



GUIDANCE NOTES ON

DESIGN AND INSTALLATION OF DYNAMICALLY INSTALLED PILES

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Foreword (1 December 2017)

These Guidance Notes provide ABS recommendations for the design and installation of dynamically installed piles for offshore service.

Included in these Guidance Notes are methodologies for the geotechnical design and structural assessment of dynamically installed piles. Recommendations in these Guidance Notes are based on finite element analysis using appropriate soil modeling and simulation of soil-pile interaction. Alternatively, other approaches that can be proven to produce at least an equivalent level of safety will also be considered.

These Guidance Notes are applicable to the design of dynamically installed piles, as a component of taut, semi-taut, or catenary mooring systems.

The December 2017 edition incorporates a new Appendix 4, “Methodology to Calculate the Anchor Reverse Catenary Line”.

These Guidance Notes become effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that this version of these Guidance Notes is the most current.

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SECTION 1 General

1 Background

Dynamically installed piles are finned piles designed to be released from a height of 20-100 m above the seabed and reach velocities of 20-35 m/s at the seabed before self-embedment. They may be stabilized with multiple fins at the trailing edge. Tip penetration is expected to be two to three times the pile length and holding capacity after consolidation is expected in the range three to six times the pile weight.

The main purpose of these Guidance Notes is to provide recommendations for the design and installation of a dynamically installed pile for taut, semi-taut or catenary mooring systems. The design and installation of dynamically installed piles are to be based on all applicable requirements of the *ABS Rules for Building and Classing Offshore Installations (OI Rules)*, the *ABS Rules for Building and Classing Floating Production Installations (FPI Rules)*, and the *ABS Rules for Building and Classing Mobile Offshore Drilling Units (MODU Rules)*.

3 Scope and Application

These Guidance Notes covers the geotechnical design, structural assessment and installation of a dynamically installed pile as a component of taut, semi-taut, or catenary mooring systems.

5 Submission of Documents

The design documentation to be submitted should include the reports, calculations, plans and other documentation necessary to verify the adequacy of the foundation and structure. The extensiveness of the submitted documentation should reflect the uniqueness of the pile design and its application.

5.1 Plans

Plans showing the scantlings, arrangements, specification for material, welding and fabrication, as well as construction details of the pile's structure should be submitted and approved before the work of construction is commenced. These plans are to indicate clearly the details of welding, welding consumables, mass, and vertical center of gravity of the pile, etc.

5.3 Reports

Reports indicating the soil conditions, holding capacity verification, and structural behavior should be submitted to ABS for review.

In general, the following documents should be submitted for review, reference, and file:

- Site investigation reports including complete geophysical/geological/geotechnical reports as well as an integration/interpretation report.
- Geotechnical design report to evaluate the adequacy of the holding capacity of the pile. Pile calculation documents should provide minimum penetration and maximum allowable inclinations of a pile from the vertical axis. After pile installation, if significant deviation is found, this report should be updated to verify the adequacy of the pile for the as-installed condition.
- Structural design report to evaluate the adequacy of the pile structure and the mooring padeye.
- Installation procedures and report for piles, including the design and final coordinates for pile installation, design and recovered monitoring data for pile penetration depth, orientation angle with vertical and azimuth angles of fins, when applicable.
- If the reference site is within a seismic zone, the site specific seismic hazard report should be submitted.



SECTION 2 Site Investigations

1 General

The soil investigation should satisfy the requirements given in 3/6.3 of the *ABS Rules for Building and Classing Offshore Installations (OI Rules)*. It is recommended that a high-quality, high-resolution geophysical survey be performed over the entire areal extent of the foundation. It is important that the geophysical and geotechnical components are planned together as integrated parts of the same investigation. Such an integrated study can then serve as a guide to develop a scope of work for the vertical and horizontal extent of the final geotechnical investigation and to aid in the interpretation of the acquired geotechnical data.

The sequence for the investigation program should be:

- Desk study
- Topographical and geophysical survey
- Geotechnical survey and laboratory testing
- Additional geophysical and/or geotechnical surveys and/or laboratory testing as required

Depending on the size of a project and/or the complexity of the geotechnical context and associated risks (geohazards), additional intermediate stages may be necessary.

The soil investigation for a dynamically installed pile should give the basis for a geotechnical design comprising evaluation of:

- Pile embedment depth
- Ultimate holding capacity
- Structural adequacy in term of strength and fatigue resistance

3 Desk Study

The desk study assembles existing data for preliminary site assessment and will formulate requirements for subsequent geophysical and geotechnical investigations. The desk study should include a review of all sources of appropriate information, collect and evaluate all available relevant data for the site including:

- Bathymetric information
- Geological information
- Information and records of seismic activity
- Existing geotechnical data and information
- Previous experience with foundations in the area
- Regional meteorological and oceanographic data

A desk study alone is not sufficient for detailed engineering purposes, but it should be sufficient for conceptual engineering to move forward in a focused manner and provide the basis upon which to design and plan subsequent site investigation work.

5 Geophysical Surveys

Geophysical investigation can provide information about soil stratigraphy, local soil condition and evidence of geological features. The survey area should cover the full extent of the pile spread. The areal extent of soil layers can sometimes be mapped if good correspondence is established between the soil boring and in-situ test information and the results from the seabed surveys. Site specific, high-resolution geophysical information of a regional character obtained from seafloor and sub-bottom surveys at or near the project site should be submitted for review.

The types of equipment for performing geophysical investigation can include the following:

- Echo sounder or swath bathymetric system for water depth and seafloor morphology.
- Sub-bottom profiler for structural features within the near-surface sediments.
- Side-scan sonar for seafloor features and seafloor reflectivity.
- Seismic sources for the structure to deeper depths up to approximately 100 m below the seafloor. The minimum depth of seismic profile should be the anticipated penetration depth plus a zone of influence of about ten times the equivalent pile diameter. The Equivalent Pile Diameter (EPD) is the diameter of a circle that circumscribes the pile structure including fins and shaft.
- Direct observation of the seafloor using a remotely operated vehicle (ROV) or manned submersible.

7 Geotechnical Surveys

The geotechnical evaluation includes sampling for soil classification and engineering property testing, and in-situ soil profiling and strength testing. To establish the soil characteristics at the foundation locations, at least one boring or probing should be taken at pile cluster locations to a depth of the anticipated penetration depth plus a zone of influence of 15.2 m. Additional bore holes may be needed if significant discontinuities of the soil characteristics are verified, from cluster to cluster. If the foundation location is at a significant distance from the boring/probing location, additional verification boring/probing may be needed to validate the extrapolated data.

In deep water, the relief of hydrostatic pore pressure and its resulting effect on any dissolved gases can produce soil properties significantly different from in-situ conditions. Because of these effects, in-situ testing is encouraged as it may provide a more reliable estimate of soil parameters with less sample disturbance. Typical tools used include the remote vane, the piezoprobe, PCPT (piezocone penetrometer tests), T-bar or ball penetrometer, etc. If the soil investigation is performed primarily using PCPT, it is recommended that at least one boring with sampling be taken to properly calibrate the PCPT results. This boring/core should be taken at one of the PCPT locations. The sampling interval should not exceed 1.0-1.5 m.

The soil parameters for pile design will require high quality sampling in combination with advanced laboratory testing and correlations with in-situ test results. Consideration should be given to the performance of permeability and consolidation tests in order to assess set-up effects and capacity consideration for the dynamically installed pile. The site investigation and laboratory testing program should provide the information needed for the reliable design of piles, as shown in Section 2, Table 1. The expected pile embedment and cyclic loading capacities are presented in the Appendices of these Guidance Notes.

If the reference site is within a seismic zone, geotechnical investigations should include tests to determine dynamic soil properties and liquefaction potential.

TABLE 1
Basic Soil Parameters

<i>Clay</i>	<i>Sand or Silt</i>
• General description, classification and index testing • Grain size distribution • Organic material content • Mineralogy • Total unit weight • Water content • Undrained shear strength • Remoulded shear strength and soil sensitivity • Permeability • Soil thixotropy • Soils stress history and over consolidation ratio • Strain rate effects and cyclic response • Creep effect for loss of strength under sustained load • Carbonate content	• General description, classification and index testing • Grain size distribution • Maximum and minimum densities • Relative density • Water content (silt) • Carbonate content • Organic material content • Angularity • Angle of shearing resistance • Soils stress history and over-consolidation ratio



SECTION 3 Geotechnical Design

1 Introduction

The main characteristics of a typical dynamically installed pile include: total mass, length and diameter of shaft, number and size of fins, center of gravity and buoyancy, etc. Pile ballast materials, such as lead, are normally used to provide a lower center of gravity, which reduces pile inclination during installation.

The penetration depth and ultimate holding capacity are a function of:

- Soil conditions and geotechnical soil properties
- Impact velocity at seabed
- Pile aspect ratio and tip geometry
- Fin geometry and number
- Pile mass and center of gravity
- Pile verticality after installation
- Mooring line orientation on top of pile
- Type and size of mooring line

Normally the pile's impact velocity increases with an increase in the dropping height. However, there is a threshold value of maximum impact velocity which does not increase beyond a certain dropping height. Instead of deploying the pile installation line at the water surface, a submerged release link can be used to reduce the drag effect from the line, hence increasing the pile's impact velocity.

3 Design Methodology

3.1 Embedment Depth Prediction in Cohesive Soil

Physical modeling including centrifuge tests, small scale tests and field tests are common methods of investigating the penetration depth and subsequent holding capacity of dynamically installed piles. The pile embedment depth is able to be assessed using True's method [Ref.1], accounting for both strain rate effect and inertia drag. The model starts with Newton's second law as follows [Ref.2]:

$$m \frac{d^2 z}{dt^2} = W_s - F_{resistance} - F_b - F_{drag} \dots \dots \dots (Eq.1)$$

where

- | | | |
|------------------|---|---|
| m | = | submerged mass of the pile, in kg (kgf, lbf) |
| t | = | time, in sec |
| z | = | embedment depth at the pile tip, in m (m, ft) |
| W_s | = | submerged weight of the pile in water, in N (kgf, lbf) |
| $F_{resistance}$ | = | upward force resisting movement of the pile through the soil including bearing and frictional resistances, in N (kgf, lbf) |
| F_b | = | buoyancy weight of the displaced soil, calculated as the soil displaced volume which is limited to the pile volume multiplied by the soil submerged unit weight γ' , in N (kgf, lbf) |
| F_{drag} | = | fluid mechanics drag term, in N (kgf, lbf) |

F_{drag} should be considered for very soft viscous clay encountered at soil surface and is calculated using Morison's equation:

$$F_{drag} = \frac{1}{2} v^2 \rho_s A_{tip} C_d$$

where

- v = pile velocity, in m/s (m/s, ft/s)
- ρ_s = density of soil, in kg/m³ (kg/m³, lb/ft³)
- A_{tip} = projected area of the pile, in m² (m², ft²)
- C_d = drag coefficient

Field tests show that the equivalent drag coefficient, C_d , on a pile's frontal cross section is relatively small, on the order of 0.15-0.18 [Ref.3]. A value of 0.23 is suggested for the pile with the ratio of the pile length over the shaft diameter over 4 [Ref.2]. When the pile enters cohesive soil, the resisting force is calculated using the design method for driven piles:

$$\begin{aligned} F_{resistance} &= R_f(F_{bear} + F_{friction}) \\ F_{friction} &= a(S_{u,ave}A_s + S_{u,avef}A_{sf}) \dots\dots\dots (Eq.2) \\ F_{bear} &= N_c S_{u,tip}A_{tip} + N_{cf} S_{u,bf}A_{pf} \end{aligned}$$

where

- R_f = strain rate function
- F_{bear} = end bearing resistance at tip of pile and fins, in N (kgf, lbf)
- $F_{friction}$ = frictional resistance along the shaft and fin walls, in N (kgf, lbf)
- a = friction ratio of limiting shear strength to undrained shear strength, conveniently estimated as the inverse of soil sensitivity, S_t
- $S_{u,ave}$ = shear strength averaged of the soil over the embedded shaft length, in kN/m² (kgf/m², lbf/ft²)
- $S_{u,avef}$ = shear strength averaged of the soil over the embedded fin length, in kN/m² (kgf/m², lbf/ft²)
- A_s = projected side surface area of the embedded pile shaft, in m² (m², ft²)
- A_{sf} = projected side surface area of the embedded pile fin, in m² (m², ft²)
- N_c = bearing capacity factor of pile tip
- N_{cf} = bearing capacity factor of pile fin
- $S_{u,tip}$ = undrained shear strength at pile tip, in kN/m² (kgf/m², lbf/ft²)
- $S_{u,bf}$ = undrained shear strength of the soil at bottom of pile fins, in kN/m² (kgf/m², lbf/ft²)
- A_{tip} = cross sectional area of pile tip, in m² (m², ft²)
- A_{pf} = projected cross-sectional area of the pile fin, in m² (m², ft²)

Bearing capacity factors from theoretical and experimental cone penetration tests range from 6 to 20, which is a relatively wide range. In the absence of project-specific tests, the N_c value of 12 is recommended. Each pile fin possesses a shape similar to a strip footing, and bearing capacity factor N_{cf} of 7.5 is recommended [Ref.4].

The most uncertain factor in the prediction of embedment depth is the strain rate function, R_f . During installation, it is reasonable to assume that at any given location, the operational strain rate may be proportional to v/d , where v is the pile impact velocity and d is the shaft diameter.

$$R_f = \left(\frac{v/d}{(v/d)_{ref}} \right)^\beta$$

where $(v/d)_{ref}$ is the reference strain rate associated with the reference value of undrained shear strength.

Typically, the “strain rate parameter”, β has been back-calculated from measured experimental data, which is found to vary for different kinds of clay. For preliminary purposes, in the absence of project-specific test values, a β of 0.11–0.136 may be used with $(v/d)_{ref}$ of $0.17s^{-1}$ [Ref.2].

The differential equation for the velocity at any given depth or time is solved numerically using a finite difference approach. The predicted embedment corresponds to the depth of pile tip where the velocity of the pile goes to zero. The detailed numerical procedure is given in Appendix 1 as well as the results of a sample calculation.

3.3 Holding Capacity Prediction (1 December 2017)

With regard to the pile capacity, the API RP 2A [Ref.5] criteria for pile capacity are typically used for loads applied in the axial or horizontal directions. However, the API approach is unable to explicitly account for a particular mooring line loading angle. The pile capacity can be assessed using three dimensional finite element analysis considering an assumed in-place condition. A potential drawback of the analytical and finite element capacity prediction methods, however, is that they fail to simulate the dynamic pile installation process, which may influence the validity of the subsequent pile capacity prediction.

Recently a computational fluid dynamics (CFD) approach has been used to model the complete installation event including: the release and free-fall through the water column, the transition from water into the seabed and the subsequent motion of the pile through the soil. The calibration and validation of these methods against field or experimental data should be pursued.

5 Estimation of Pile Capacity in Cohesive Soil

The simplified solutions predict the lower bound of the measured value, demonstrating that simplified capacity calculations may be used in situations where an estimate of long term capacity is needed.

5.1 Axial Pile Capacity

The theoretical capacity under axial loading is provided by the friction from pile shaft and fins, and pile weight. The ultimate pile pull-out capacity under axial loading F_v in cohesive soil can be calculated by the equation:

$$F_v = W_s + F_{friction} \dots\dots\dots (Eq.3)$$

where

W_s = submerged weight of the pile, in N (kgf, lbf)

$F_{friction}$ = frictional resistance along the shaft and fin walls, in N (kgf, lbf), see Equation 2.

5.3 Lateral Pile Capacity

For static lateral loads the ultimate unit lateral bearing pressure of pile in soft clay varies between $8S_u$ and $12S_u$ (S_u is soil's undrained shear strength) except at shallow depths where failure occurs in a different mode due to minimum overburden pressure. In the absence of more definitive criteria, the following is recommended:

$$F_h = 9S_u A_{s,h} \dots\dots\dots (Eq.4)$$

where

$A_{s,h}$ = laterally projected area of the pile's main body, in m^2 (m^2 , ft^2)

To be conservative, the projected area of pile's fins is not taken into account.