

Designing of Deep Foundation Systems for Offshore and Onshore Facilities – Similarities and Dissimilarities

Hafeez Baba & Henri Sangam
SNC-Lavalin Inc., Toronto, Ontario, Canada



ABSTRACT

Driven steel tubular piles are most commonly used for offshore structures and are becoming popular onshore as well. Typically, offshore piles are required to support large loads and are bigger in diameter, wall thickness, length, use high performance steel and require high-energy impact hammers to install. Pile drivability predictions are critical for selecting the appropriate hammer(s) to successfully install the pile to the required depth. The pile drivability assessment is carried out using a combination of a wave equation analysis and the soil resistance to driving (SRD). However, the methods to estimate SRD and the drivability analysis vary between offshore and onshore. This paper presents some selected experiences for both onshore and offshore locations for estimating SRD and carrying out drivability analysis. The procedures for SRD estimations for offshore include use of CPT data and friction fatigue concept during installation. The similarities and dissimilarities between the onshore and offshore situations are demonstrated for SRD predictions and drivability analysis.

RÉSUMÉ

Les pieux tubulaires en acier entraînés sont le plus souvent utilisés pour les structures extracôtières (offshore) et deviennent également de plus en plus populaires sur terre (onshore). Généralement, les pieux offshore sont nécessaires pour supporter des charges importantes, ils ont un diamètre, une épaisseur de paroi et une longueur, utiliser de l'acier de haute performance plus importants et nécessitent l'installation de marteaux à des impacts à énergie forte. Les prédictions de la maniabilité des pieux sont essentielles pour sélectionner le(s) marteau(x) approprié(s) pour installer le pieu à la profondeur requise. L'évaluation de la maniabilité du pieu est réalisée en combinant une analyse de l'équation d'onde et la résistance du sol au battage. Cependant, les méthodes d'estimation de la résistance du sol au battage et l'analyse de la maniabilité varient entre offshore et onshore. Cet article présente quelques expériences choisies sur des sites onshore et offshore pour estimer la résistance du sol au battage et effectuer une analyse de la maniabilité. Les procédures d'estimation de la résistance du sol au battage pour l'offshore incluent l'utilisation des données CPT et le concept de fatigue par friction lors de l'installation. Les similitudes et les dissemblances entre les situations onshore et offshore sont démontrées pour les prédictions de la résistance du sol au battage et l'analyse de la maniabilité.

1 INTRODUCTION

Driven steel tubular open ended piled foundation systems are most commonly used for offshore hydrocarbon installations, commonly called as 'jacket' platforms supported on groups of driven piles. Piles can be driven into the seabed from above the water using jack-up rigs or other floating barges with pile driving hammers, an operation like the onshore pile driving. For deeper water offshore structures, the piles may be driven using a remotely operating vehicle (ROV) and by underwater hydraulic hammers. Offshore pile foundations usually have bigger axial (compression and tension) and lateral loads and may also have to resist larger torque. Offshore piled foundations sometimes may have shorter design life (20 to 40 years) compared to onshore piled foundations (typically 30 to 50 years or longer). Offshore piles are subjected to large cyclic loads from the ocean environment. Therefore, offshore piled foundations tend to have much bigger pile diameter, wall thickness, and longer lengths, often use high performance steel and are driven with the high-impact energy hammers, and the number of hammer blows could be larger. The pile driveability assessment is carried out using a combination of a wave equation analysis and the soil resistance to driving (SRD) estimates. However, the

methods to estimate SRD and drivability analysis vary between offshore and onshore. This paper presents some selected experiences in pile drivability assessment for the selected onshore and offshore locations. The procedures for SRD estimations for offshore include use of CPT data and friction fatigue concept during installation. The similarities and dissimilarities between the onshore and offshore situations are demonstrated for SRD predictions and input to wave equation analysis. Typically soil profiles are modelled as "sand" and "clay" profiles. Soil Parameters typically include cone resistance, sleeve friction, unit weight, friction angle and undrained shear strength as key inputs for SRD estimates. The soil data is more refined for offshore projects and the methods are more rigorous compared to the onshore projects. Load testing is carried out for onshore projects to confirm or optimise on mobilized pile capacities while as offshore pile more relied on PDA analysis, lessons learned from previous operations and load tests are seldom carried out.

Pile drivability predictions are critical for installation and to the installation contractor in selecting appropriate hammer(s) to successfully advance the pile embedment to the termination depth, and for the designer in selecting the pile material appropriate to keep the driving stresses and driving fatigue damage within tolerance.

2 PILED FOUNDATION INSTALLATION

The most common method of installing steel piles is by impact driving using hydraulic hammers. Sometimes driving is assisted with predrilling. Steel pipe piles are preferred for offshore installation and are becoming popular onshore as well. Figures 1 to 3 show typical installation methods for onshore, nearshore and offshore.



Figure 1. Typical Onshore Pile Installation Set-up



Figure 2. Typical Near-shore pile installation Set-up (from Brzeninski and Baba 2013)

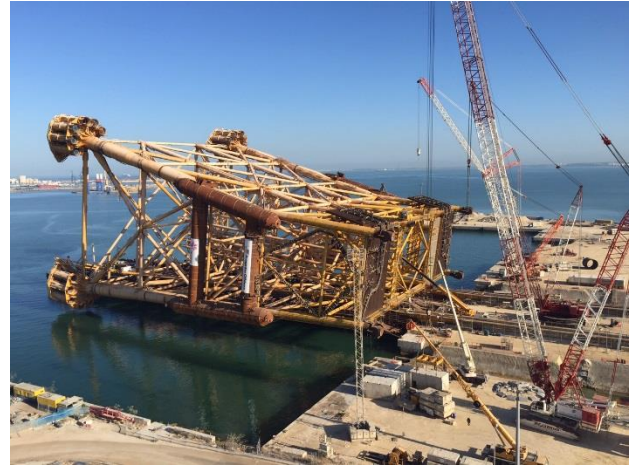


Figure 3. Typical Deep-offshore Jacket Sleeves for Pile Cluster Installation with Underwater Hydraulic hammers (Dragados Offshore 2015).

In Figure 3, six (6) piles are clustered around each leg of the jacket. The jacket is fixed to the seabed by piles installed through sleeves attached to the legs. Piles are installed using underwater hammers and are grouted to the sleeve after installation.

3 PILE MATERIALS AND LOAD CAPACITIES

Table 1 presents typical pile geometry and material properties, typical soil conditions, and pile capacities in compression from two project sites (onshore and offshore) to illustrate the differences. The project example for onshore is from a discontinuous permafrost site where the upper 8 m were ice rich and not considered to contribute to the capacity in compression due to degradation of permafrost (ice melting) over time. The offshore project example is from a site in North Sea. Pile wall thickness is controlled by a combination of axial load and bending moment which may vary along its length, however for this paper it is assumed to be constant.

Table 1. Pile Geometry, Material Grade and Soil Conditions

Characteristics (%)	Onshore ¹	Offshore
Pile Geometry:		
(Dia. x wall thickness)	356x15mm	2438x100mm
Embedment Length	15 m	40 m
Material:		
Grade	ASTM Gr 3	Steel Y45
Yield Strength	300 MPa	460 MPa
Tensile Strength	400 MPa	550-770 MPa
Load Capacity	1,500 kN	90,000 kN
Soils	2m GRAVEL fill followed by 6 m thick ice rich MIXED soil, over hard TILL	Very stiff to very hard CLAY and dense to very dense SAND

¹Refer: Baba et al 2015

4 SOIL RESISTANCE TO DRIVING

Computation of the soil resistance to pile driving is analogous to the computation of ultimate axial capacity (compression) by the static method. The resistance to driving is the sum of the shaft resistance and the point resistance. The shaft resistance is computed by multiplying the average unit skin friction during driving and the embedded surface area of the pile. The point resistance is computed by multiplying the unit end bearing and the end bearing area. Driving resistance is the lesser of summation of outer shaft friction plus full end bearing or outer and inner friction plus pile wall end bearing.

Soil profile idealization and parameters representing a moderately conservative profile are used as the basis for SRD estimates in comparison to the static capacity where a relatively lower bound generalized profile and parameters are used. Soils are usually treated as “clay” or “sand” model as in the static capacity estimates. For example, in Canada, for onshore structures, the Canadian Foundation Engineering Manual, CGS (2006) is followed to estimate SRD. A similar approach is followed in other jurisdictions for onshore and to a large extent by the American Petroleum Institute API (2007) for offshore structures.

$$SRD = Q_u = Q_s + Q_t = f_s A_s + q_t A_t \quad [1]$$

Where:

- Q_u = ultimate pile capacity or SRD;
- Q_s = skin friction resistance;
- Q_t = total end bearing;
- f_s = unit skin friction in compression;
- A_s = side surface area of pile;
- q_t = unit end bearing capacity
- A_t = cross sectional area of pile toe

The key is in accurate estimation of f_s and q_t for given soil model.

4.1 “Sand” Model Soil Profile

For cohesionless soils, the unit skin friction and unit end bearing at any depth z along the pile or at tip is given by relating to the effective vertical stress adjacent to the pile or at tip at that location:

$$f_s = \beta \sigma' \text{ or } K \tan \delta \sigma' < f_l \quad [2]$$

Also known as beta or effective stress method

$$q_t = N_t \sigma' < q_l \quad [3]$$

Where:

- β = a combined shaft resistance factor;
- K = coefficient of lateral earth pressure;
- σ' = effective overburden stress adjacent to pile at a depth or at the pile toe;
- δ = friction angle soil/pile interface;
- f_l = limit unit skin friction;
- q_t = unit toe bearing;
- N_t = bearing capacity factor;

4.2 “Clay” Model Soil Profile

For cohesionless soils, the unit skin friction and unit end bearing at a depth along the pile or at tip is given by relating to the undrained shear strength at that location:

$$f_s = \alpha s_u \quad [4]$$

Also known as alpha or total stress method

$$q_t = N_c \sigma' < q_l \quad [5]$$

Where:

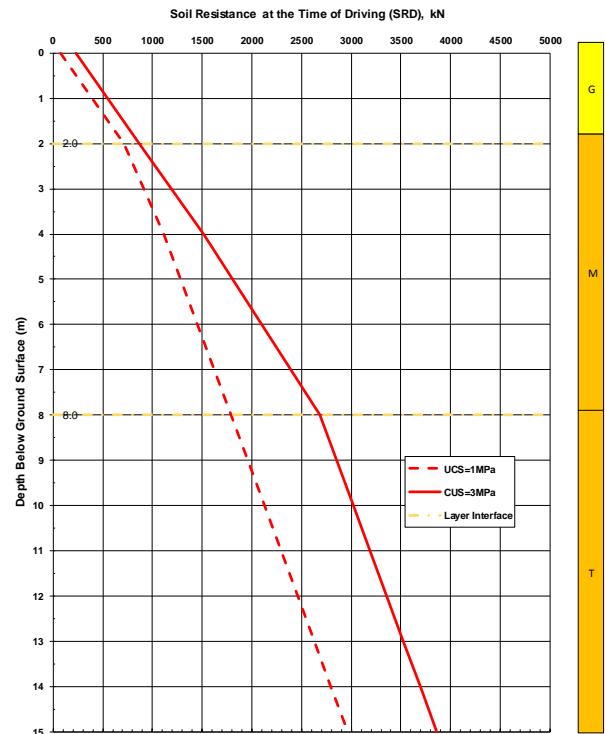
- s_u = undrained shear strength (UCS/2);
- α = soil/pile interface adhesion factor ≤ 1 ;
- N_c = bearing capacity factor $N_c = 9$ for smaller diameter piles;

Limiting unit skin friction and limiting unit end bearing apply depending on soil density/type.

The SRD estimate for an onshore pile driving operation through hard till in Northern Manitoba, is presented here, for details refer to Baba et al (2015). SRD predictions were based on assuming very hard till through full penetration depth of 15 m and the following soil model parameters were assumed:

- Unit Skin Friction: 150 kPa;
- Unit End Bearing: $9s_u$ (s_u of 500 and 1500 kPa) or 4,500 kPa and 13,500 kPa range.

The SRD prediction for this onshore example is shown in Figure 4.



Notes: G: Pit run gravel fill; M: Mixed Soil; T: Hard Till

Figure 4. SRD Profile Typical Onshore Development

Cone penetration testing CPT forms the main investigation tools for offshore structures facilitating improvements in prediction of SRD. The CPT is a model

test for the penetration of a pile. The most common methods used for offshore pile driveability and more so for North Sea conditions are Alm and Hamre (2001), and Toolan and Fox (1997) methods, both using CPT data to refine SRD predictions.

Alm and Hamre (2001) method is based on the friction fatigue concept used in both clays and sands, wherein pile unit friction at a given elevation tends to decay during driving as the pile penetration progresses. Thus, friction reduction would be more prominent for long piles. Primarily the cone data is used for SRD computation: the net cone resistance is used for estimating unit bearing both in sands and clays; and the cone sleeve friction for estimating unit skin friction in clays. API friction angles for sand are used for estimating unit skin friction in sands with no limits applied. The method uses a conservative average of the cone resistance and sleeve friction profile for estimating conservative best estimate SRD. For the upper bound SRD, a factor of 1.25 on the best estimate SRD is applied.

Toolan and Fox (1997) method for clays is based on remoulded shear strength (S_{ur}) as unit shaft friction with a limit of 250 kPa. Indirect measurements of remoulded shear strength are available to obtain S_{ur} profile from CPT shaft friction profile and known soil properties. The end bearing during driving may be calculated directly from the cone resistance as being unit end bearing with no limit. For sands the improvement includes that the end bearing values are supplemented by cone penetration test data, with a limitation of 60% of the measured cone point resistance subject to maximum of 50 MPa.

Using the above two methods, the SRD prediction for an example North Sea site, from our project files, is shown in Figure 5. As can be seen from Figure 5 SRD profile the Toolan & Fox method produced predictions on the conservative side in comparison to Alm & Hamre method, as expected due to friction fatigue concept, particularly for long piles.

The above assumptions are for unit shaft resistance and unit end bearing resistance during driving and not for re-driving where a "set-up" may apply, and the SRD may be higher.

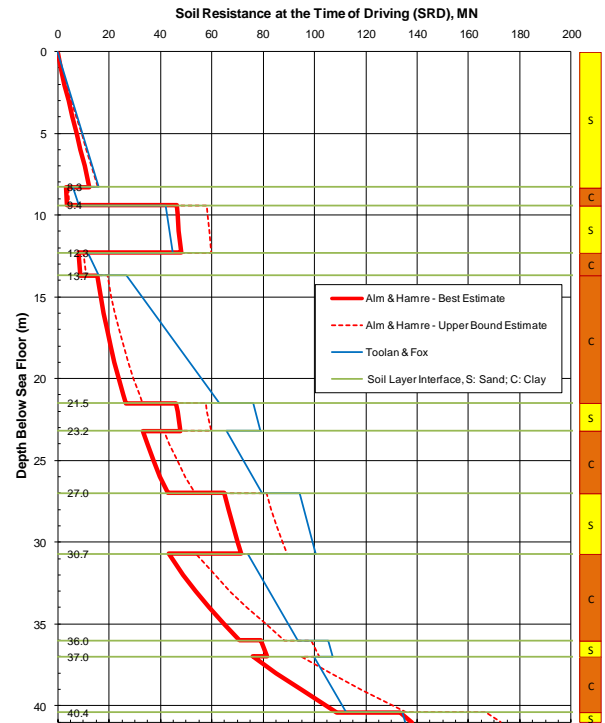
Several other methods are also in use for SRD prediction for offshore structures that include Semple and Gemeinhardt (1981) and Steven (1982) just to name a few.

In general, similar approaches are being used onshore and offshore applications for SRD estimation. Friction fatigue concept is an improvement for offshore applications and it has potential to be applicable for onshore long piles. Offshore methods tend to be site specific.

5 PILE DRIVABILITY ANALYSIS

A wave equation analysis is used to investigate the dynamic behaviour of the pile during driving, predicting:

- The maximum resistance that the hammer can overcome or the refusal depth
- Blow count v/s penetration depth;
- Maximum stresses (tension and compression) v/s depth; and
- The maximum resistance that the hammer can overcome or the refusal depth



Notes: S: "Sand" model; C: "Clay" Model

Figure 5. SRD Profile Typical Offshore Development

Pile Dynamics Inc. (2005) computer program GRL WEAP is used for wave equation analysis. The inputs to the program include the values of quake and damping as presented in Table 2, and hammer data as presented in Table 3. Sometimes the damping values are determined specific to site and SRD method, since the SRD methods are refined after back analysis or calibrations from the site and soil specific data.

Typically results from one dimensional wave equation analysis are presented as a bearing graph result shown in Figures 6 and 7 and/or as drivability graphs as shown in Figures 8 and 9.

Table 2. Wave Equation Parameters

Damping in clays	Damping in sands	Quake in clays and sands
Smith (1960)		
Side - 0.656 s/m Point - 0.492 s/m	Side - 0.164 s/m Point - 0.492 s/m	Side - 2.54 mm Point - 2.54 mm
Toolan & Fox Method		
Side - 0.656 s/m Point - 0.33 s/m	Side - 0.164 s/m Point - 0.492 s/m	Side - 2.54 mm Point - 2.54 mm
Alm & Hamre Method		
Side - 0.25 s/m Point - 0.20 s/m	Side - 0.25 s/m Point - 0.2 s/m	Side - 2.54 mm Point - 2.54 mm

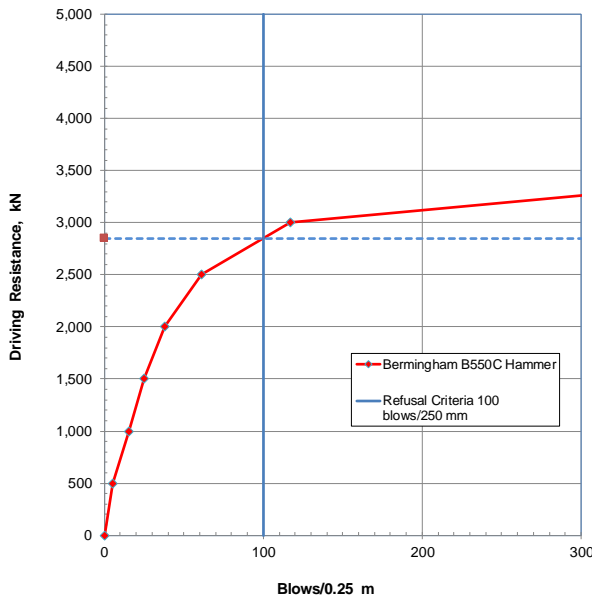
Table 3. Hammer Data

Damping in clays	Birmingham B550C	MHU 3000
Maximum net impact energy, kNm	119	3000
Hammer efficiency	0.8	0.85
Ram mass, kN	48	1619
Anvil mass, kN	-	383
Spring constant ram-anvil, kN/mm	43000	50000
Coefficient of restitution ram-anvil	0.8	0.95

If the refusal criterion is considered as 100 blows/250mm. The bearing graph for onshore structure indicated that the refusal would occur at about SRD = 2850 kN. Therefore, to overcome the full SRD of 4000 kN, predrilling ahead of driving was required.

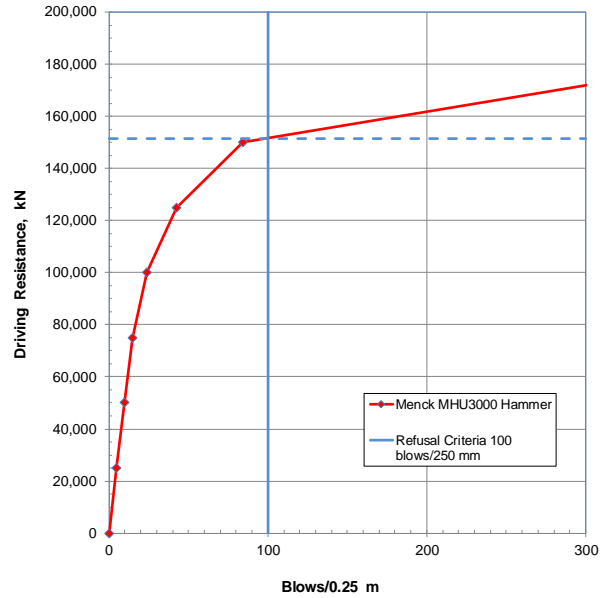
For the offshore structure it indicated that for the given hammer/pile system the refusal would occur at about SRD = 150MN. Therefore, the hammer was capable to drive to the full embedment length.

For both the structures, the pile steel stresses tension and compression were within the allowable stress ranges. It is to be noted here that offshore structures tend to use high performance steel.



Notes: 75% shaft; Pile Details as per Table 1 and Hammer Details as per Table 3.

Figure 6. Typical Bearing Graph – SRD v/s Blow Count (Onshore Structure)



Notes: 75% shaft; Pile Details as per Table 1 and Hammer Details as per Table 3.

Figure 7. Typical Bearing Graph – SRD v/s Blow Count (Offshore Structure)

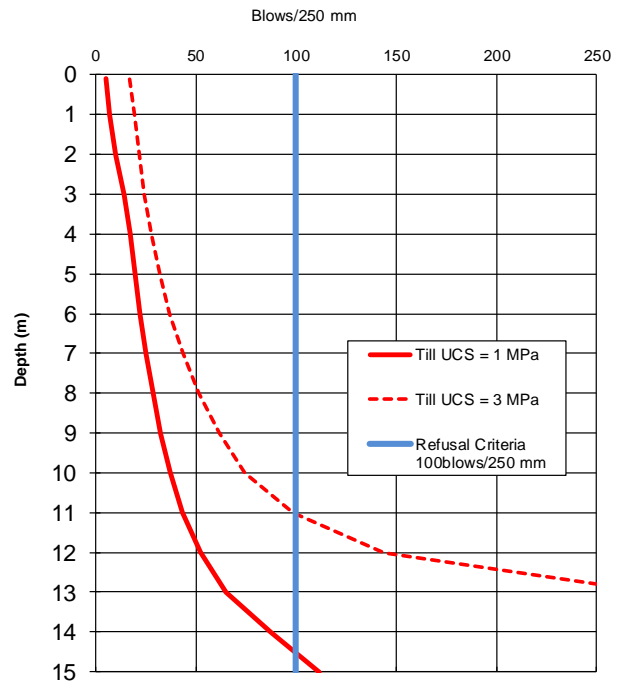


Figure 8. Blow-count v/s Depth for Onshore Structure

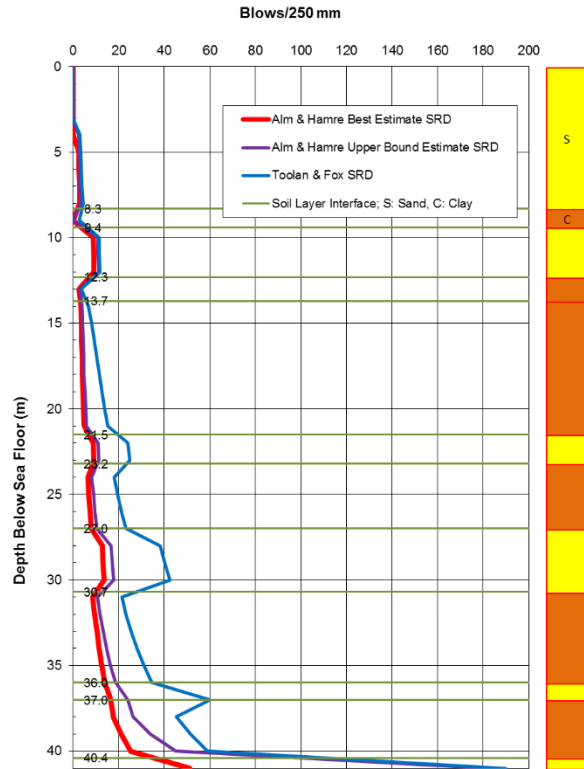


Figure 9. Blow-count v/s Depth for Onshore Structure

Therefore, similar approaches are being used onshore and offshore applications for pile drivability analysis, with modified inputs based on site-specific database.

6 CONCLUSIONS

Pile drivability predictions are critical for the installation and design of driven pile foundation systems. The pile drivability assessment is carried out using a combination of a wave equation analysis and the soil resistance to driving (SRD). The methods used to estimate SRD are empirical and have been developed from the back-analysis of pile-driving records. Different procedures are developed for cohesionless soils "sand" and cohesive soils "clay". Computation of the SRD is analogous to the computation of ultimate axial capacity (compression) by the static method, hence the accurate estimation of f_s and q_t during continuous driving for a given soil model is the key. Soil profile idealization and parameters representing moderately conservative profile are used as the basis for SRD estimates in comparison to the static capacity where relative lower bound generalized profile and parameters are used. The SRD estimate for onshore and offshore structures uses the same concept, however, offshore developments rely more on cone penetration data and calibrations in terms of inputs to SRD and Wave equation parameters from back analysis albeit site specific. Friction fatigue concept is an improvement for offshore applications and it has potential to be applicable for onshore long piles. Similar approaches are being used onshore and offshore applications for pile drivability analysis.

Given the offshore structures support large loads, the piles are larger in diameter/wall thickness and offshore hammer are heavy and required large number of blows to reach to the design penetrations, tend to use high performance steel.

Steel tubular piles are used for offshore structures and these are becoming popular onshore as well. With increasing applications for offshore structures, offshore SRD methods are also finding way in onshore application.

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