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Introduction and Conclusions

Introductions

This booklet provides information about the installation of foundation piles for fixed platforms. It is provided by Seaway Heavy Lifting Engineering (SHL), and it incorporates the experience of SHL as a successful installation contractor for the oil and gas industry. This booklet intends to provide additional information to come to a “total cost” approach for platform foundation designs. From SHL experience, the pile installation aspects of a platform are not always properly incorporated into the design. Typically, pile design is based on ultimate axial and lateral capacity requirements only. Driveability of the piles, which are of major importance to the economics of an overall platform installation, is often not considered. With this booklet, SHL clarifies that investing in pile material can have a very compelling money saving potential for the overall project.

Specific Interests of Parties Involved

Operators, EPIC contractors and installation contractors have different interests in a platform design:

- The operator requires a sound platform at the lowest cost. The platform must last for many years so that it can become a hub in the event of substantial finds in the same area.
- The EPIC contractor designs the platform at the lowest fabrication cost. These contractors generally bid for the work in a very competitive market especially in case of a design competition. The competitive process causes bidders to ignore the installation aspects of the platform and the piles, which may add to the material costs. Soil mechanics is not an exact science and soil properties are not always precisely known. These factors often cause EPIC contractors to select the lightest possible pile design and by doing so, they jeopardise pile driveability. These contractors assume that the pile can be driven to an acceptable penetration without requiring remedial actions.

- Installation contractors are focused on an optimum vessel schedule with the lowest uncertainty about durations. Hence, the installation contractor requires a pile design that allows the use of a larger hammer in case of heavy driving. This approach reduces the chance for remedial work caused by pile refusal.

Pile refusal is an unacceptable risk for an installation contractor as it could double or triple the overall installation duration and these unanticipated delays (due to remedial work), cause disruption to their schedule and may well affect subsequent projects. An installation contractor’s bid will reflect this potential commercial impact. Therefore, the installation contractor always puts great effort into analysing the driveability of the piles.

In the section “Pile Make-Up and Driveability” the effect of the pile wall thickness on its driveability is explored further. The commercial implications for two different pile designs are examined at the end of this booklet.

Key Features

- Proper pile design can save millions.
- Pile refusal is an unacceptable risk for installation contractors.
- Pile driveability analysis must be part of the platform foundation design.
- Pile wall thickness is of major importance to the pile’s driveability.
Soil Investigation

General

Site investigations are often in progress when budgets are restricted because the final investment decision has not yet been made. There is always pressure to minimise costs and therefore, also the scope of work. Furthermore, platform location may not yet be certain. These factors, unfortunately, conflict with the future success of the project.

The extent of the soil investigation has significant implications on the cost of a project. If only limited information is available to the engineering contractor, a conservative approach with regards to the pile design is adopted with subsequent cost effects. Since soil investigations are the first site works, the soils information may not yet be available to the engineering contractor or EPIC contractor to optimize the foundation design. This approach can lead to piled foundations that are often over-designed.

This “waste”, which is ultimately paid for by the operator, can be greatly reduced if sufficient soils data is available before the pile design starts.

Furthermore, the cost and time overruns are attributable to inadequate information about the soil conditions. It is important therefore, to strike the correct balance between the cost of the soil investigation and its accuracy. Identification of the type of tests performed, the required results and the correct borehole locations optimise the total project cost.

Effective soil investigation has the purpose of risk and cost reduction. Hence, it is important that these investigations have an accurate specification and direction. Any soil investigation should be carried out by a specialised geotechnical company, preferably under the supervision of an operator representative. At the proposed platform location, typically one or two boreholes are drilled to a depth likely exceeding the pile’s design penetration. At regular intervals, or when soil layer changes are foreseen, soil samples are taken for laboratory tests.

Conclusions

• A good foundation design not only results in an efficient installation, but also it reduces the overall cost of a platform.
• Premature refusal could cost millions of dollars exceeding the original price for the platform installation itself. Therefore, to reduce this risk, a proper driveability study during the design phase is required.
• Remedial work on the pile foundation could take weeks. This delay may jeopardise the first production date of the platform and incur costs for remedial work.
• In a good pile design, the pile wall thickness must be sufficient to transfer the hammer’s energy.
• An optimal pile design allows for a more powerful hammer to be stabbed when harder than expected driving is encountered.
• Installation aspects, such as allowable freestanding pile lengths versus required hammer energy, should be considered for the final pile make-up.
• The accuracy of a pile driveability study can be highly optimised by incorporating other knowledge, such as performing back analyses using the observed blow counts of the as-installed piles of a nearby platform.
The goal of these laboratory tests is to indicate the soil's characteristics. A cone penetration test (CPT) can be carried out in the hole and indicates the density of the soil. A CPT generally consists of two measurements: tip resistance and shaft friction. An electrical cone is pushed into the undisturbed strata at a preset speed. The cone resistance is an indication of the in-situ density of the soil and the shaft friction is an indication of the likely friction the soil can mobilise. Other kinds of special tests can also be performed in the borehole. For example, a vane shear test and dissipation test can be added. Where harder clays, higher density sands, or cemented materials are encountered and if the CPT capacity is insufficient, coring is advised. With the soil sample, the soil engineer can observe and determine the properties of the material. It is important to assess the hardness or strength of the material, as well as the thickness of the layer.

When a soil investigation is performed and reported, pile axial and lateral ultimate capacity computations are made. Piles are then designed as a foundation for the proposed structure. If the soil investigation is of poor quality, for example, if the investigation has unreliable CPTs and is done without proper sampling or coring, then lower limits are applied for the ultimate static capacity calculations. This application of lower limits might result in an approach that is too conservative and as such, the foundation is over-designed, which is not economical.

For an effective installation, the installation contractor must know the upper boundary strength of the soils. With this knowledge, the contractor can select the hammer that will “certainly” drive the piles to their target penetration. Often this data is not available due to a poor quality CPT or the lack of cores taken and tested, particularly in areas where cemented soils, calcarenite, or gypsum are evident.

This lack of information and this intolerance for risk of an inadequate pile design often leads to over-designed (deeper) target penetration when hard driving is foreseen. Ultimately, in the event of pile refusal, the operator runs a significant risk of budget overrun and late platform delivery.

Soils Investigation and Pile Installation

Piled platforms are common worldwide. Offshore pile driving has been carried out at numerous locations by many contractors, although not always with success. Sometimes, premature refusal or too-easy driving to target penetration is encountered. In both cases, the platform installation work stagnates. Installation can be resumed only after the problem is resolved – initiate remedial activities or accept the situation. If remedial action is required, which remedial action needs to be carried out? Whatever action is chosen, the overall platform installation time takes longer and costs more than expected. These additional costs can be very high, especially if specific equipment for a remedial activity was not mobilised with the installation spread.

Therefore, it is important to establish the pile make-up, not only on the soil strength reported and on the required design loads for the piles, but also incorporating the installation aspects. The platform loads define a pile target penetration only. However, hard layers might be evident between the seabed and the defined target penetration. In such cases, premature refusal might occur in the hard layer. If the pile make-up is designed to cope with that hard layer and the piles are matched with a properly selected pile-driving hammer, then that premature refusal probably can be avoided.

Soils can be classified in different groups, with their own characteristics in relation to pile ultimate static capacity. Likewise, soils can be characterized by their behaviour during pile driving. A desk study to define the suitable hammer to drive the piles is always needed to evaluate the most economical installation for the given situation. The study avoids the requirement for too many add-ons and reduces beforehand the risks related to premature refusal or drop falls (loss of hammer-pile contact, damage to the crane) caused by a pile resistance that is too low.
Soil Set Up

Due to pile driving, the soils will remould (fatigue) along the pile wall. After a pause or stop in pile driving, the soil has a tendency to obtain its original strength again. This phenomenon is called soil set up. Set up is dependant on the soil type: The set-up factor in sands is relatively low, while the set-up factor in plastic clays is high. Therefore, consider set up when planning the intermediate stops to reach target penetration.

Shaft Friction and Tip Resistance

Soils that typically cause premature refusal are cemented layers, calcarenite, gypsum, large boulders as well as very hard clays and very dense sands. Associated problems are the depth at which these layers or boulders are found: near the seabed or at greater depth. Regardless of where the hard layer is encountered, if low frictional resistance occurs in the soft layers above, then practically all hammer energy can still be transferred to the pile toe to obtain tip displacement. However, if substantial frictional resistance is already built up along the pile wall when the hard layer is reached, then much of the hammer energy is needed to overcome the frictional resistance. In this case, only a small portion of energy is available to achieve tip displacement into the hard layer. Therefore, the risk of refusal is higher when the hard layer occurs at deeper depth, especially in combination with a high friction resistance buildup.

In some soils, soft layers are present over intervals and low frictional soil resistance is built up along the pile wall at that depth. Driving in these soils brings the risk that the pile falls free after a single blow, even at a low energy setting of a hydraulic hammer. In such a situation, the pile-hammer contact is lost and another blow might then damage the crane. A similar situation could occur where the resistance is unexpectedly low near target penetration. Too much energy in the hammer blows might force the pile farther than the target penetration, i.e., the pile might be “lost” in the leg or sleeve.

Such situations are more common with a steam hammer than with a hydraulic hammer. The reason is that the energy output in a hydraulic hammer can be fully controlled.

Stops during pile driving are caused by a hammer breakdown, bad weather or scheduled stops to weld add-ons. Planned stops should be carefully scheduled for welding add-ons. Do not schedule a stop when the pile toe is at or in a hard layer. In this case, not only will the pile toe have to overcome the increased frictional resistance due to set up, but also it must overcome a higher pile tip resistance to penetrate into a hard layer at the same time. This combination can easily lead to premature refusal when a change-over to a larger hammer cannot be initiated. The larger hammer may have a restriction in relation to the pile-free length. Or, the hammer needed to overcome the soil resistance may exceed the pile’s maximum allowable driving stress. Therefore, a good driveability study must account for set up.
Back Analysis

Even when a soil investigation is carried out to the highest standard, soil remains a natural substance and its behaviour is not 100% predictable. Generally speaking, a back analysis of driving results of a nearby (as-installed) platform is strongly recommended whereby local experience can be incorporated in the predictions for the new piles. This local experience is useful especially if intermediate hard layers and/or hard driving conditions near target penetrations are expected. The back analysis results in an optimal scheduling of add-ons, a good assessment of the required wall thickness (W. Th.) of the pile sections and selection of the most suitable hammer. Therefore, the installation can be started with a high degree of confidence that the piles can be driven to target penetration, without the risk of premature refusal.

Key Features

• Adequate soil investigation reduces the project risk.
• Cone penetration tests should be executed to the maximum capacity of the equipment giving the soil’s density.
• Soils data should identify not only the hard layers but also the soft layers (to reduce the risk of refusal and drop falls, respectively).
• Intermediate stops during pile driving can cause premature refusal due to set up of the soil.
• Back analysis of local experience improves the accuracy of the driveability analysis.

Platform Foundation Piles

General

To account for natural variations in soil conditions and soil behaviour, there could be a preference to minimize the shear load on foundation piles, in particular when the top soils are soft. Minimum shear loads are realised by inclining the piles. By doing so, the piles are installed through the platform legs and the whole pile installation operation is performed battered.

Skirt Piles

An alternative for piles installed through inclined platform legs is to use skirt piles. Skirt piles are installed along battered platform legs through guides and using “long” followers. The advantages of skirt piles are to use less pile material and to have the option of adding more piles around the jacket leg to transfer the jacket loading to the soils. The disadvantage of using these battered skirt piles is longer installation duration due to follower handling. This negative effect can be omitted by using vertical skirt piles.
Vertical Skirt Piles

The most economical solution is to drive vertical skirt piles. The hydraulic hammer drives directly on top of the skirt pile or is used in combination with a “short” front follower. The driveability of vertical skirt piles is of crucial importance. If the pile meets refusal, it must be drilled out. The drilling assembly must be operated above water at a relatively large distance from the jacket top elevation and the assembly requires a special outrigger. Therefore, a vertical skirt pile is recommended only if the driveability of the piles is verified properly and the risk of premature refusal is negligible.

For vertical skirt piles combined with soft top soils, a thicker W.Th. is required for the pile section near seabed. This added thickness is needed because the shear loads in this case are not transferred as per battered piles. Vertical skirt piles have the following advantages:

- The total installed pile length is much shorter than a pile installed through a jacket leg, saving significant pile material.
- If a front follower is used, then the pile head can be driven almost flush with the top of the pile sleeve, again saving pile material. In this context, it must be noted that the required front follower is costly and only favourable if a series of skirt piles are to be installed.

- A vertical skirt pile is typically installed in one section. This pile configuration is possible since allowable freestanding pile lengths are much longer for vertical skirt piles than for inclined piles. The hydraulic hammer can be regulated at a low energy setting at the start of driving. Gradually, the energy setting can be increased in accordance with soil resistance met during driving (SRD). Therefore, often only one piling hammer is needed for the installation.
- Consequently, no driving stops for stabbing and splicing of add-ons are required. Thus, fast installation and less risk of premature refusal are realised.
- During installation, the loading on the jacket’s mud mats is substantially less when vertical skirt piles are used than for a main pile. When a very soft seabed is evident, vertical skirt piles also reduce the installation risk of additional levelling upon completion of the piling operation.
- Skirt pile installation is faster than main pile installation because fewer pile sections are used.
- Vertical skirt pile can accommodate hydraulic hammers directly in contrast to inclined skirt piles, which require followers.
- The jacket is secured faster with vertical skirt piles than with inclined skirt piles or main piles.
Followers

General

Followers are used for the installation of piles when driving directly on top of the pile is not possible or not preferred. The stabbing point of a follower may be subjected to severe acceleration forces. External forces acting on the gravity connector are caused by:

- Pile inclination
- Jacket out of level
- Rotation due to clearance in guides
- Rotation due to clearance in the gravity connector
- Bending of the pile or follower string, including second-order effects caused by dead loads, hammer weight, wind, waves, current and vessel excursion

Driving heads for followers are subject to the same design rules as piles. Follower attachments must be designed for acceleration forces.

Vent holes are required in a front follower when driving directly on a pile under water. A vent hole discharges a volume of water equal to the reduction of the volume inside the pile under the fastest progress during driving. Drill vent holes carefully to prevent cracks during pile driving.

The effect of the use of a follower in relation to energy transfer from the top of the follower to the top of the pile is typically a loss of approximately 10%.

Flying Follower

A flying follower is a follower extending the generally inclined pile above its support. A flying follower is typically applied when the top of a main or skirt pile is to be driven through the top of the leg or through a top guide. Depending on the hammer scheduled, follower length and pile batter, severe bending moments may occur in the gravity connector of the follower. For that purpose, these followers are equipped with a moment resistant gravity connector.

Long Follower, Supported by Vessel

A long follower is used for the installation of a freestanding anchor pile with the follower supported against the installation vessel. The pile can be kept upright and installed within vertical tolerances. Depending on the hammer selected, follower stiffness, pile stiffness and the water depth, the gravity connector can encounter a high bending moment.

Front Follower

A front follower is typically used in combination with a hydraulic hammer to drive the piles flush with the template or jacket skirt pile sleeve. Front followers are usually short and the piles to be driven with them are usually vertical. Thus, bending moments in the gravity connector of a front follower are small.
Pile-Driving Hammers

General

Today, hydraulic hammers are accepted as the proper tool to install foundation piles. These hammers are suitable for above water as well as underwater operations. Although steam hammers are still operational, hydraulic hammers have many advantages over steam hammers and are therefore highly preferred.

Energy Levels

It is better to compare pile-driving hammers by their net driving energy rather than by their rated energy. Energy losses occur due to mechanical losses, such as downward travel of the ram, inclination, losses over the cushion and losses over the anvil. The definitions below are important in this context for a better understanding of hammer efficiencies.

In the field of pile-driving hammers, the following definitions are used:

- **Rated energy** is the energy the manufacturer has rated the hammer.
- **Potential energy** – Energy potential of the hammer with the ram at highest point of maximum stroke.
- **Kinetic energy** – Energy of the hammer immediately before impact on the anvil.
- **Enthru energy** can be defined as energy transferred into the pile head.
- **Enthru efficiency** can be defined as the ratio between the enthru energy over the rated energy.

For hydraulic hammers, typically the rated energy is the kinetic energy. Depending on the configuration of the anvil and the pile, the efficiency of these hammers is 65% - 100%. A hammer has 65% efficiency when it is equipped with a relatively large anvil to drive large diameter piles. For example, an S-600 hammer in combination with a special purpose anvil, with a ratio anvil weight over ram weight of factor 3, to drive open-ended piles with an outside diameter (O.D.) of 5 m for a windmill foundation.

For typical piled platforms, the enthru efficiency is 90% - 100%. For steam hammers, the rated energy is typically the potential energy. The enthru efficiency of these hammers is about 58% - 67%.

Steam Hammers versus Hydraulic Hammers

One of the differences between hydraulic hammers and steam hammers is that steam hammers have an offshore cage. Hydraulic hammers have no offshore cages. However, hydraulic hammers do use a hammer sleeve. The hammer sleeve is stabbed over the pile and aligns the hammer with the pile. The advantage of working without an offshore cage is that less weight is involved. Owing to their refined design, hydraulic hammers are also lighter than steam hammers with a comparable energy level.

To ensure sufficient clearance between the piling hammer and the jacket construction at the end of drive, a pile make-up should always be designed to have 0.50 m clearance between the bottom of the hammer sleeve and the top of a jacket leg (main piles) or the top of a catcher on a pile sleeve (skirt piles). The stick-up at the end of a drive is therefore fixed by a hydraulic hammer and determined by the hammer sleeve used.

In contrast to hydraulic hammers, steam hammers use cushions (asbestos/steel laminations for Vulcan hammers and Bongossi wooden cushion blocks for Menck hammers). The cushion prevents damage to the hammer assembly during driving. However, energy absorption occurs over the cushion and in combination with mechanical losses in the system (especially by driving under a batter) is in the order of 58% - 67% for enthru/rated energy.

The hammer signature of a hydraulic hammer differs from that of a steam hammer. A hydraulic hammer produces a shorter signature with a higher peak value. This short signature with a high peak value is caused by the use of a steel anvil with no additional cushion. Consequently, special anvils are required to make steel-to-steel driving possible. Since the hydraulic hammers do not use cushions, no cushion changes are required, which in turn lessens the risk of set up. The hydraulic hammer signature is favourable when driving into dense or hard soils.
A disadvantage of the hydraulic hammer is that the higher peak stress in the pile affects the allowable stick-up of the pile. To overcome this disadvantage, use a thicker wall and/or use a higher yield stress of the pile material.

Hydraulic hammers can be used for above water as well as underwater pile driving. When driving vertical piles under water (such as when driving skirt piles), the hammer can be placed directly on top of the skirt pile or a front follower (connected to the hammer’s pile sleeve). In principle, the hammer stays under water and drives all skirt piles in a batch. When a front follower is scheduled, the overall length of the skirt piles can be reduced to drive the pile flush with the skirt pile sleeve. In this configuration, the front follower ensures that the hammer sleeve has sufficient clearance with the skirt pile sleeve.

Hydraulic Hammer Energy Setting

The energy level of hydraulic hammers can be adjusted. This capability has various advantages with regard to optimisation of the pile make-up and pile driving:

1. When low SRD is evident, a low energy level is required. For example, the SRD is low at the start of driving and a reduced hammer energy prevents drop falls. The energy level may also be low near target penetration. Controlled driving with a low energy level reduces the risk of loss of pile hammer contact where the pile head disappears into the leg.
2. If a pile can be driven with a reduced energy level, then the:
   • Blow rate is increased, resulting in a faster installation.
   • Stresses in the pile are lower, thus the pile encounters less fatigue.
   • Lower dynamic component for the total stresses occur at the top support, resulting in a longer allowable pile stick-up and probably fewer add-ons.

Summary of Hydraulic Hammers versus Steam Hammers

<table>
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<tr>
<th>Hydraulic Hammer</th>
<th>Steam Hammer</th>
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<tr>
<td>Above and underwater use</td>
<td>Only for above water</td>
</tr>
<tr>
<td>Fully controlled impact energy 5% - 100%</td>
<td>No control on impact energy</td>
</tr>
<tr>
<td>Lower weight / energy ratio, thus longer add-ons possible</td>
<td>Higher weight / energy ratio, thus shorter add-ons required</td>
</tr>
<tr>
<td>Integral monitoring system</td>
<td>No energy monitoring system</td>
</tr>
<tr>
<td>Fixed hammer sleeve length</td>
<td>End of drive cage can be lifted</td>
</tr>
<tr>
<td>High reliability</td>
<td>More sensitive to breakdown</td>
</tr>
<tr>
<td>No cushion changes</td>
<td>Regular cushion changes</td>
</tr>
<tr>
<td>Negligible energy losses</td>
<td>Substantial energy losses over cushion</td>
</tr>
<tr>
<td>Less risk of soil set up</td>
<td>Risk of soil set up</td>
</tr>
</tbody>
</table>

Key Features

• Hydraulic hammers are more reliable and efficient than steam hammers.
• Hydraulic hammers can work above and under water.
• The impact energy for the hydraulic hammer can be controlled from 5% to 100%.
• The hydraulic hammer performance is monitored automatically.
Pile Make-Up and Driveability

General

Often the driveability of the piles is not thoroughly investigated by the engineering company due to a lack of knowledge or experience. When the pile driveability is to be assessed on inadequate soil data, the result might be a too optimistic driveability expectation. For instance, piles are predicted to reach target penetration with a relatively low-capacity hammer.

The allowable freestanding pile length above the top of pile guide or jacket leg is related to the weight of the hammer used. A heavier hammer allows for less freestanding pile length. A check for dynamic stresses combined with bending stresses must always be made. The criterion is usually static buckling. Hence, the lighter hydraulic hammers tend to allow greater freestanding pile lengths than steam hammers with comparable energy levels.

At the end of pile driving (target penetration) the soil resistance during driving is usually high. Therefore, a hammer with appropriate energy to overcome the expected SRD is required. A high-capacity hammer is heavier than a low-capacity hammer. Thus, the associated allowable stick-ups become shorter.

If change-out from a smaller hammer to a larger hammer is scheduled, the change-out should occur before refusal is met. Furthermore, the expected blow count at the start of driving with the new hammer preferably shall not be greater than 50 - 60 blows/250 mm.

The pile lead section must be made as long as possible considering all installation aspects, followed by assessment of the add-ons length. Installation aspects such as allowable freestanding length, pile top interference and pile wall thickness will determine the add-on length. It is emphasised that the installation is more economical with fewer add-ons to a pile.

Pile Make-Up Aspects for Installation

- Pile-driving hammers required
- Pile wall thickness
- The number of add-ons
- Jacket un-piled stability
- Stoppers, driving head and/or driving shoe requirements
- The SRD at initial pile driving
- Intermediate hard layers
- Driving resistance set up

Effect of Wall Thickness on the Pile Driveability

A stiffer pile is strongly recommended when pile driving through dense sands and/or hard layers. A stiffer pile requires a lower blow count and thus, the installation has less risk for premature refusal and/or pile damage. A stiffer pile can be obtained by increasing the wall thickness above the requirement for the in-place condition. To illustrate this effect, a comparison of the expected blow count is shown in the graph overleaf: The predictions are made for a pile with an O.D. of 1219 mm and a W.Th. of 25.4 mm, 38.1 mm and 50.8 mm (O.D. 48” with a W.Th. of 1”, 1.5” and 2”) in combination with the S-500 hydraulic hammer driving into very dense sands.

Key Features

- A larger wall thickness improves the pile driveability and reduces the risk of pile refusal.
- A proper pile wall thickness allows a bigger hammer to be used earlier.
- A proper pile wall thickness reduces overall installation time.
- Pile driveability assessment should always be an integral part of the pile make-up design.
- A pile make-up design is “good” when the pile can be driven to penetration with “certainty” (i.e., the expected blow count remains less than 50 - 60 blows/250 mm for continuous driving).
- When harder layers are met prior to target penetration, the pile make-up should be designed for a large hammer.
Driving Stresses

The hammer blow introduces a stress wave into the pile head. The highest driving stresses may occur at the following locations in the pile:

1. At the pile head. The anvil should be flat and rest on the full cross-sectional area of the pile. To avoid pile-head damage, no eccentricity of the stress wave transfer to the pile head should occur; otherwise, the pile head can be damaged and get stuck in the hammer sleeve. Consequently, the pile must be cut to remove the hammer from the pile. A driving head reduces risk of pile-head damage. For each project, it is recommended to check whether a driving head is required.

2. At the transition of pile to shoe (i.e., in the thinner section of the two wall thicknesses). Typically, a changeover of wall thickness occurs at the start of the pile shoe. At that location, the risk is high of overstressing the pile. For example, if the pile toe is at a hard layer and the hammer is at high energy level, in combination with low frictional resistance along the pile wall and the pile is made of low-yield stress material, then the pile could become overstressed at the wall thickness transition above the pile shoe.

3. Near the pile toe. If almost no frictional resistance is built up, then practically the full stress wave travels to the pile toe.

4. At interface of a soil layer change. If a pile has a uniform thickness, then the highest stresses may occur at a transition layer in the soil.

Peak driving stresses by hydraulic hammers are higher compared to driving stresses of steam hammers for comparable enthru energy level. However, the duration of this peak value is very short. When driving, the governing criteria with regards to the maximum allowable stress level in the pile are whichever of the following criteria is met first:

- Start driving is allowed only if the driving (dynamic) stresses in the pile at the top support level do not exceed 80% - 90% of the pile’s yield strength.
- The total pile stresses (static + dynamic) may not exceed the pile’s yield strength.
- The maximum driving stress shall not exceed 80% - 90% of the yield stress of the piles.
Driving Head

In general, a top 500 mm to 1500 mm of pile section should be removed after the end of driving of that particular section before splicing another section. This cut-off allowance is needed to:

- Allow perfect fit up of the next section
- Remove the magnetized pile section (due to driving); otherwise, welding is not possible.

Risk of damage of the pile top is considered to be higher in the following conditions and should therefore be prevented:

- Hammer blows that are too eccentric in case of battered piles
- Hammer energy levels that are too high

A driving head, which is a strengthened section at the top of a pile, may be required if driving stresses are such that pile-head damage can be expected. Moreover, a driving head is used where a front follower is required to ensure a proper fitting between the front follower and the pile or where very hard driving conditions are expected. The function of a driving head is:

Without follower:
- To resist eccentricities of the hammer blow
- To prevent local buckling

With a follower the driving head has the following additional purposes:
- To fit the gravity connector of the follower correctly
- To prevent the pile top from splitting open

The length of the driving head should be one to two times the outside diameter of the pile. A driving head of such length reduces the risk of buckling of the pile head. The wall thickness of the driving head shall be at least equal to or exceeding the wall thickness of the pile section below the driving head. When designing driving heads, consider the driving stresses and material yield strength of the pile and anvil.

Vent Holes

When driving a pile under water, the space inside the piles containing water is reduced. To avoid driving on the water column, the water must be discharged. Vent holes are provided in the pile or follower to let the water bleed off during driving. The holes shall not be closed off by the soil or by any structural element (including the grout sleeve) at any stage of driving under water.

The vent holes must be designed carefully. The holes must be large enough to discharge the water to keep pace with a fast rate of driving. Periodic inspection of the holes is also necessary. The holes are an irregularity in the smooth pile or follower wall and are therefore sensitive to fatigue. Moreover, cracks can initiate along the edges of the holes. Also, the vent holes in followers are frequently used for suspending the follower from the hammer. This suspension can be done either with use of a bar through the holes or with slings. The holes must be checked for bearing stresses and radius of rounding.

Pile Toe Provision

A driving shoe is a strengthened section at the pile toe. The function of a driving shoe is to:

- Reduce the (inside) driving resistance in clay
- Prevent damage to the pile toe during hard driving

When hard driving is expected in clay or where a high pile toe resistance could be encountered, a driving shoe of at least one diameter in length is recommended. The wall thickness of the shoe will be approximately 1.5 times the section above. Typically, 1 m - 3 m long internal driving shoes are used.
Aspects of Premature Refusals

General

When a pile refuses to drive to its target penetration, one or more of the following sequential actions can be taken:

   In case of a driving hammer malfunction, the problem can be solved by improvement of hammer operation (such as adjustment of hammer energy) or by the use of a more powerful hammer.
   Whatever changes are made, they must keep driving stresses within tolerance.
2. Re-evaluation of the pile design.
   Reconsideration of pile loads, deformations, required capacities of individual piles and the foundation as a whole must be done. This effort may identify available reserve capacity.
3. Review and interpret the pile driving records in conjunction with pile instrumentation results. This review could lead to design soil parameters or stratification revisited and pile capacity being increased.
4. Remedial action.

Possible Remedial Actions

Possible remedial actions include:

• Plug removal.
   The soil plug inside the pile is removed by jetting and air lifting or by drilling to reduce pile driving resistance. If plug removal results in inadequate pile capacities, the removed soil plug should be replaced by a gravel grout or concrete plug.
   The replacement plug must have sufficient load carrying ultimate capacity to replace that of the removed soil plug. Attention should be paid to plug/pile load transfer characteristics, particularly in cohesive soils.

• Soil removal below the pile toe.
  Soil below the pile toe is removed either by drilling an undersized hole or by jetting. Drilling an undersized hole has unpredictable effect on pile ultimate capacity unless there has been previous local experience under similar conditions. Jetting below the pile toe has unpredictable results and should be avoided.

• Drilling an oversized hole under the pile toe.
  Typically, this form of drilling is done where a pile has to penetrate a calcarenite or a rock layer.

Use two-stage driven piles.

• A first stage or outer pile (casing) is driven to a predetermined depth, the soil plug is removed, and a second stage or inner pile (insert pile) is driven inside the first-stage pile. The annulus between the two piles is grouted to permit load transfer and develop composite action. In a pre-planned situation, the performance can be good, although material costs are higher than for normal piles.
• If insert piles are deployed as a remedial action, consideration must be given to ensure that the grouted connection between the two piles is effective. The initial pile was not designed for this use. Moreover, special attention must also be given to the pile’s heavy wall section, when applied, which might now be at the wrong elevation.
During pile driving, energy losses occur over the anvil and cushion. Furthermore, energy may be lost due to deformation of the pile head. Therefore, the energy the ram delivers at impact is higher than the energy that drives the pile. Pile monitoring allows the measurement of the latter energy, which is the enthru energy and as such gives an indication of the performance of the hammer.

Pile monitoring also provides the input for the computation of the soil resistance the pile meets during driving. This dynamic resistance can be converted into estimates of the static ultimate pile capacity using generally accepted engineering practice. Should structural damage to the pile occur during driving, the instruments would show it immediately.

The technique requires that two sets of instrumentation, comprising a strain transducer and an accelerometer, be mounted on opposite sides of the pile. The instruments are bolted onto the pile in pre-drilled holes, such that they are not sheared off by the hammer cage/sleeve or pile sleeve. Hardwire connects the instrumentation to the data acquisition system onboard the installation vessel.

For the analyses, the strains are converted into forces. The accelerations are integrated once or twice to determine velocities and displacements, respectively.

From instrumentation, the following information can then be calculated and/or presented per blow in real time:

- Enthru energy, forces, accelerations, velocities and pile head displacements as a function of time. Hammer performance is monitored on a blow-to-blow basis.
- Soil resistance during driving.
- Values for blow count, blow rate, centricity of the blows, maximum stresses in the pile and estimated static soil resistance.

Pile monitoring is a relatively low-cost technique that reduces risk during pile installation driving operations and provides valuable data for future projects.
Cost Savings of a Proper Pile Design

General

This section describes a typical platform installed in approximately 34 m of water and supported by four inclined main piles. The commercial risks and consequences are assessed in the event that the selected wall thickness of the pile is too thin and remedial drilling is required to reach target penetration. A comparison is made with a pile of larger wall thickness that could be driven to target penetration without remedial work.

Pile Type - I 1219 mm O.D., 30 mm with shoe 1219 * 40 mm
The make-up is composed of one lead section and four add-on sections.

Pile Type - II 1219 mm O.D., 50 mm, flush
The make-up is composed of one lead section and two add-on sections of 22 m. The vertical target penetration depth is 62 m.

For the analysis, the following soil profile was used:

<table>
<thead>
<tr>
<th>Depth Below Seabed (m)</th>
<th>Soils Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 - 4.5</td>
<td>Clays, increasing Su from 10 kPa to 50 kPa</td>
</tr>
<tr>
<td>4.5 - 21.0</td>
<td>Clays, increasing Su from 50 kPa to 150 kPa</td>
</tr>
<tr>
<td>21.0 - 28.5</td>
<td>Strong cemented layer and/or calcarenite</td>
</tr>
<tr>
<td>28.5 - 57.0</td>
<td>Hard clays, Su = 350 kPa</td>
</tr>
</tbody>
</table>

Immediately after pile driving, all data can be presented as a function of pile toe penetration or for a particular blow.

For an accurate analysis of the static ultimate capacity of the pile “as installed”, signal matching techniques are available. Theoretical and processed forces and velocities are matched in an iterative process. The parameters used to obtain the best match are used to convert from dynamic to static skin friction and toe resistance. Data on the set-up potential of the soils is also taken into consideration.

Key Features

- When the piles meet premature refusal, costly remedial work is required.
- Too-thin wall thickness causes non-driveable piles.
- An increased pile wall thickness could ultimately result in a faster pile installation.
- To overcome set-up resistance, consider restart with a heavier hammer than required to reach target penetration.
- Removal of the soil plug in case of premature refusal always has a negative effect on the pile’s ultimate capacity.
- If piles meet lower resistance than computed or if they meet premature refusal, then pile instrumentation can help determine how to have the piles accepted.
The relatively thin wall of Pile Type I causes higher static stresses (due to hammer stabbing and environmental conditions) as well as higher dynamic stresses (due to driving). This make-up not only requires a higher blow count, but also it reduces the maximum stick-up lengths. The add-on lengths have to be reduced to allow for the application of the S-500 hammer at the proper energy level.

The Type - I pile meets the refusal criteria when driving through the hard layer at 21.0 m - 28.5 m for the upper-bound condition, and thus pile refusal is to be expected at that depth and remedial work might be required. Drilling equipment must be mobilised, at least as a contingency measure. In addition, this pile make-up needs to be installed with two additional add-ons compared with the Type - II pile make-up. Mobilisation of a hammer larger than the S-500 is not an option. The wall thickness of 30 mm limits higher energy input, even with the application of the two extra add-ons.

The driveability expectation for the Type - I pile is given on page 34.

The Type - II pile, with a flush wall thickness of 50 mm can be driven with the S-500 hammer through the hard layer found at 21.0 m - 28.5 m and to the target penetration of 62 m without meeting the refusal criteria even in the upper-bound prediction. The S-500 hammer can be used at any moment at an energy setting of 90%, including at restart after welding an add-on.

The driveability expectation for pile Type - II is given on page 36.
Commercial Implications

An indication of the cost associated with premature refusal and the economical impact of pile make-up choices is presented hereafter. The figures used are indicative only. With the volatile market, the ultimate cost to the client could be much higher, especially if the heavy lift vessel (HLV) rescheduling cost and late first production costs are included.

Premature refusal with the Type-I pile make-up could add about US$4 million to the cost of the project. In contrast, with the Type-II pile make-up an additional cost of only US$213,500 for pile material reduces the risk of premature refusal considerably.

The details of this assessment are elaborated in the next sections.

Additional Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Type - I US$</th>
<th>Type - II US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra pile material</td>
<td></td>
<td>213,500</td>
</tr>
<tr>
<td>Costs associated with difference in:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation duration</td>
<td>625,000</td>
<td></td>
</tr>
<tr>
<td>Remedial work (including drill rig on standby)</td>
<td>3,039,000</td>
<td></td>
</tr>
<tr>
<td>Continue piling and weld back</td>
<td>125,000</td>
<td></td>
</tr>
<tr>
<td>Add-on (after remedial work)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grout spread on board</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td>TOTAL EXTRA COST</td>
<td>3,989,000</td>
<td>213,500</td>
</tr>
</tbody>
</table>
Remedial Action

Drilling Out the Piles:
When the piles reach refusal before target penetration, remedial activity, like drilling out the piles, is required. In our example, the installation contractor identified this risk and mobilised a drill rig to be operational onboard together with its crew. This advance planning prevents unnecessary standby of the HLV.

Unfortunately, in many cases, more remedial action is needed when the piles are drilled out. Often, premature refusal occurs when the top of the pile extends substantially above the jacket can. Consequently, prior to commencement of drilling, a temporary cut-off needs to be made and the section needs to be reinstated before driving can be resumed. It is assumed that remedial work is required at all four piles.

The costs associated with a drilling out of the piles are as follows:

Remedial Costs for Type I Pile

<table>
<thead>
<tr>
<th>Description</th>
<th>Mobilisation</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobilisation of the drill rig and its crew:</td>
<td>US$ 450,000</td>
<td></td>
</tr>
<tr>
<td>Six-man drilling crew on stand by during jacket installation</td>
<td>US$ 24,000</td>
<td></td>
</tr>
</tbody>
</table>

Drilling:
- Drill rig working: US$ 20,000/day
- HLV spread: US$ 250,000/day
- Total HLV spread: US$ 270,000/day
- Remedial work: 9.5 days @ US$ 270,000/day

| TOTAL REMEDIAL WORK | US$ 3,039,000 |

Material

Based on a steel price of US$ 3,500/t, the cost of four numbers piles is compared in the table below.

Material Cost Comparison

<table>
<thead>
<tr>
<th>Type - I Piles (97 mt)</th>
<th>Type - II Piles (158 mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US$ 339,500</td>
<td>US$ 553,000</td>
</tr>
</tbody>
</table>

Installation

For the assessment of the overall project duration, it was assumed that all piles can be driven in batches of four.

The welding of a Type - II pile add-on takes longer due to the increased pile wall thickness. However, because the add-ons are longer, fewer of them are needed. Therefore, the total time to weld Type - II add-ons is less. Furthermore, the increased wall thickness reduces the driving time.

Additional Installation Cost

<table>
<thead>
<tr>
<th>Description</th>
<th>Type - I Piles 2.5 days extra installation time</th>
<th>Type - II Piles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed day rate of US$ 250,000 for a HLV</td>
<td>US$ 625,000</td>
<td>213,500</td>
</tr>
</tbody>
</table>

Consequently, the balance for the pile design is $411,500 in favour of Type II even when no remedial work is considered.
Continue Driving:
Once the pile has been drilled out, the pile section removed is reinstated before driving is resumed. It is expected that welding of the last add-on occurs only on the vessel’s critical path. Stabbing and welding of the last pile section takes approximately 12 hours at vessel’s day rate at US$ 250,000/day.

Setting a Grout Plug:
The cost associated with the grouting spread is about US$ 200,000. This cost includes its specialised crew, grouting spread, grout, silos, mobilisation and so on to set four numbers of grout plugs; one in each pile.

Conclusions

1. A top-quality pile design, which includes superior foundation quality at an economical price, reduces the risk and associated hazards for the main contractor and operator.
2. A good pile foundation gives the operator the option of future expansion of the platform. In a properly driven foundation pile, the safety margin with regard to ultimate bearing capacity is higher than that of a foundation pile that needs remedial activities to reach target penetration.
3. Even when the operator insists on having drilling and grouting equipment onboard (as a contingency to address the encounter of an unexpected hard layer) a good driveable pile remains much less expensive than a pile that encounters refusal.
4. The “total installed cost” for a good driveable pile is less than for foundation concepts focusing on material cost only.

Key Features

- An inadequate pile design can increase the installation costs by 50% - 100%.
- An inadequate pile design can result in the platform being delivered late and thus missing the targeted first production date.
- Additional measures to reach target penetration always hamper the platform foundation and could cause pile capacity limitations in the future.
- Remedial actions to drive the pile to penetration could cost millions even exceeding the installation costs.
Acknowledgements

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If the reader has any questions or any suggestions, please do not hesitate to contact us.

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Disclaimer

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