I_D, \text{ respectively}$$

For a given I_D , the design value of ϕ' can be determined using the general strength-dilatancy framework established by [Ref.3] which makes allowance for different sand types and loading conditions as follows.

$$\phi' = \phi_{cv} + mI_{RD}$$

$$I_{RD} = I_D [Q_{crushing} - \ln(p')] - 1 \quad 0 \leq I_{RD} \leq 4$$

where

$$m = \text{constant}$$

$$= 3 \text{ for failure under triaxial or general loading conditions}$$

$$= 5 \text{ under plane-strain conditions}$$

$$I_{RD} = \text{relative dilatancy}$$

$$Q_{crushing} = \text{particle crushing strength on a natural log scale, in kPa (kgf/mm}^2\text{, lbf/in}^2\text{)}$$

$$p' = \text{mean effective stress which in turn depends on the value of } \phi', \text{ in kPa (kgf/mm}^2\text{, lbf/in}^2\text{)}.$$

As an approximation, the recommendation is to treat p' as the maximum preload pressure.

The value of ϕ_{cv} may be obtained from direct shear tests on disturbed sand, from the “steady state” friction angle in the later stages of the test. Some of the reported values for ϕ_{cv} and $Q_{crushing}$ by [Ref.4] are given in Section 2, Table 3. The above procedures provide an estimate of the peak angle of friction, including the effect of the average stress level in the soil. It is important to note, however, that as a spudcan continuously penetrates the soil, the peak strength is not mobilized simultaneously throughout the deforming soil. As a result, calculations of spudcan resistance based solely on peak strength of a rigid-plastic soil can result in overestimates of resistance. [Ref.5] addresses this issue by employing reduced friction angles. An alternative approach is suggested in Section 3 where a mobilization factor is applied to the calculated resistance.