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Assessment of Pier Foundations in Offshore and Coastal Structures

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Abstract

This study assesses the foundation performance of a pier structure subjected to significant loading in a riverine environment, with implications for offshore structures. The pier is designed to support a load of 3000 t, and the water depth is 15 m above the riverbed. In offshore conditions, water penetration below the bed level is a key consideration, influencing the soil behavior around the foundation. The underlying soil at the foundation base is in a saturated state due to this water penetration, while the topsoil is in both saturated and moist conditions. In offshore environments, these conditions can be more pronounced, given the additional influence of tidal variations, wave action, and seasonal water level changes. The soil's water absorption capacity is 16%, and for determining the depth of saturated soil, this factor plays a crucial role in evaluating the soil's shear strength and settlement potential. Understanding the soil conditions is vital for the design of offshore pier foundations, where soil structure interactions (SSI) impact the overall stability of the structure under static and dynamic loads. In offshore applications, factors such as wave-induced forces, sediment transport, and the potential for soil liquefaction due to seismic or operational vibrations must also be considered. This study highlights the importance of evaluating the depth and extent of saturated soil layers for accurate foundation design, ensuring the safety and durability of offshore structures subjected to both static and dynamic environmental loads.

Keywords: Soil stabilization, offshore foundations, lateral load analysis, pier foundation, marine geotechnics, saturated soil conditions, foundation depth, bearing capacity, offshore pier design, soil stabilization techniques, lateral load resistance, gravel and sand mixture, seabed soil strength, water penetration effects on soil, geotechnical engineering for offshore structures

INTRODUCTION

The design and stability of foundations for offshore structures, particularly piers, are critically influenced by soil conditions beneath the waterbed. In both riverine and offshore environments, the interaction between water and soil plays a significant role in determining the bearing capacity of the soil, which is crucial for supporting large structures. This study focuses on assessing the impact of saturated and moist soil conditions on the bearing capacity of foundations, specifically in the context of piers subjected to substantial loading, such as the 3000 t load in this scenario [1–3].

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In the case of pier foundations located in regions where water penetrates below the riverbed or seabed, the underlying soil undergoes significant changes. For foundations placed in such environments, the topsoil and underlying soil layers may both experience saturation due to water infiltration, leading to a reduction in their bearing capacity. The topsoil, in a saturated state and moist condition, experiences a reduction in bearing capacity, while the underlying soil, also in a saturated and moist condition, faces an even greater

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decrease of 37.5%. Combined, this results in a 75% reduction in the overall bearing capacity of the soil beneath the foundation.

This reduction in soil strength necessitates a deeper foundation design to compensate for the loss of bearing capacity. In offshore applications, this challenge is compounded by the dynamic nature of the environment, including tidal movements, wave action, and potential seismic forces, all of which influence the soil's mechanical properties. To ensure the stability and safety of offshore structures, the foundation depth must be carefully optimized to account for these reductions in soil bearing capacity. Additionally, the study explores the need for appropriate engineering solutions to mitigate the impact of soil saturation, ensuring that the structure remains stable and functional over its intended lifespan [4–6].

RESULTS AND DISCUSSION

The analysis of the pier foundation's performance under the given loading and soil conditions involves several critical parameters. The depth of water above the bed level of the river is 15 m, and the water penetration into the soil is calculated as 0.6 times the water depth, resulting in a penetration depth of 9 m. The depth of saturated soil is determined by considering the topsoil's saturation state, and the underlying soil, which extends to 7.56 m, is in a moist condition [7–9].

The load on the pier is 3000 t, and the weight of the pier is calculated based on its dimensions: 8 m in length, 0.8 m in thickness, and 18 m in height above the riverbed. Using a unit weight of concrete at 24 kN/m^3, the weight of the pier is determined to be 276 t. Hence, the total load on the pier is the sum of the applied load and the weight of the pier, amounting to 3276 t [10].

Additionally, the weight of the foundation is included in the calculations, and the load on the foundation base is determined to be 3604 t. The load intensity is calculated using the dimensions of the foundation base, which measures 8 m in length and 2 m in width. For this analysis, the unit weight of the soil (γ) is taken as 1.8 t/m^3, and the effective friction angle (φ) of 30° is used to compute the bearing capacity of the soil. This leads to an estimated foundation depth (Df) of 14 m.

However, due to the soil's saturation and moist conditions, the bearing capacity of the underlying soil is reduced by 75%. This reduction necessitates a deeper foundation to compensate for the loss of strength. The depth of the foundation is recalculated for a saturated soil condition, where the unit weight of soil is reduced to 1.6 t/m^3, and the friction angle (φ) is adjusted to 15° for the saturated state. This results in a required additional foundation depth of 41 m, leading to a total depth of 55 m for the foundation.

Safety Check for Foundation

The total load acting below the bed level of the river is 3604 t. Lateral loads acting on the pier below the riverbed are calculated using a lateral load coefficient of 0.217, yielding a lateral force of 782 t. The overturning moment produced by this lateral load is determined, and the stability of the foundation is analyzed by considering the restoring moment generated by the surrounding soil.

The surrounding soil is stabilized by a mix of 1 part gravel and 8 parts sand, and after considering a 50% reduction in bearing capacity due to the saturation state, the resulting soil strength is 4011 t/m^2. The restoring moment produced by the stabilized soil is calculated to be 22,582 t-m, which is greater than the overturning moment of 21,505 t-m. Thus, the foundation is deemed safe against overturning.

Furthermore, the lateral load produces an overturning moment of 440 t-m, which is less than the restoring moment, confirming that the foundation is safe. The model also highlights the influence of key variables, such as load, foundation base thickness, foundation size, and rainfall, on the required depth of the foundation. This model provides a comprehensive understanding of the relationship between these factors, ensuring the safety and stability of offshore and riverine pier foundations under varying environmental and load conditions (appendix 1).

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- Since depth of water above bed level of river =15 m.
- Penetration depth of water =0.6×15=9 m
- Depth of saturated soil $= \frac{16}{100}\ x\ 9 =\ 1.44\ m$ depth of top soil will be in saturated state and 9–1.44⇒7.56 m soil will be in moist condition same thing for underlying soil.
- Load on pier =3000 t weight of pier =8 m×0.8×18×24=276 t
- Where,
  8 m= Length of pier,
  0.8 m= Thickness of pier,
  18 m= Height of pier above bed level of river, and
  24 KN/m^3= Unit weight of concrete.
  Hence total load for pier =3000+276=3276 t
- Weight of foundation $= \frac{10}{100}\ x\ 3276 =\ 328\ t$
- Hence load on foundation base = 3276 + 328 = 3604 t
- Load intensity $q = \frac{3604}{8\ x2} = 225\ t/m^2$
  Where,
  8 m= length of foundation base, and
  2 m= width of foundation base.
- Hence depth of foundation $D_f\ = \frac{225}{1.8}\ x\ 0.111$
  Where unit weight of soil γ=1.8 t/m^3
  ϕ=30° hence $\left[\frac{1-Sin\varphi}{1+Sin\varphi}\right]^2$= 0.111
- Hence D_f=14 m.
- Since bearing capacity of underlying soil is reduced by 75%.
- Hence reduction in bearing capacity of soil $= \frac{75}{100}\ x\ 250 = 188\ t/m^2$
- For this much reduction we have to provide more depth of foundation
  Hence $D_f\ = \frac{188}{1.6}\ x\ 0.347$
  Where, γ=1.6 t/m^3
  ϕ=15° for saturated state.
- Hence more depth of foundation =41 m needed.
- Hence total depth of foundation =55 m is to be provided.

Check for Safety of Foundation

- Total load below bed level of river =3276+328=3604 t.
- Lateral load acting on pier below bed level of river =0.217×3604=782 t
  Where $\frac{1-Sin\varphi}{1+Sin\varphi}$=0.217
  for ϕ=40° for concrete.
- This lateral load will act at middle of depth of foundation i.e. $\frac{55}{2}\ meter.$
- Hence overturning moment produced at base of foundation $782\ x\frac{55}{2} = 21505\ t-m$
- At foundation base soil surrounding the foundation base is stabilized by 1 part gravel soil and 8 parts sand hence after reduction in bearing capacity of soil surrounding the foundation base $\frac{44\ +\ 2000\ x\ 8}{2}$ =8022 t/m^2, due to 50% reduction in saturation state bearing capacity =$\frac{8022}{2}$ $= 4011\ t/m^2$.
  Where strength of gravel =44 t/m^2, and
  Strength of sand =20 N/mm^2=2000 t/m^2
  Saturation state bearing capacity =4011 t/m^2 (After 50% reduction in strength because underlying soil in foundation base is in saturated state).

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Table 1. Data for load acting on column, depth of foundation, foundation base thickness, foundation base size and rainfall.

S.N.	Load acting on column (t) (W)	Depth of foundation (m) (D_f)	Foundation base thickness (mm) (t)	Foundation base size in m^2 (b×d)	Rain fall in mm (p)
(1)	100	1.693	150	2.24 m×2.24 m	300
(2)	120	2.109	180	2.5 m×2.5 m	500

Table 2. Date for $\frac{W}{W_{max}}, \frac{D_f}{D_{fmax}}, \frac{t}{t_{max}}, \frac{b\ x\ d}{(b\ x\ d)_{max}}$ and $\frac{p}{p_{max}}$.

S.N.	$\frac{W}{W_{max}}$	$\frac{D_f}{D_{fmax}}$	$\frac{t}{t_{max}}$	$\frac{b\ x\ d}{(b\ x\ d)_{max}}$	$\frac{p}{p_{max}}$
(1)	0.833	0.803	0.833	0.803	0.600
(2)	1.000	1.000	1.000	1.000	1.000
Average	0.917	0.902	0.917	0.902	0.800

- Hence restoring moment produced by stabilized soil $=4011\ x\ 10\ x\ \frac{1.126}{2}$ =22582 t-m>21505 t-m
- Where 10 m length of foundation base concrete slab taken and thickness of foundation base slab =1.126 m taken.
- Hence foundation is safe.
- Total load at foundation base =3604 t.
- Hence overturning moment produced by lateral load at foundation base =0.217×3604=782 t.
- Overturning moment at base $= 782\ x\ \frac{1.126}{2}$
  ⇒ 440 t-m< Restoring moment produced by stabilized soil at foundation base hence safe.
- Model formation for depth of foundation with load, foundation base thickness, foundation base size and rainfall (Tables 1 and 2).
- Variable parameters: $\frac{W}{W_{max}\frac{p}{p_{max}}}$
- Output parameters: $\frac{D_f}{D_{f\,max}}, \frac{t}{t_{max}}$ and $\frac{b\ x\ d}{(b\ x\ d)_{max}}$
- Relationship for $\frac{D_f}{D_{f\,max}}$ with $\frac{W}{W_{max}}$ and $\frac{P}{P_{max}}$

  Average value of $\frac{D_f}{D_{fmax}}$=0.902≈1.000

  Corresponding value of $\frac{W}{W_{max}} = 1.000$ and $\frac{P}{P_{max}} = 1.00$.

  Average value of $\frac{W}{W_{max}} = 0.917$ and $\frac{P}{P_{max}} = 0.800$.

  Hence power of $\frac{W}{W_{max}} = \frac{0.917}{1.000} = 0.917, Power\ of\ \frac{P}{P_{max}} = \frac{0.800}{1.00} = 0.800$.

  Hence $\frac{D}{D_{f\,max}} = x \left[\frac{W}{W_{max}}\right]^{0.917} \left[\frac{p}{p_{max}}\right]^{0.800}$

  Average value of $\frac{D_f}{D_{f\,max}} = 0.902$

  Average value of $\frac{W}{W_{max}} = 0.917$

  Average value of $\frac{p}{p_{max}} = 0.800$

  Hence 9.902=x $(0.917)^{0.917}$ $(0.800)^{0.800}$

  ∴ x=1.167

  Hence model is $\frac{D_f}{D_{f\,max}} = 1.167 \left[\frac{W}{W_{max}}\right]^{0.917} \left[\frac{p}{p_{max}}\right]^{0.800}$

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- Prediction:
  For load =150 t, p=600 mm
  $\frac{D_f}{D_{f\,max}} = 1.167\left[\frac{150}{120}\right]^{0.917}[1.157]$
  D_f=3.494 m.
- Optimization (Maximized model) for $\frac{D_f}{D_{fmax}}$:
  Using model:
  $\frac{D_f}{D_{f\,max}} = 1.167\left[\frac{W}{W_{max}}\right]^{0.971}\left[\frac{p}{p_{max}}\right]^{0.800}$
  $1.000 = 1.167\left[\frac{W}{W_{max}}\right]^{0.971}[0.800]^{0.800}$
  Keeping $\frac{p}{p_{max}}$ = Constant = Average value
  $= 1.167\left[\frac{W}{W_{max}}\right]^{0.971}[0.837]^{0.800}\left[\frac{W}{W_{max}}\right]^{0.971}$
  $\frac{W}{W_{max}} = [1.024]^{1.030} = 1.025$
  Average value of $\frac{W}{W_{max}}$=0.971
  0.971x=1.025
  x=1.156
  Hence $\frac{W}{W_{max}}$=1.156 $\left[\frac{W}{W_{max}}\right]$
  Hence optimized model.
  Using the previous model:
  $\frac{D_f}{D_{f\,max}} = 1.167\left[\frac{W}{W_{max}}\right]^{0.971}\left[\frac{p}{p_{max}}\right]^{0.800}$
  $= 1.167\left[1.156\left(\frac{W}{W_{max}}\right)\right]^{0.971}[0.800]^{0.800}$
  $= 1.167\left[1.151\left(\frac{W}{W_{max}}\right)^{0.971}\right][0.837]$
- Hence optimized model for $\frac{D_f}{D_{f_{max}}}$is
  $\frac{D_f}{D_{f\,max}} = 1.124\left[\frac{W}{W_{max}}\right]^{0.971}$
- Prediction from optimized model:
  For load 150 t
  D_f = 2.947 m
  D_{fmax} = 2.109 m
  W_{max} = 120 t

Model for Depth of Foundation with Load on Column and Rain Fall

$$\frac{D_f}{D_{f\,max}} = 1.167\left[\frac{W}{W_{max}}\right]^{0.917}\left(\frac{p}{p_{max}}\right)^{0.800}$$

- Where, D_f= depth of foundation in meter.
- W= Load on column in ton.
- p= Amount of rainfall in mm.
- Interpretation of model:
  Load on column is increased by 20% from 120 t load
  Hence load on column = $\frac{20}{100} x\ 120 = 24\ t$
- Hence load on column =144 t
- Using model keeping rainfall = constant i.e. its average value =0.800

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- Hence,
  $\frac{D_f}{D_{f\,max}}$ 1.167 $\left[\frac{144}{120}\right]^{0.917}$ $[0.800]^{0.800}$
  $=1.167\ (1.20)^{0.917}\ (0.837)$
  =1.167(1.182) (0.837)
  =1.155
  D_f=2.435 m
- For 120 t load depth of foundation =2.109 m

Increase in Depth of Foundation

In 2.109 m increase (2.435–2.109)
=0.326 m
1 → $\frac{0.326}{2.109}$
100 → $\frac{0.326\ x\ 100}{2.109}$
→ 15.46%

Findings

Particularly for piers or foundations submerged in water, the influence of environmental factors such as load and rainfall on foundation depth is critical for ensuring stability and safety.

Effect of Increased Load on the Offshore Structure

A 20% increase in the load on the column of the offshore structure leads to a 15.46% increase in the depth of the foundation. While the increase in load is significant, its effect on the foundation depth is relatively modest compared to other environmental factors, such as changes in water penetration due to rainfall.

Effect of Increased Rainfall on Offshore Foundation

In offshore environments, rainfall directly impacts the water penetration into the seabed, leading to changes in the soil's moisture and saturation levels. With a 20% increase in rainfall, the amount of water penetration into the soil increases, causing the soil to become more saturated and moist. For this analysis, the rainfall amount is set at 600 mm, and using the model with a constant load, the foundation depth increases to 2.631 m, an increase of 0.522 m (or 24.76%).

Interpretation in Offshore Environments

Rainfall influences the water level, which in turn affects the soil beneath the seabed or riverbed. The penetration of water below the seabed leads to the soil becoming saturated and moist, a condition particularly significant in offshore environments where wave action, tides, and seasonal fluctuations affect soil conditions. In the saturated state, the bearing capacity of the soil is reduced by 50%, and in the moist condition, it is reduced by 25%. These reductions significantly lower the soil's ability to support the foundation, requiring adjustments to the depth of the foundation to ensure stability.

Comparison of Load and Rainfall Effects in Offshore

When comparing the impact of increased load versus increased rainfall, the effect of increased rainfall on foundation depth is much more pronounced. While a 20% increase in load results in a 15.46% increase in foundation depth, the same increase in rainfall causes a 24.76% increase. This highlights the fact that soil saturation, influenced by rainfall, plays a much more significant role in foundation design than the increased structural load in offshore conditions.

Due to 20% increase in load on column, the depth of foundation is increased by 15.46%.

- Amount of rainfall is increased by 20%.
- Increase in rainfall $\frac{20}{100}\ x\ 500\ = 100mm$
- Amount of rainfall =600 mm

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- Using the model keeping load is constant =0.917 $\left(\frac{W}{W_{max}}\right)$ (Average value)
- Using the model:
  $\frac{D_f}{D_{f\,max}} = 1.167[0.917]^{0.917}\left[\frac{600}{500}\right]^{0.800}$
  $\frac{D_f}{D_{f\,max}} = 1.167\,[0.924]\,[1.157] = 1.248$
  D_f=2.631 m.
- Increase in depth of foundation
- In 2.109 m increase (2.631–2.109)=0.522
  1 $\rightarrow$ $\frac{0.522}{2.109}$
  100 $\rightarrow$ $\frac{0.522\ x\ 100}{2.109}$
  $\rightarrow$ 24.76%
- *Findings:* Due to 20% increase in rainfall depth of foundation is increased by 24.76%.
- Hence, we can conclude that due to increase in rainfall the depth of foundation is increased more as compared to increase in load on column.
- *Interpretation*:
- Due to rainfall penetration of water into soil below GL will take place hence soil will be in saturated and moist condition.
- For saturated condition of soil bearing capacity is lowered by 50% and for moist condition of soil bearing capacity is lowered by 25%.
- Hence average reduction in bearing capacity of soil 1 =$\frac{25\ +\ 50}{2}\ =\ 37.5\%$.
- Since there is more reduction in bearing capacity of soil as compared to increase in load intensity (i.e. 20% increased).
- Hence, we need more depth of foundation due to increase in amount of rainfall.
- *Findings:*
- Hence, we can say that increase in penetration of water due to rainfall is dominant parameter in model as compared to increase in load for increase in depth of foundation.

CONCLUSION

In the design and stability of offshore pier foundations, the soil surrounding the foundation base and above the base plays a crucial role in supporting the structure and ensuring its stability against lateral loads. To enhance the soil's bearing capacity and its ability to resist lateral forces, the soil surrounding the foundation base is stabilized by mixing 1 part gravel with 8 parts sand. This stabilization improves the overall strength and cohesion of the soil, ensuring that it can better withstand the loads exerted by the pier.

Additionally, the soil above the foundation base is further stabilized using a mixture of 1 part gravel and 8 parts stone particles. This combination of materials is selected to ensure that the lateral load from the pier is effectively absorbed by the strengthened soil, reducing the risk of failure or excessive displacement of the foundation under operational and environmental stresses.

The stabilization of soil using gravel, sand, and stone particles plays a critical role in maintaining the safety and integrity of offshore structures, particularly piers, in dynamic and challenging marine environments. The effective bearing capacity of the soil, reinforced by these materials, ensures that the foundation can support both vertical and lateral forces without significant settlement or instability.

Thus, it can be concluded that the stabilization of surrounding and overlying soils with a proper mixture of gravel, sand, and stone particles is essential for optimizing the performance of offshore pier foundations. This method helps distribute lateral loads more efficiently, contributing to the overall safety, durability, and performance of the structure over its lifespan.

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APPENDIX

Notation

- D_f = Depth of foundation in meter.
- γ = Unit wt of soil in t/m^3.
- ϕ = Angle of repose in degree.
- q = Load intensity in t/m^2.

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