ABSTRACT: There are currently more than 220 fixed jacket platforms related to exploration/production of hydrocarbon in shallow water areas in the Indian offshore with open ended, tubular piles of steel as their foundation. The forces, bending moments and deflection in the piles are studied by carrying out interactive analysis of the structure, soil and pile with models of actual combination of these three components. Axial & lateral capacities, driveability, run down, pile make-up and scouring aspects also depend on the soil condition. Variable and difficult soil conditions in different areas of the Indian offshore need to be taken into account while designing the piles. The paper discusses and highlights the important design aspects of piles.

INTRODUCTION
Fixed jacket type platforms for offshore oil and gas fields in India are founded on hollow tubular piles of steel. These piles are driven through the jacket legs or through skirt sleeves. There may be main pile or skirt pile or both in a platform. Piles are designed for adequate soil resistance to bear the axial and lateral forces and moments. Piles are also designed to bear the stresses of lifting, due to stick up during installation. Again feasibility of driving and level of stress arising from the hammer bows during installation are also examined during design. The soil condition plays a vital role in selecting its diameter, wall thickness, material, length and also the selection of hammer for installation by driving. The behaviour of the structure made from steel is considered as linear in the stress-strain behaviour whereas the soil is essentially of non linear behaviour. Therefore, soil-pile-structure interactive analyses are carried out for calculation of the pile loads, deflections and stresses. Further, the aspect of difficulty and uncertainty of installation is a factor in the design of the piles due to the occurrence of cemented soil often encountered in the offshore off the west coast of India.

SOIL PROPERTY
The soil properties vary from site to site. The soils in the Mumbai High Field are combinations of sandy and clayey soils within the zone of pile penetration, say up to 125m. There is generally high carbonate content in the sands. Clays, generally calcareous, are normally consolidated to slightly over consolidated. Zones of cemented sand are found especially at greater depths. In Bassein towards the east of Mumbai High, the soil is predominantly clayey. There is an over consolidated zone of a few metres near the seabed at many sites in the area. Towards the south east of Mumbai High, the soil is again predominantly clayey up to a significant depth with sand layers at deeper strata. In the eastern offshore Krishna Godavari Basin, the soil profiles show predominantly clayey soil. The gradient of increase of shear strength of clays with increasing depth below seabed is often low, typically 1-1.5KN/m² per m. It is evident from the changes in the soil condition that the pile design will vary in different sites with respect to their diameter, wall thickness, material strength and depth of penetration.

AXIAL AND LATERAL CAPACITY
Apart from gravity, environmental forces are taken into account in the design of the piles. One of the major contributors to pile loads is the wave force. The piles in the Indian offshore platforms are driven to a depth typically from 60m to 125m below the seabed. The range of diameter is generally 24 inches to 84 inches for the steel tubular piles. They are driven as open ended but they eventually behave as plugged pile in most of the cases in static loading as the internal skin friction becomes very high compared to the end bearing of the soil plug as they are long enough. The main factor governing the axial pile capacity at a location is the soil condition and pile diameter. As the skin friction is the major component of the capacity, the increase of diameter increases the skin friction part and adds significantly to the total axial capacity. The other factor is the soil condition at the tip of the pile. Since all the piles in the range of the diameter mentioned above plugs under long term static resistance, the end bearing component depends on the full cross sectional area of the pile and the soil strength near the tip of the pile. Therefore, other things remaining the same, the soil near the tip can make a lot of difference to the end bearing resistance and the total capacity.

Several axial capacity curves for compression loading in the soils of different areas are calculated and shown in Fig. 1. Same pile geometries and procedure [1] are considered in the calculation. There is significant variation of capacity from site to site. The axial capacity in tension varies as well. However, it is observed that in most of the cases, the safety due to axial loading in a platform is governed by compressive capacity of the piles. Presence of clay layers within the length of the pile generally adds higher skin friction resistance when compared to presence of sand, considering that the shear strength of clay increases with increase of effective overburden pressure in normally
consolidated clay, whereas skin friction mobilized by sands are limited beyond certain depth. Further, presence of thick layers of sand with high quantity of carbonate reduces the skin friction component.

The importance of soil layers with high strength in offshore structures cannot be overstated. For example, a clay layer at pile tip with 250 KN/m² as undrained shear strength offers 2250 KN/m² as ultimate unit end bearing resistance [1] compared to a cemented sand layer typically having ultimate unit end bearing resistance of 5000 to 8000 KN/m². Therefore, such cemented slayers are normally the choice for targeting pile tips in them.

As per the API code [1], in a layered soil profile, if the pile tip is in a strong layer which is adjacent to relatively weak layers, the full capacity mobilization is not considered unless the tip is more than 3 diameter above the weak layer and the tip penetrates by 2 to 3 diameter into the strong layer. As such, targeting the tip into a layer with very strong end bearing does not assure mobilization of high end bearing resistance unless the thickness is sufficient. It depends on the strength of the adjacent layers, if thickness of the strong layer is not sufficiently high. In a marginal case of meeting axial capacity requirement, the choice of number of pile and their diameters may be governed by the thickness of strong layer at depths targeted for pile tips.

Offshore platforms are subjected to very high level of lateral forces and moments from wave, current, earthquake and wind forces. It may also happen that the piles are loaded by the slope failure of the seafloor. To meet the required resistance, the piles are adequately designed so that the stress in the piles is within the allowable limit and the deflection is tolerable from serviceability point of view. Soil condition in the vicinity of the seafloor is a governing factor for developing the lateral capacity of the piles in addition to its material properties, diameter and wall thickness.

PIECE DISPLACEMENT AND BENDING MOMENT

For design of offshore platforms, pile displacement and bending moment are generally computed by numerical method. Interactive analysis of soil, pile and structure is performed as their behaviour is inter-dependent. The stiffness of load-deformation springs for axial and lateral loading is representative of the soil properties and it is input through the t-z[4], q-z[4] and p-y[2,3] data generated for this purpose. A typical soil profile is given in Table 1.

<table>
<thead>
<tr>
<th>Depth of layer below mudline (m)</th>
<th>Soil type</th>
<th>Su (KN/m²)</th>
<th>( \phi' ) (degree)</th>
<th>Effective Unit wt. ( \text{KN/m}^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 to 14.6</td>
<td>Clay</td>
<td>2-14</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>14.6 to 27.1</td>
<td>Clay</td>
<td>29-72</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>27.1 to 50.3</td>
<td>Clay</td>
<td>72-77</td>
<td>-</td>
<td>8.5</td>
</tr>
<tr>
<td>50.3 to 62.8</td>
<td>Sand</td>
<td>-</td>
<td>30</td>
<td>10</td>
</tr>
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Note: \( Su \) – Undrained shear strength, \( \phi' \) – Drained angle of internal friction

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Fig. 1 shows the high lateral deflection of a pile of the platform with extreme wave load due to weak soil condition in the vicinity of the mud line as per of Table 1.

Fig. 2 Calculated lateral deflection of one pile in a platform under extreme environmental load [5]
deflection will be even higher. The soil in this location has very soft clay up to 14.6m below the mudline having relatively weak response to lateral load. In such situations, attempt to arrest the high lateral deflection of piles and the platform may invite significant extra cost for the platform. Changes in platform configuration, number of piles or diameter of piles are the general measures required in such cases.

For the lateral load-deformation curves, cyclic load is considered with recommended degradation of soil resistance. Bending moment pattern as shown in Fig. 3 indicates that the maximum bending moment is at the pile head with another peak at about 20 metres below the mudline.

![Bending moment distribution along a pile](image)

Fig. 3 Bending moment distribution along a pile [5]

The depth of occurrence and magnitude of the second peak bending moment, of course, varies under different conditions. Results of an interactive analysis for the same soil profile as in Table 1 have been presented in Table 2.

<table>
<thead>
<tr>
<th>Pile outer Dia. (m)</th>
<th>Wall thickness (mm)</th>
<th>δ (cm)</th>
<th>B.M. (MN. m)</th>
<th>F (MN)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.219</td>
<td>51</td>
<td>36.5</td>
<td>16.1</td>
<td>2.11</td>
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<td>70</td>
<td>34.0</td>
<td>16.7</td>
<td>2.16</td>
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<tr>
<td>1.219</td>
<td>70</td>
<td>37.5</td>
<td>17.6</td>
<td>2.11</td>
<td>*</td>
</tr>
<tr>
<td>1.219</td>
<td>70</td>
<td>39.0</td>
<td>17.9</td>
<td>2.08</td>
<td>**</td>
</tr>
</tbody>
</table>

Note: δ – lateral deflection, BM – Pile bending moment, F – shear at pile head; # Undisturbed soil condition, * soil shear strength in top 14.6m reduced to half of original, ** soil strength in top 14.6m reduced to one third of original

The effect of change of wall thickness and the remoulding of soft clay in the top layer is also observed. Table 2 also shows that considering wall thickness of 70mm instead of 51mm in the zone of significance, the lateral deflection in the pile is reduces from 36.5cm to 34cm. Considering the remoulding of the zone of the very soft soil with sensitivity as 2.0 in the top of the soil profile, the lateral deflection increased from 34cm to 37.5cm (about 10% more). Similarly, considering remoulded strength with a sensitivity of 3.0 in the very soft clay increased the lateral deflection from 34cm to 39cm (about 15% more). Remoulding effects are normally considered in piles affected by penetration of jack up rig foundation deployed near the well head platforms.

Due to high bending moment zone and axial load pile sections require higher thickness or higher strength of material or both in the vicinity of the mudline. Design is carried out with appropriate pile sections to limit the stresses within allowable values. Axial deflections are far less than lateral deflections with the factor of safety 1.5 and 2.0 applied against axial load for design of the offshore piles for operating and extreme environmental loading [1] respectively. From interactive analysis, it is also observed that redistribution of loading takes place among the piles depending on the relative stiffness of the soil-structure-foundation system when some pile is overloaded or soil is weaker around some pile.

**DRIVEABILITY, STICK UP AND RUN DOWN STUDY**

For a platform location with water depth of say, 80m, typically the total length of one pile is about 200m from tip to the final cut-off level above sea water level. They are installed by driving with suitable hammers. Analysis based on one dimensional stress wave equation is carried out to ensure driving by suitable hammers and application of appropriate amount of energy. It is observed that there is some uncertainty in the driveability, especially in cemented sand layers which may lead to pile refusal. Fig. 4 shows the curve of static resistance to driving (SRD) of the soil versus blow count, for the piles of a platform site.

![Variation of blow count of hammer with soil resistance](image)

Fig. 4 Variation of blow count of hammer with soil resistance at a platform location (Calculated using GRLWEAP®) [6]

It may be observed that the curve becomes flat after about 600 blows/m. Over 40MN of soil resistance, the blow count...
shoots up from 600 blows/m to 1500 blows/m for an incremental soil resistance of 3MN, a small fraction of the total SRD. In a marginal situation, a little ‘set up’ of the clays or slight increase of the end bearing resistance may lead to pile refusal in such cases.

Planning for different sections of the pile installation requires estimation of the depth of penetration of pile length with self weight and with the hammer weight, called “run-down”. It also depends upon the capability of the handling equipment and soil stratigraphy. Analysis is carried out to find out how much length of pile section is allowable to “stick up” as a new section considering the forces on the pile section.

After completion of driving, piles are grouted with the main legs of the jacket structure or with the skirt sleeves through which they were driven. Piles are also driven with some batter normally in the range of (vertical to horizontal) ratios 5:1 to 8:1. When the seabed soil is soft clay up to significant depth, the run-down length is higher due to the low skin friction resistance of the soft soil. It also depends on the sensitivity of the soft clay as remoulding in the process of penetration of the pile reduces the soil resistance to stop penetration of the pile.

**SCOUR**

Pattern of current in the seabed may change due to the obstruction from piles and other members of the structure near the mudline. As a thumb rule, local scour is accounted in the design by considering a depth of 1.5 times the outer diameter of the pile or the thickness of susceptible layer at the seabed. In some sites where the seabed current is high and the soil at the seabed is susceptible to scouring, there may be complete removal of soil from a large area of the platform site which is called general scour. Scour exceeding 3m is observed at some sites. Scour has, generally, little effect in axial capacity as the piles are long. However, it has significant impact on the pile stress and displacement, which is taken care in the design. Scour is normally observed to have occurred when the soil in the seabed is sand or silt in loose condition. It is also observed in some locations where the seabed soil is very soft clay.

**CONCLUSIONS**

1. There is a lot of vertical and lateral variation of soil condition especially in the west offshore of India. At shallow depth, such variation affects the lateral deflection, stresses and run down of the piles. At greater depth, driveability and ultimate capacity is affected by the changes of soil condition.

2. Skin friction is the main component of ultimate axial capacity generally in the range of 60%-90% of the total capacity. However, positioning of the pile tip in a dense/cemented sand layer with sufficient thickness often makes up a significant proportion of axial capacity by end bearing.

3. Lateral deflection for design extreme environmental load may be quite high exceeding 30cm in sites where the soil condition is soft clay in the zone near the seabed.

4. It is generally observed that maximum bending moment occurs at the pile head and the piles have quite high amount of rotational restraint at the pile heads.

5. Given a hammer-pile-soil combination, blow counts during driving may increase rapidly beyond a range of soil resistance leading to refusal of pile in many situations.

Oil and Gas platforms in the Indian offshore have not faced the extreme events so far, for which they are designed. However, with the uncertainty in the assessment of environmental loads and soil properties, design of the offshore piles require careful considerations for successful installation and satisfactory performance given the huge loads they support and keeping in view the consequences of any failure.

**ACKNOWLEDGEMENT**

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**REFERENCES**


