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Offshore Seabed Pile Foundation Analysis: Soil-Pile Interaction and Load Conditions, and Design Recommendations

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Original scientific paper

Edy Soesanto[1]*, Dicky Muslim[2], Evie Hadrijantie Sudjono[3], Cipta Endyana[4]

[1]*Geological Engineering Department, Padjadjaran University, Dipati Ukur Street No. 35, Lebakgede, Coblong District, Bandung, West Java 401328, Indonesia, ORCID 0000-0003-0104-0939*

[2]*Geological Engineering Department, Padjadjaran University, Dipati Ukur Street No. 35, Lebakgede, Coblong District, Bandung, West Java 401328, Indonesia, ORCID 0000-0001-9004-5955*

[3]*Geological Engineering Department, Padjadjaran University, Dipati Ukur Street No. 35, Lebakgede, Coblong District, Bandung, West Java 401328, Indonesia, ORCID 0000-0002-1782-5469*

[4]*Geological Engineering Department, Padjadjaran University, Dipati Ukur Street No. 35, Lebakgede, Coblong District, Bandung, West Java 401328, Indonesia, ORCID 0000-0001-9448-1789*

Abstract

Offshore pile foundations are essential for supporting structures, such as wind turbines, oil platforms, and bridges. Important factors influencing soil-pile interactions and assessing the impact of various environmental loads, including axial, lateral, and moment loads. This study begins with a comprehensive review of the analytical and numerical methods used for pile analysis. This research aims to analyze the behavior of piles in the offshore seabed environment, taking into account various factors, such as soil-pile interactions, environmental load conditions, and the design of a sturdy pile foundation. This research method exploits the importance of accurate modelling to ensure the stability and longevity of offshore structures. The strength and performance of offshore structures, such as wind turbines, oil platforms, and bridges, are highly dependent on the integrity of the pile foundations. This research will provide a detailed analysis of piles in offshore seabed environments, emphasizing the importance of soil-pile interactions, varying loading conditions, and robust pile designs. These findings underscore the need for an integrated approach that combines geotechnical data, advanced modelling, and ongoing monitoring to ensure the stability and longevity of offshore pile foundations. This research produces a foundational analysis of pile behavior in offshore environments, considering factors such as soil-pile interactions, environmental load conditions, and variations in pile diameter. Piles with a diameter of 1.067 m demonstrate the highest axial and lateral capacities, making them ideal for more extreme environmental load conditions, such as strong ocean currents and high wind loads.

Keywords:
offshore pile foundations; soil-pile interaction; axial load capacity; lateral load analysis; geotechnical engineering;

1. Introduction

The geographical and economic context of Semarang, Semarang as the capital of Central Java Province, is one of the main economic centers in Indonesia which has a large port, namely the Port of Tanjung Emas, as well as various industrial facilities and other maritime infrastructures (**Mukhlisin et al., 2022**). Located on the north coast of Java Island, Semarang has a strategic position as a trade and logistics center (**Surya & Yunus, 2020**). This makes the development of offshore marine infrastructures, such as docks, bridges, and wind power plants, a priority to support economic growth and connectivity (**Sarah et al., 2021**).

Geotechnical Challenges in the Semarang area or coastal areas of Semarang face several unique geotechnical challenges, including soft soil and alluvial deposits (**Hassan et al., 2021**). Most of the land around the coast of Semarang consists of soft alluvial deposits and marine clay. These soils have low shear strength and high compressibility properties, which can cause stability problems and soil settlement (**Masi et al., 2021; Sarah et al., 2021**). Then there is tidal flooding and land subsidence because the Semarang area experiences significant land subsidence and tidal flooding, which can affect the stability of offshore pile foundations and the structures above them (**Ardi et al., 2021**). This land subsidence is triggered by groundwater extraction and environmental changes (**Löfroth et al., 2021; Muthu Manokar et al., 2020**). Apart from that, there are also variations in sea topography, meaning that the topography of the seabed around Semarang varies with the presence of geological structures such as sediment, sand, and clay, which adds complexity to the analysis of soil and pile interaction (**Ren et al., 2020**).

* Corresponding author: Edy Soesanto
e-mail address: edy22001@mail.unpad.ac.id

The relevance of pile foundations for offshore infrastructure in Semarang is very important, considering that this city requires infrastructure that can survive in the long term and can withstand various environmental loads, such as waves, sea currents, and wind. The construction of offshore pile foundations is very relevant, especially because the Semarang coastal area faces geotechnical challenges in the form of soft soil and land subsidence. As discussed in this research, pile foundation design that integrates soil-pile interactions, load conditions, as well as accurate modelling is essential to ensure the stability and longevity of offshore structures, such as ports, bridges, and energy platforms (**Khoiriyah et al., 2023**). Some of the main reasons for the importance of pile foundation analysis in this area include increasing the stability and performance of the structure (**Govindarajan et al., 2021**). This is because a well-designed pile foundation can provide stable support for structures such as ports, bridges, and industrial buildings, thereby reducing the risk of damage due to ground subsidence and lateral loads from currents and waves (**Zheng et al., 2019**). Apart from that, to support the development of energy infrastructure, the Semarang region has great potential in developing offshore wind power plants. A sturdy pile foundation design is essential to support wind turbines in harsh marine conditions, including dynamic loads from wind and waves, as outlined in the research of **Skarin et al. (2015)**. A strong foundation will ensure the stability and longevity of wind power plants in the region (**Skarin et al., 2015**). A strong pile foundation is essential to withstand the dynamic loads generated by wind turbines in harsh sea conditions (**Mukhlisin et al., 2022**). Adaptations to local conditions and pile foundation designs tailored to local geotechnical conditions help ensure the efficiency and reliability of maritime structures, taking into account the challenges of soft soils and variations in environmental loads unique to Semarang (**Ji et al., 2023**).

Several analytical and numerical methods are used to analyze offshore piles. Traditional approaches include the use of empirical formulas and simplifications, whereas modern methods utilize Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) to provide more accurate results (**Luthfie et al., 2019**). FEA is used to model the interaction between soil and piles, enabling a detailed analysis of pile behavior under cyclic loads from waves and wind. These simulations help identify potential failure mechanisms, allowing design adjustments that improve offshore platform stability (**Moga et al., 2022**). CFD are applied to analyze the impact of dynamic ocean currents and waves on wind turbine pile foundations. By simulating the interaction between fluid and structure, this research succeeded in optimizing the pile design to better withstand the harsh conditions at sea, ensuring the structure's longevity (**Bhatti et al., 2020**). An example of FEA Application is the Analysis of Pile Structures on Offshore Foundations. FEA is used to model the response of pile foundation structures that resist static and dynamic loads. In this study, FEA can be used to dampen and stress the piles due to wave loads, ocean currents and the weight of the structure. This analysis helps ensure that the foundation is strong enough to withstand the acting forces without experiencing structural failure. An example of CFD application is fluid flow analysis around pile foundations. CFD are used to model the interaction between seawater flow and offshore pile foundations. This is useful for understanding hydrodynamic forces, such as pushing and resistance from ocean currents and waves. CFD results can provide important data regarding the forces acting on the structure as well as flow patterns around the pile which affect foundation stability. These two methods, FEA and CFD, provide a deeper understanding of the behavior of offshore piles in complex marine environments and contribute to safer and more reliable designs.

Recent advances in software and computing power have significantly improved the accuracy of this analysis (**Govindarajan et al., 2021**). Offshore piles are subjected to various types of loads, including axial loads, lateral loads, and moments. Environmental factors such as waves, currents, and wind also contribute to the overall loading conditions. Understanding the combined effects of these loads is critical to the reliable design of offshore pile foundations (**Mukhlisin et al., 2022**). In the context of pile foundation design in offshore environments, it is important to consider pore water pressure and effective circumferential stress, which can influence the stability and bearing capacity of the pile (**Zadravec & Krištafor, 2018**). This research method uses a different approach, where the water force is not directly applied as a load, but instead focuses on soil characteristics and bearing capacity.

The new approach of this research emphasizes the importance of soil-pile interaction in offshore pile analysis. This study highlights soil type, pile material, and installation methods as key factors that influence the response of piles to loads. In addition, previous research has shown differences in pile behavior in cohesive soils compared to granular soils, which is of primary interest in this analysis. This research aims to analyze the behavior of pile foundations in the offshore seabed environment, taking into account various factors, such as soil-pile interactions, environmental load conditions, and the design of a sturdy pile foundation. The contribution of this research is to provide comprehensive insight into the behavior of offshore pile foundations under various load conditions, emphasizing the importance of soil-pile interactions in ensuring the long-term stability and durability of offshore structures such as oil platforms, wind turbines, and bridges.

2. Methods

2.1. Study area

In this section, we will discuss research methods that use experimental simulation methods for installing piles

(a) (b)

Figure 1: Geological map of the study area: (a) (scale 1:1,344,000) (b) Survey location

on the coast by taking into account Soil-Pile Interaction (SPI) and Load Conditions (LC) combined with Design Recommendations (DR). This research location is located in the coastal area of North Semarang, precisely offshore. Details regarding the research location can be seen in **Figure 1**.

Based on **Figures 1a** and **1b** that the location of this research is in the Semarang area, the capital of Central Java Province, which is one of the main economic centers in Indonesia. This city has a large port, namely Tanjung Emas Port, as well as various industrial facilities and other maritime infrastructure on the north coast of Java Island, making it a strategic trade and logistics center. The Semarang coastal region faces several unique geotechnical challenges, including soft soils and alluvial deposits that have low shear strength and high compressibility properties. Another problem is tectonic movements (faults) and soil settlement, which can affect the stability of offshore pile foundations in this area. The sea coast around Semarangvaries, includes the presence of geological structures such as sediment, sand and clay. These variations add complexity to the analysis of soil-pile interactions in offshore foundations. Given these geotechnical challenges, the design of strong pile foundations for coastal infrastructure is critical to support infrastructures such as ports, bridges, also taking into consideration the growing marine wind energy generation in the region. Robust infrastructure is expected to be able to withstand dynamic and diverse sea conditions.

2.2. *Research steps*

This type of research includes descriptive and exploratory studies, meaning it describes offshore conditions and explores several improvement plans so that coastal abrasion or landslides do not occur around the coast (**Chen et al., 2020**). The research steps can be seen in **Figure 2**.

Based on **Figure 2**, this research begins by determining the research objectives of driving piles on the offshore seabed, evaluating the mechanism of soil-pile interaction, and discussing the impact of loading conditions. The next step is analyzing soil properties where accurate determination of soil properties is fundamental for pile analysis. The next step in determining the pile design involves selecting appropriate pile types, materials, and dimensions based on site-specific conditions and loading requirements. Common types of offshore piles include monopiles, jacket piles, and driven piles. Material choices typically involve steel or concrete, with considerations for corrosion resistance and durability. Further analysis of the offshore piles includes the following steps (**Chen et al., 2020**):

- Site investigation: collecting soil data through geotechnical surveys.
- Load assessment: determining the magnitude and direction of loads.
- Pile-soil interaction modelling: using analytical or numerical methods to simulate the interaction between the pile and seabed.
- Design verification: ensuring the pile design meets safety and performance criteria.

A. The ultimate axial capacity of the pile (Qu) can be estimated using the formula:

$$Qu = Qs + Qb \tag{1}$$

Where:

Qs – Shaft resistance,
Qb – Base resistance.

Shaft resistance for the shaft resistance in cohesive and cohesionless soils:

$$Qs = \Sigma\,(fs \cdot As) \tag{2}$$

Where:

fs – Unit skin friction,
As – Surface area of the pile in the soil layer – $As = \pi$ DL.

Base resistance is for the base resistance in cohesive soils:

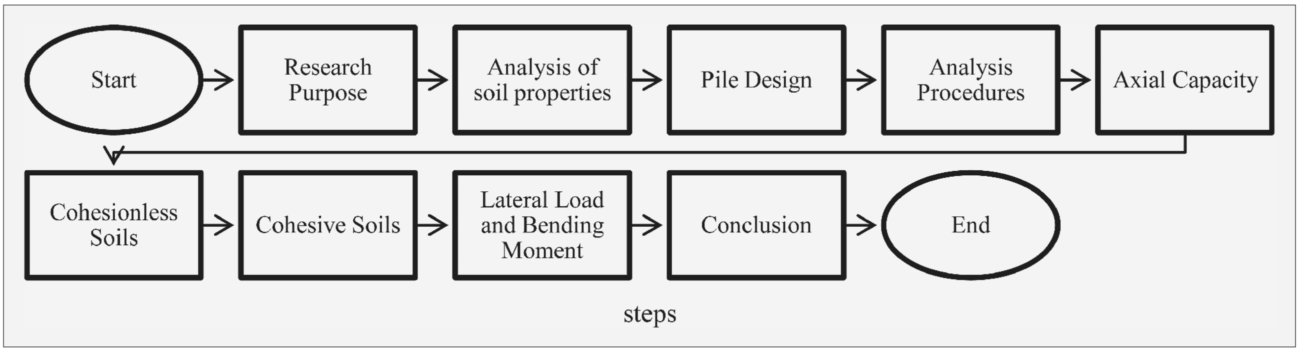

Figure 2: Research steps

$$Qb = qb \cdot Ab \quad (3)$$

Where:

qb – End resistance per unit area at the base of the pile (kN/m²),

Ab – Cross-sectional area the base of the pile (m²) $[Ab = \frac{\pi}{4} D^2]$.

Ultimate axial capacity (ultimate axial compression capacity, Qu):

- Unit: kN (kilo Newton)
- Explanation: ultimate axial capacity is the maximum load that a pile can withstand before failure. This calculation is important to ensure that the pile has sufficient bearing capacity to withstand the vertical load of the offshore structure built on it.

Friction resistance (shaft resistance, *Qs*):

- Unit: kN (kilo Newton)
- Explanation: frictional resistance is the force that arises from the interaction between the pile surface and the surrounding soil. Calculating Qs is important to understand the contribution of soil friction in supporting pile stability, especially in cohesive soils.

Base Resistance (Qb):

- Unit: kN (kilo Newton)
- Explanation: end resistance provides additional bearing capacity of the pile base which interacts directly with the hard soil layer. This is important to ensure extra bearing capacity at a certain depth, where a denser layer of soil supports the pile tip.

B. Static lateral load pile capacity

$$Qlat = k\,D\,L \quad (4)$$

Where:

Qlat – Static lateral capacity (kN),

k – Soil lateral reaction coefficient (kN/m²),

D – Pile diameter (m),

L – Effective pile length (m).

Static lateral load pile capacity (Qlat):

- Unit: kN (kilo Newton)
- Explanation: lateral load capacity is important to assess how the pile can withstand horizontal forces from ocean currents or wind. This analysis helps in the design of structures that are stable against significant lateral forces in offshore environments.

C. Pile head deflection:

$$\delta = \frac{PL^3}{3EI} \quad (5)$$

Where:

δ – Pile head deflection (mm),

P – Lateral load (kN),

L – Pile length (m),

E – Modulus of elasticity of the pile material (kN/m²),

I – Moment of inertia of the pile cross-section (m⁴).

Deflection of the mast head:

- Unit: mm (millimeter)
- Explanation: pile head deflection indicates how much lateral displacement occurs in the pile head under lateral load. This calculation is important to ensure that the deflection is within safe limits to avoid damage or instability to the supported structure.

Moment Inertia (I): $I = \frac{\pi D^4}{64}$ (6)

D. Lateral load and bending moment

The pile behavior can be modeled for lateral load and bending moment using p-y curves. The deflection *y* at a depth *z* due to lateral load *H* and moment *M* is calculated using the beam-on-elastic-foundation approach **(Guerra et al., 2018)**:

$$\mathrm{EI}\frac{d^4 y}{dz^2} = -p(y) \quad (7)$$

The bending moment at each segment can be calculated using the second derivative of the lateral deflection *y*:

$$M(x) = -EI\frac{d^2 y(x)}{dx^2} \quad (8)$$

$$M = P.h \quad (9)$$

Where:

M(x) is the bending moment at depth,

E – Young's modulus of pile material,

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I – Moment of inertia of the pile cross-section,
y – Lateral deflection,
$y(x)$ – Soil reaction, a function of y.

E. The shear force at each segment is obtained by differentiating the bending moment:

$$V(x) = \frac{dM(x)}{dx} \qquad V = P \tag{10}$$

Where:

V(x) is the shear force at depth x,

M(x) is the bending moment at depth x.

Parameter A (pile friction resistance): it is important to determine the interaction between the pile surface and the soil, which affects the axial bearing capacity of the pile. Parameter B (pile end resistance): helps measure the soil support at the base of the pile, relevant for foundations that require direct support at the base of hard soil or dense layers. Parameters C and D (lateral capacity and pile head deflection) determine lateral stability, especially for foundations exposed to lateral loads from sea currents and wind, so considering pile head deflection helps in ensuring structural safety. Meanwhile, the research procedure begins with soil data collection through a cone penetration test (CPT), where data related to soil resistance parameters is collected for more accurate calculations. Load analysis and soil-pile interaction: uses numerical methods, such as finite difference models, to simulate pile response to loads, including lateral deflection and bending moments.

2.3. Pile analysis

When the ocean surface or submerged structures are constructed, the main concern is to maintain the structure stability from wind, wave pressure, ocean current, or ship impact by applying a mooring system. Mooring by permanent anchor can be accomplished by the use of a permanent anchor at the seabed with a rope (a line, cable, or chain) running to a floating structure on the surface. The tensile stress of rode transferred to the anchor, resulting in pull-out and lateral force at the top of the anchor pile.

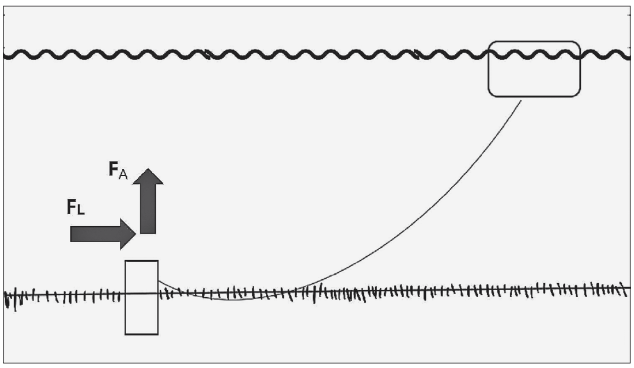


Figure 3: Sketch of Axial and Lateral load on Anchor Pile

Based on **Figure 3**, FL (Lateral Force) describes the horizontal force acting on the pile. On offshore structures, lateral forces can come from waves, wind, and currents. These forces cause the pile to experience lateral bending and deflection, which is an important factor in pile design to ensure the pile can withstand these forces without excessive movement or failure. FA (Axial Force) refers to the vertical load applied along the length of the pile, usually from the weight of the structure above it (for example, a platform or wind turbine). The Anchor Pile is a vertical structural element that is embedded in the ground, with an axial load represented by a downward arrow along the pile. Meanwhile, lateral loads are represented by horizontal arrows that are perpendicular to the length of the pile. Soil reaction is represented by arrows showing soil resistance to piles.

Piles are used to provide support against horizontal and vertical forces in a variety of engineering structures, such as offshore platforms, retaining walls, and mooring systems. Understanding the effects of axial and lateral loads on piles is critical to ensuring stability and structural integrity. The results of soil mechanic analysis based on laboratory tests can be seen in **Table 1** in the attachment.

Based on **Table 1**, the results of these numbers are the data needed to produce results:

1) Interpretation of index properties:

- Soil classification: index properties help classify soils for the initial prediction of soil behavior under load.
- Identify potential deformation: Atterberg limits and grain analysis provide insight into how soil will deform under changes in water content and pressure.
- The subsoil encountered by the soil boring at BH-01 at KP-16B comprises generally clays with increasing consistency from mud line to 34m penetration, with a sandy layer at 34.30 m to 36.40 m. A summary of the major strata encountered and its strength from soil boring of BH-01 is presented in the following **Table 2**.

The subsoil encountered by the soil boring at BH-02 (or KP.16A) comprises generally silty clay with increasing consistency from mud line (seabed) to the end of the boring depth, with a sandy layer at 35.00 m to 36.40 m depths. A summary of the major strata encountered during the soil boring of KP.16A is presented in **Table 3.**

2) Interpretation of engineering properties:

- Foundation design: parameters such as shear strength, bearing capacity, and soil reaction modulus are used directly in foundation design to ensure stability and safety.
- Slope stability and settlement evaluation: consolidation and permeability data are used to predict soil behavior under long-term loading and how water will flow through the soil, which is important for slope stability and settlement control.

Table 1: Analysis of Soil Mechanic Laboratory Test

L O C A T I O N: Semarang, Central Java														Summary of soil mechanic laboratory test							
No	Borehole	Field No	Depth (meter)	Classification USCS	Index Properties: Determination of dry density & moisture content						Index Properties: Specific grafity	Engineering Properties: Triaxial UU		Unconfined compression			Mini vane test			Consolidation Test	
					Wn (%)	gn (gr/cm³)	gd (gr/cm³)	Void Ratio e	Porosity n	Sr (%)	Gs	Total Stress F Degree	Total Stress C kg/cm²	QUU kg/cm²	QUR kg/cm²	Sensitivity kg/cm²	Cu kg/cm²	Cr kg/cm²	Sensitivity	Cc	Cv cm²/sec
1	BH-02 (KP.16 + 000 A)	1	3.00 - 3.75	CH	56.885	1.407	0.897	1.900	0.655	77.880	2.601	2.505	0.029	0.059	0.039	1.513	0.027	0.021	1.317	0.591	3.00E-04
2	BH-02 (KP.16 + 000 A)	2	6.00 - 6.75	CH	98.370	1.386	0.699	2.673	0.728	94.462	2.567	3.111	0.041	0.091	0.048	1.896	0.042	0.032	1.297	0.832	2.80E-04
3	BH-02 (KP.16 + 000 A)	3	9.00 - 9.75	CH	96.335	1.418	0.722	2.511	0.715	97.273	2.535	4.856	0.057	0.071	0.054	1.315	0.039	0.029	1.351	1.002	3.30E-04
4	BH-02 (KP.16 + 000 A)	4	12.00 - 12.75	CH	51.501	1.640	1.083	1.408	0.585	95.367	2.607	3.280	0.101	0.262	0.178	1.472	0.112	0.082	1.366	0.623	4.40E-04
5	BH-02 (KP.16 + 000 A)	5	15.00 - 15.75	CH	57.072	1.617	1.029	1.456	0.593	99.117	2.528	6.281	0.476	1.037	0.542	1.913	0.510	0.343	1.488	0.974	8.80E-04
6	BH-02 (KP.16 + 000 A)	6	18.00 - 18.75	CH	62.308	1.608	0.991	1.645	0.622	99.251	2.621	6.185	0.312	0.638	0.450	1.418	0.301	0.216	1.394	1.124	1.22E-03
7	BH-02 (KP.16 + 000 A)	7	21.00 - 21.75	CH	66.198	1.580	0.951	1.750	0.636	98.898	2.614	6.612	0.222	0.577	0.305	1.892	0.255	0.175	1.457	0.855	5.50E-04
8	BH-02 (KP.16 + 000 A)	8	24.00 - 24.75	CH	58.006	1.519	0.962	1.725	0.633	88.110	2.621	7.174	0.143	0.320	0.220	1.455	0.164	0.123	1.339	0.972	2.15E-03
9	BH-02 (KP.16 + 000 A)	9	27.00 - 27.75	CH	63.514	1.517	0.928	1.818	0.645	91.315	2.614	6.367	0.115	0.480	0.252	1.905	0.212	0.149	1.428	0.642	1.48E-03
10	BH-02 (KP.16 + 000 A)	10	30.00 - 30.75	CH	37.052	1.640	1.197	1.150	0.535	82.898	2.574	7.163	0.449	1.162	0.813	1.429	0.589	0.438	1.346	0.553	2.82E-03
11	BH-02 (KP.16 + 000 A)	11	33.00 - 33.75	CH	59.577	1.516	0.950	1.689	0.628	90.089	2.554	6.635	0.110	0.263	0.150	1.753	0.103	0.071	1.444	0.491	2.66E-03
12	BH-02 (KP.16 + 000 A)	12	36.00 - 36.75	CH	34.403	1.637	1.218	1.086	0.521	80.477	2.541	8.256	0.472	1.491	1.019	1.463	0.722	0.514	1.405	0.356	3.28E-03
13	BH-01 (KP.16 + 000 B)	1	3.00 - 3.75	CH	88.665	1.423	0.755	2.368	0.703	95.151	2.541	3.884	0.037	0.065	0.045	1.444	0.033	0.275	0.118	1.143	1.27E-03
14	BH-01 (KP.16 + 000 B)	2	6.00 - 6.75	CH	51.597	1.651	1.089	1.357	0.576	97.628	2.567	4.875	0.051	0.198	0.136	1.456	0.093	0.066	1.420	0.614	3.70E-04
15	BH-01 (KP.16 + 000 B)	3	9.00 - 9.75	CH	50.172	1.607	1.070	1.411	0.585	91.736	2.580	5.773	0.151	0.411	0.265	1.551	0.208	0.151	1.382	0.492	1.02E-03
16	BH-01 (KP.16 + 000 B)	4	12.00 - 12.75	CH	47.346	1.695	1.150	1.221	0.550	99.067	2.554	7.607	0.267	0.883	0.570	1.549	0.430	0.301	1.429	0.555	1.09E-03
17	BH-01 (KP.16 + 000 B)	5	15.00 - 15.75	CH	60.260	1.490	0.930	1.803	0.643	87.123	2.607	8.044	0.304	0.726	0.482	1.506	0.384	0.275	1.397	0.770	1.67E-03
18	BH-01 (KP.16 + 000 B)	6	18.00 - 18.75	CH	66.772	1.585	0.950	1.766	0.638	99.392	2.628	8.184	0.171	0.307	0.227	1.352	0.159	0.113	1.409	0.867	1.03E-03
19	BH-01 (KP.16 + 000 B)	7	21.00 - 21.75	CH	56.921	1.634	1.041	1.544	0.607	97.642	2.649	9.152	0.150	0.596	0.344	1.733	0.255	0.175	1.457	0.933	1.45E-03
20	BH-01 (KP.16 + 000 B)	8	24.00 - 24.75	CH	60.088	1.612	1.007	1.616	0.618	97.957	2.635	9.209	0.144	0.453	0.277	1.635	0.224	0.162	1.380	0.951	8.90E-04
21	BH-01 (KP.16 + 000 B)	9	27.00 - 27.75	CH	62.952	1.600	0.982	1.669	0.625	98.884	2.621	6.997	0.211	0.764	0.432	1.769	0.364	0.256	1.420	0.596	1.19E-03
22	BH-01 (KP.16 + 000 B)	10	30.00 - 30.75	CH	61.133	1.612	1.000	1.634	0.620	98.594	2.635	8.420	0.123	0.288	0.165	1.745	0.125	0.086	1.456	1.107	1.07E-03
23	BH-01 (KP.16 + 000 B)	11	33.00 - 33.75	CH	42.289	1.703	1.197	1.178	0.541	93.607	2.607	8.025	0.529	1.341	0.943	1.422	0.660	0.490	1.346	0.413	2.63E-03
24	BH-01 (KP.16 + 000 B)	12	36.00 - 36.75	CH	32.833	1.839	1.384	0.855	0.461	98.619	2.567	6.831	0.523	1.226	0.807	1.519	0.592	0.431	1.372	0.311	1.75E-03

Table 2: Subsoil Condition at KP-16B (BH-01)

Depth below seabed (m)		Thickness (m)	Description	Layer designation	Soil strength
From	To				
0.00	7.00	7.00	Very soft silty clay	Unit A	Su = 8 kPa
7.00	12.00	5.00	Soft to medium stiff silty clay	Unit B	Su = 26 kPa
12.00	34.30	22.30	Medium stiff to stiff silty clay	Unit C	Su = 42 kPa
34.30	36.40	2.10	Medium dense silty sand	Unit D	$\Theta = 30^0$
36.40	40.00	3.60	Very stiff to stiff silty clay	Unit E	Su= 78 kPa

Remarks: Location KP-16B (BH-01), Coordinates: E. 438,619.5 m, N. 9,248,709.7m, Elev: -22.6

Table 3: Subsoil Condition at KP-16A (BH-02)

Depth below seabed (m)		Thickness (m)	Description	Layer designation	Soil strength
From	To				
0.00	10.00	10.00	Very soft silty clay	Unit A	Su = 5 kPa
10.00	15.00	5.00	Soft to medium stiff silty clay	Unit B	Su = 16 kPa
15.00	35.00	20.00	Medium stiff to stiff silty clay	Unit C	Su = 40 kPa
34.30	36.40	1.40	Medium dense silty sand	Unit D	$\Theta = 30^0$
36.40	40.00	3.60	Very stiff to stiff silty clay	Unit E	Su= 90 kPa

Remarks: Location KP-16A (BH-02), Coordinates: E. 438,716.5 m, N. 9,248,734.2 m, Elev: -22.6

3) Interpretation of engineering properties:

- Foundation design: parameters such as shear strength, bearing capacity, and soil reaction modulus are used directly in foundation design to ensure stability and safety.
- Slope stability and settlement evaluation: consolidation and permeability data are used to predict soil behavior under long-term loading and how water will flow through the soil, which is important for slope stability and settlement control.

3. Results

Using p-y curves and finite difference methods, the lateral deflections and moments can be computed. This involves iterative solutions and is typically performed using specialized geotechnical software. Several case studies demonstrate the application of pile analysis methods in real-world offshore projects. For instance, the design of piles for an offshore platform in the Java Sea highlighted the importance of considering cyclic loading from waves and wind. Numerical simulations provided insight into potential failure mechanisms and informed design adjustments.

Challenges in offshore pile analysis include dealing with heterogeneous soil conditions, predicting long-term behavior, and managing construction risks. Solutions involve advanced modelling techniques, continuous monitoring, and adaptive design strategies to accommodate unexpected conditions. The results from both analytical and numerical methods will provide insight into:

- Axial capacity of the pile,
- Lateral deflection and bending moments,
- Stress distribution along the pile length,
- Soil-pile interaction characteristics.

Load conditions

The calculations for each soil layer are unit skin friction (fs) is the resistance per unit area offered by the soil along the surface of the pile. It depends on the type of soil and pile material and the depth at which the pile is embedded. The type of soil and pile material and the depth to which the piles are planted can be seen in the attachment.

The results of the static ultimate axially loaded pile capacity analyses with an embedment depth of 40 m are summarized in the following **Table 4**, to get:

1. Ultimate axial compression capacity (kN) can use **Equations 1**, **2** and **3**.

Diameter 0.762 meters

- Pile surface area (As): As=71.9 m^2
- The cross-sectional area of the tip (Ab): Ab=0.456 m^2

Qu (0.762) = 3500 kN, Qu = fs · As + qb · Ab ~ 3500 = fs · 71.9 + qb · 0.456, system of equations: 3500 = 71.9fs + 0.456qb

By using the Gaussian elimination method or using software such as Python, or MATLAB, we can solve the system of equations to get the values of fs and qb.

2. Ultimate tension capacity (kN) can use **Equations 1**, **2** and **3**

Qu = Qs, where: Qu: Ultimate axial tensile capacity (kN), Qs: Total skin friction capacity (kN)

Diameter 0.762 meters, we assume the pile length (L) is constant and the skin friction fs is the same for all diameters. For example, we assume the length of the pile L = 30 meters.

Pile surface area (As): As=71.9 m^2, Qu(0.762 m) =3240kN

Table 4: Static ultimate axially loaded pile capacity

Location	Pile type	Pile diameter (m)	Ultimate axial compression capacity (kN)	Ultimate axial tension capacity (kN)
BH-01/ CPT-BH01	Steel pipe pile	0.762	3500	3240
		0.914	4270	3880
		1.067	5060	4530
BH-02/ BH-CPT01	Steel pipe pile	0.762	3250	3000
		0.914	3960	3600
		1.067	4690	4200

Based on **Table 4**, the ultimate axially loaded capacity of a pile refers to the maximum load that the pile can bear (along the length of the pile) before failure occurs. This capacity is an important factor in pile foundation design and is used to ensure that the pile can safely support the loads applied by the structure it supports. The results of the static laterally loaded pile capacity analysis with an embedment depth of 40 m are summarized and can be seen in **Table 5**.

The results of the static ultimate axially loaded pile capacity analysis with an embedment depth of 40m are summarized in the following **Table 5**, to obtain:

1. Static lateral load pile capacity (kN) can use **Equation 4**.

Where:

Qlat - Static lateral capacity = 150 kN, D-Pile diameter = 0.762 m, L-Effective pile length = 10 m, calculated Calculating soil lateral reaction coefficient (k)-Soil lateral reaction coefficient (kN/m²):

Diameter 30 inch: 150 kN = $k \cdot 0.762 \cdot 10 \sim k = 150/(0.762 \cdot 10) \approx 19.69\,kN/m^2$

The static lateral load pile capacity value of 19.69 kN/m² is relatively small for the soil reaction modulus, which generally measures the response of the soil to the lateral load acting on the pile. This value indicates how much the soil can withstand the lateral force applied to the pile. Here are several reasons why this value could be smaller than expected:

a) Soft soil conditions: if the soil at the location is soft soil such as clay or watery soil, the soil reaction modulus tends to be smaller. Soft soil has a low lateral bearing capacity, which means it will deform more easily when exposed to lateral forces. This condition commonly occurs in coastal areas or seabeds with soft sediment.

b) Depth of pile installation: the soil reaction modulus also depends on the depth of pile installation. In shallower soil layers, the soil tends to be looser and offers less resistance to lateral forces than deeper, denser soil layers. If the pile is only installed at a relatively shallow depth, the resulting reaction modulus value can be smaller.

c) Properties of granular vs. granular soil cohesive: granular soils such as sand, when dry, have a higher modulus of lateral reaction than clay or other cohesive soils. In contrast, cohesive soils (clays) tend to have a more elastic response and compress more easily under lateral loads, which can result in a lower reaction modulus.

d) Load and pile length: if the pile is not exposed to large lateral loads or if the length of the pile exposed to lateral loads is relatively short, a low soil reaction modulus may reflect the elastic response of the soil under such load conditions.

Analysis results: the value of 19.69 kN/m² for the subgrade reaction modulus may indicate soft soil conditions, shallow pile depth, or cohesive soil properties. For situations like this, pile design needs to take into account that the soil may require additional reinforcement, increased pile installation depth, or even the selection of an alternative foundation design to withstand greater lateral forces and increase stability.

2. Pile head deflection (kN) can use **Equations 5** and **6**.

Where:

D-Pile Diameter = 0.762 m, Pile Head Deflection = 8.5 mm, Pile length = 10 m

I = π(0.762)4 /64 ≈ 0.0159 m4 ~ 8.5 = P · (10)3/3 · E · 0.0159 ~ P = 8.5 · 3 · E · 0.0159/1000

Table 5: Static laterally loaded pile capacity, diameters: 0.762 m; 0.914 m; 1.067 m.

Location	Pile type	Pile diameter (m)	Lateral pile capacity (kN)	Pile head deflection (mm)
BH-01/ CPT-BH01	Steel pipe pile	0.762	150	8.5
		0.914	200	8.4
		1.067	250	8.5
BH-02/ BH-CPT01	Steel pipe pile	0.762	150	8.6
		0.914	200	8.9
		1.067	240	8.4

Based on **Table 5**, lateral pile capacity refers to the ability of the pile to withstand the lateral load or horizontal force applied to the pile. This lateral force can come from various sources, such as wind, ocean currents, waves, or other external forces that act horizontally on offshore structures. **Table 5** shows that lateral pile capacity and pile head deflection are critical in designing piles for lateral loads, providing insight into pile behavior under such forces and guiding the selection of pile dimensions and materials for safe and effective

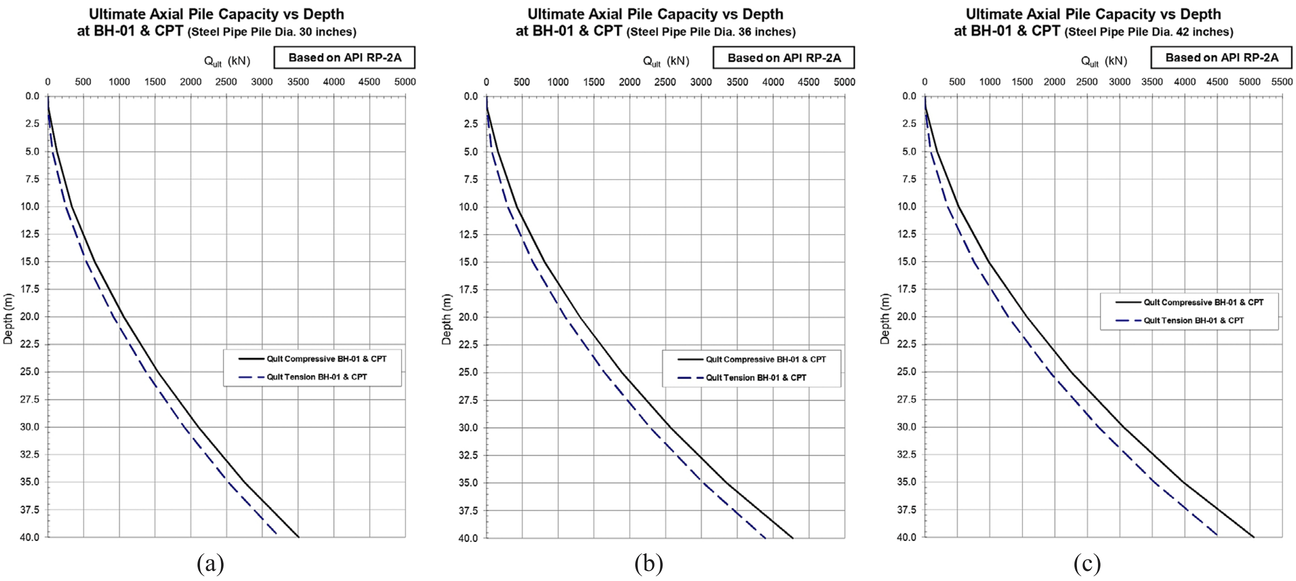


Figure 4: Ultimate axial pile capacity vs depth at BH-01 & CPT; (a): steel pipe pile diameter 0.762 m; (b): steel pipe pile diameter 0.914 m; (c): steel pipe pile diameter 1.067 m.

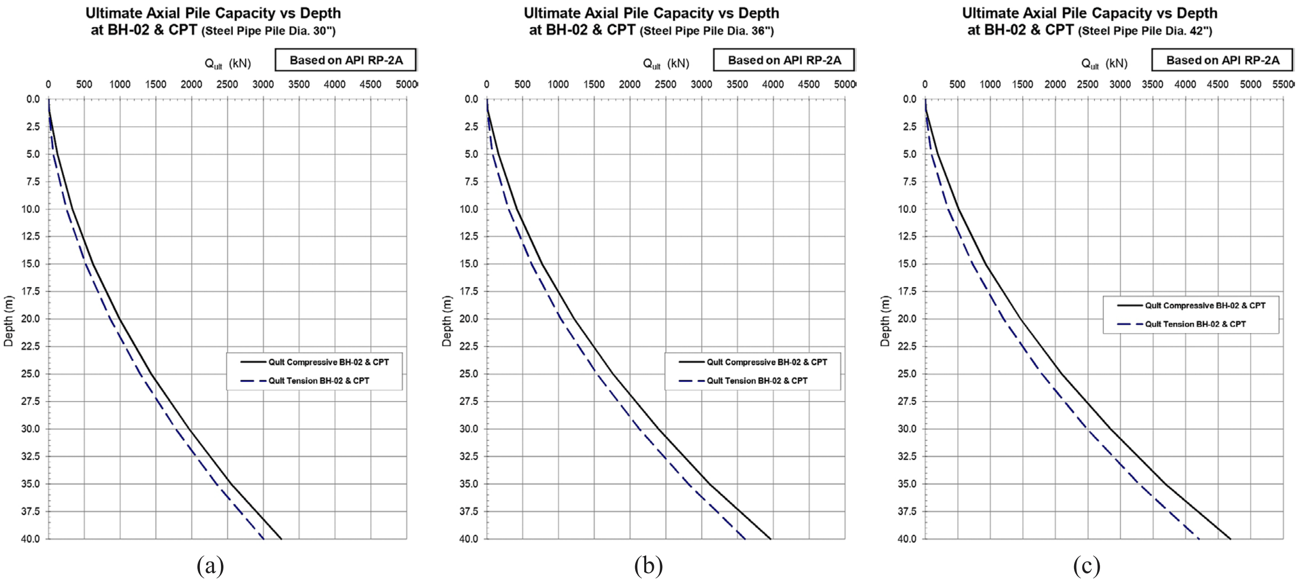


Figure 5: Ultimate axial pile capacity vs depth at BH-02 & CPT; (a): steel pipe pile diameter 0.762 m; (b): steel pipe pile diameter 0.914 m; (c): steel pipe pile diameter 1.067 m.

foundation solutions. The axial capacity of piles which varies with depth at certain drill hole locations can be seen in **Figure 4**.

The results of the lateral loaded pile bending moment (see **Figures 6** and **7**) and shear force with an embedment depth of 40 m are summarized in the following **Figures 8** and **9**, to obtain:

Given data pile diameters: 0.762 meters, 0.9144 meters, and 1.0668 meters

1. Lateral load and bending moment can use **Equations 7**, **8**, and **9**.

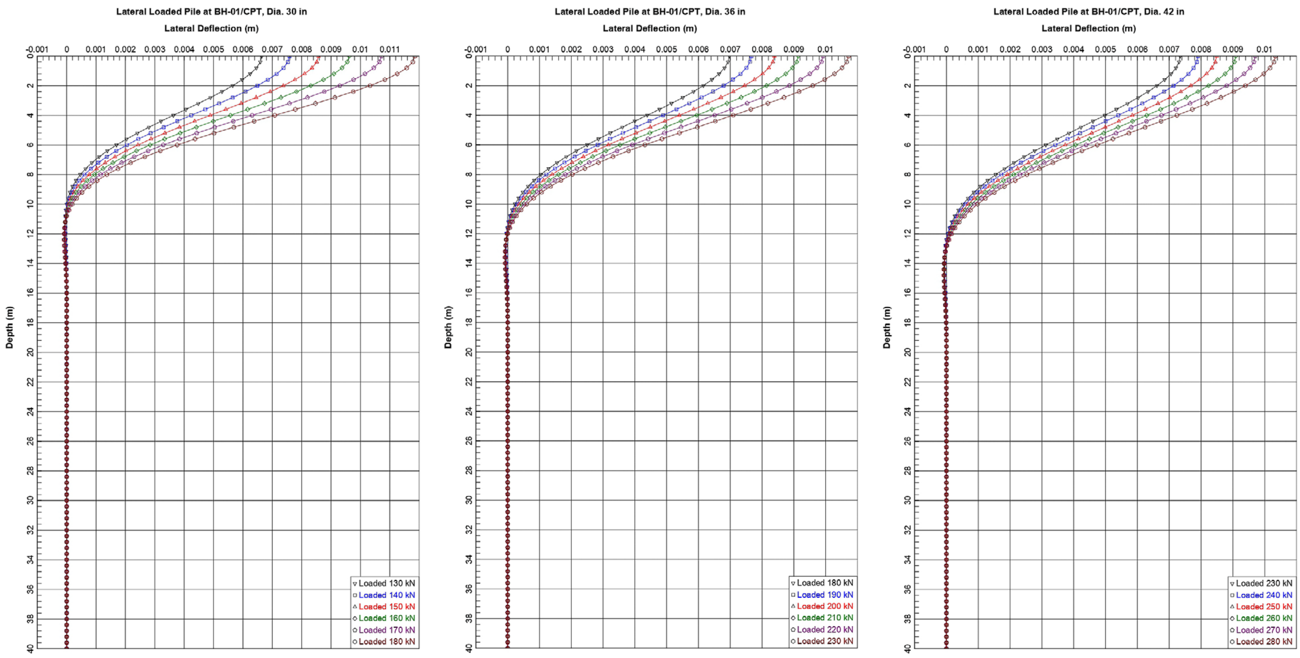
Pile lengths: 8 meters for 0.762 meters diameter, 9 meters for 0.9144 meters diameter, 10 meters for 1.0668 meters diameter.

Calculation: M30 = P.8 ~ P = 150 kN, M36 = P.9 ~ P = 200 kN, M42 = P.10 ~ P = 250 kN

The shear force at each segment is obtained by differentiating the bending moment using **Equations 6** and **10**:

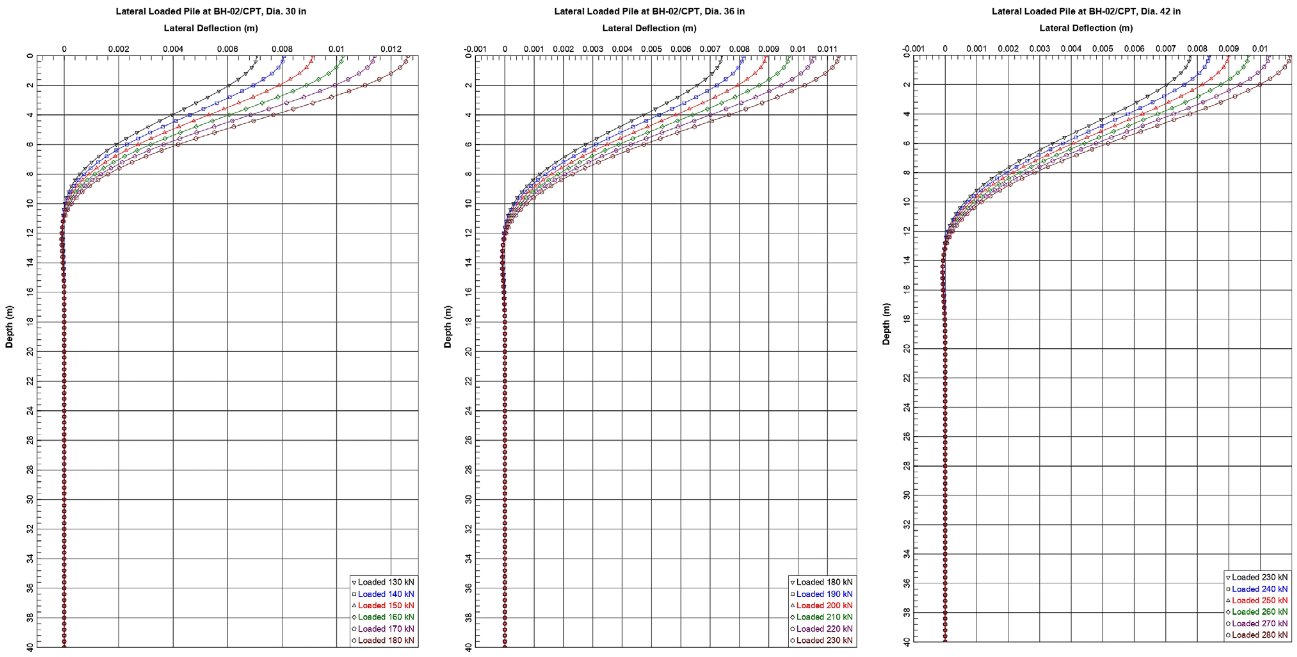
Pile lengths: 11 meters for 0.762 meters diameter, 12 meters for 0.9144 meters diameter, 13 meters for 1.0668 meters diameter. Thus enabling these calculations: V30 = P ~ P = 150 kN, V36 = P ~ P = 200 kN, M42 = P ~ P = 250 kN, steps for Python code for calculation:

1. Discretize the pile length into small segments.
2. Compute the lateral deflection profile y (x) at each segment.
3. Calculate the second derivative of the lateral deflection profile to get the curvature.



(a) (b) (c)

Figure 6: Lateral loaded pile at BH-01/CPT-lateral deflection (m); (a) diameter 0.762 m; (b): diameter 0.914 m; (c): diameter 1.067 m.



(a) (b) (c)

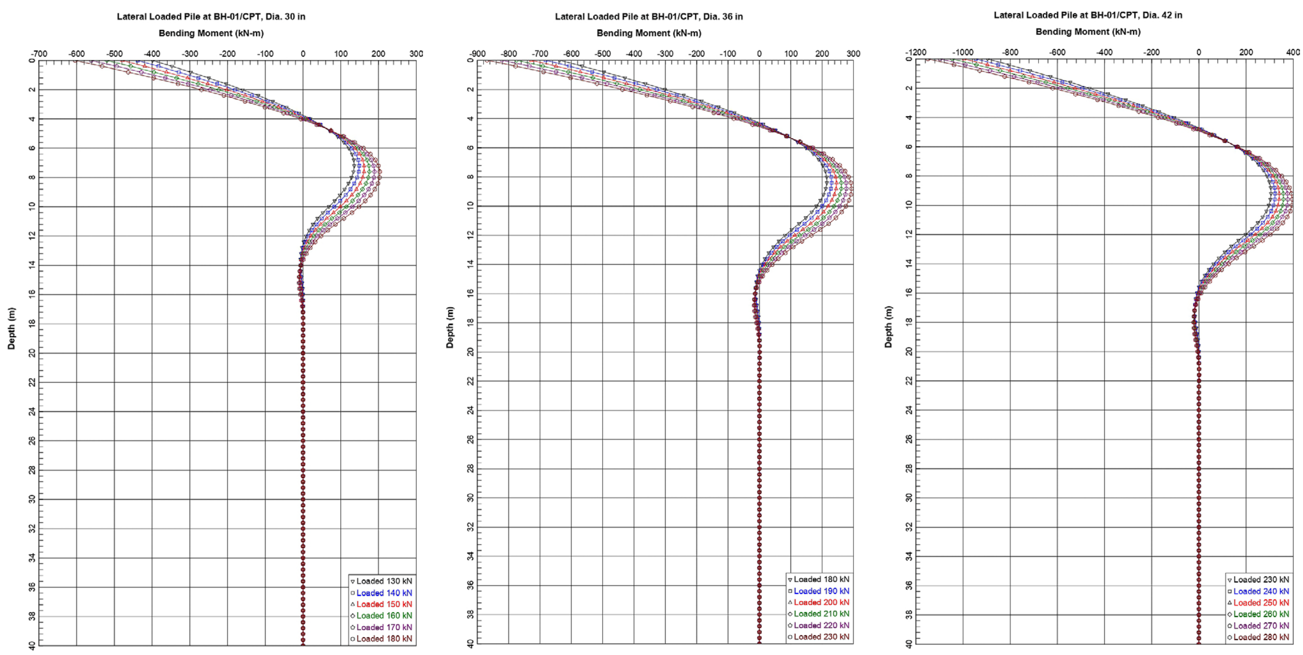
Figure 7: Lateral loaded pile at BH-02/CPT-lateral deflection (m); (a): diameter 0.762 m; (b): diameter 0.914 m; (c): diameter 1.067 m.

4. Compute the bending moment using the curvature.
5. Differentiate the bending moment to obtain the shear force.

Figure 4 illustrates how the axial capacity of the pile varies with depth for different steel pipe pile diameters (0.762 m; 0.914 m; 1.067 m) at a particular drill hole location (BH-01) and based on cone penetration test (CPT) data. The ultimate axial pile capacity vs depth at BH-02 & CPT can be seen in **Figure 5**.

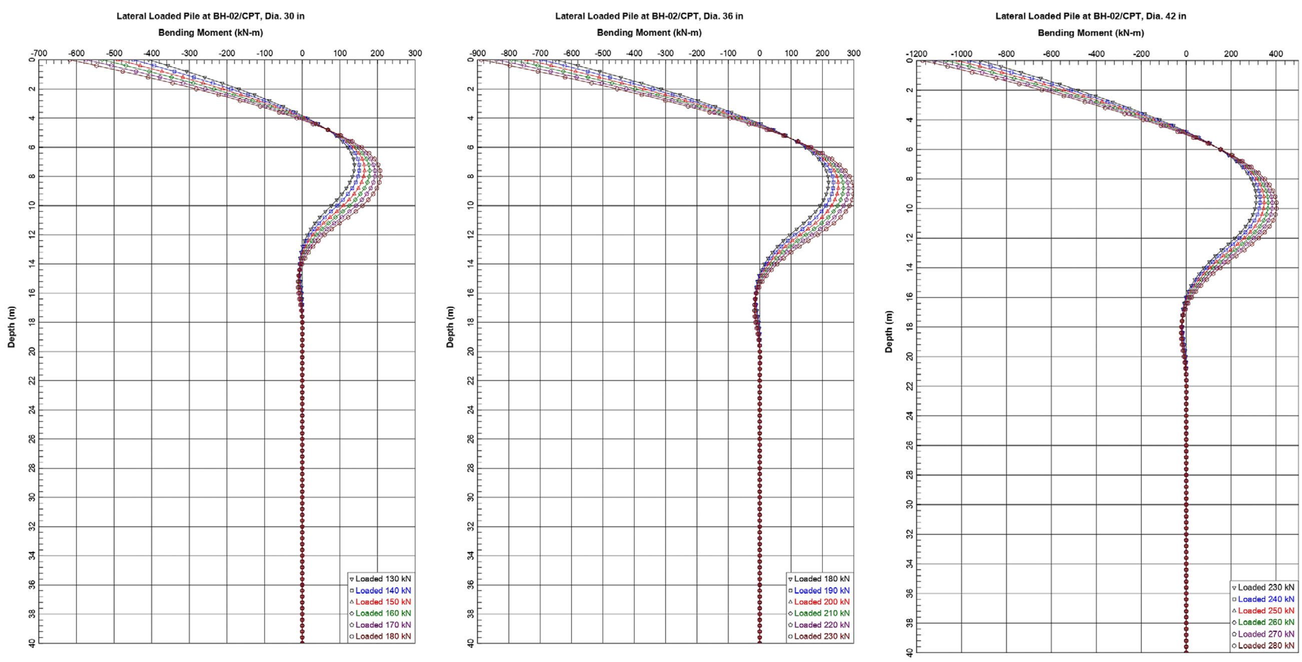
Figure 5 illustrates how the axial capacity of the pile varies with depth for different steel pipe pile diameters (0.762 m; 0.914 m; 1.067 m) at a particular drill hole location (BH-02) and based on the cone penetration test (CPT) data. As for the lateral loaded pile at BH-01/CPT-lateral deflection (m), it can be seen in **Figure 6**.

Figure 6 illustrates how the lateral deflection of the pile varies with depth and lateral load for different steel pipe pile diameters (0.762 m; 0.914 m; 1.067 m) at a



(a) (b) (c)

Figure 8: Lateral loaded pile at BH-01/CPT-bending moment (kN-m);(a): diameter 0.762 m; (b): diameter 0.914 m; (c): diameter 1.067 m.



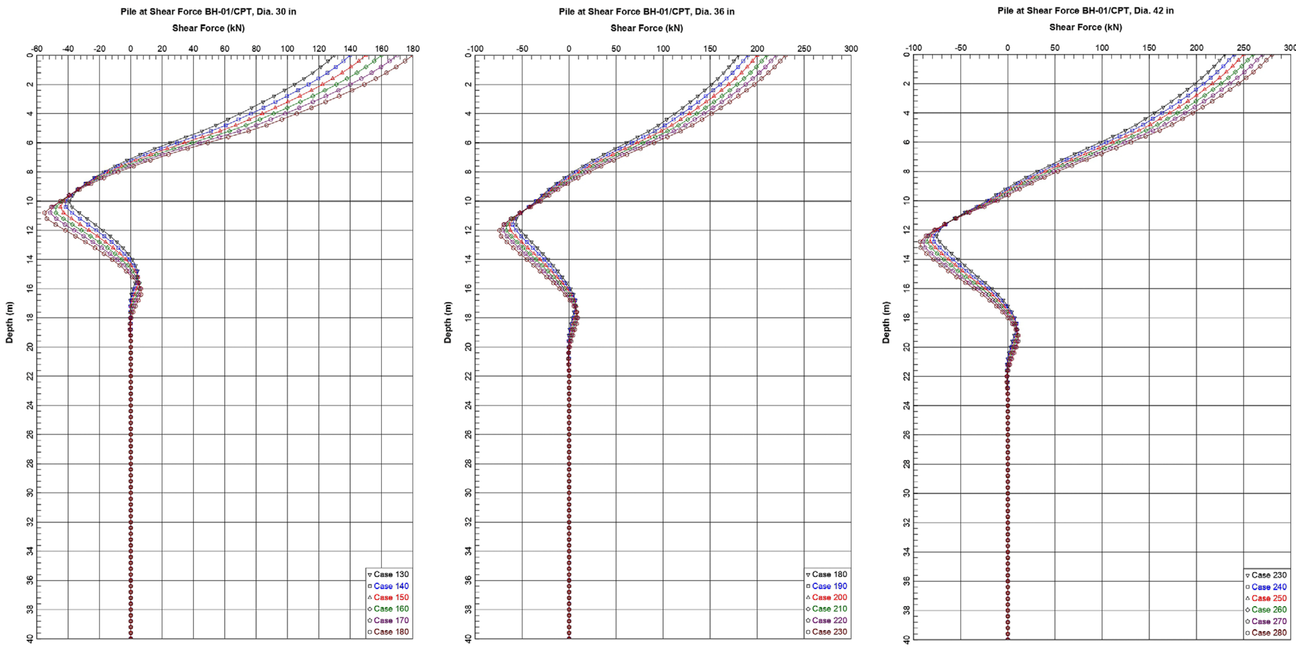
(a) (b) (c)

Figure 9: Lateral loaded pile at BH-02/CPT-bending moment (kN-m); (a): diameter 0.762 m; (b): diameter 0.914 m; (c): diameter 1.067 m.

particular drill hole location (BH-01), using data obtained from penetration cone test (CPT). The lateral loaded pile at BH-02/CPT-lateral deflection (m) can be seen in **Figure 7**.

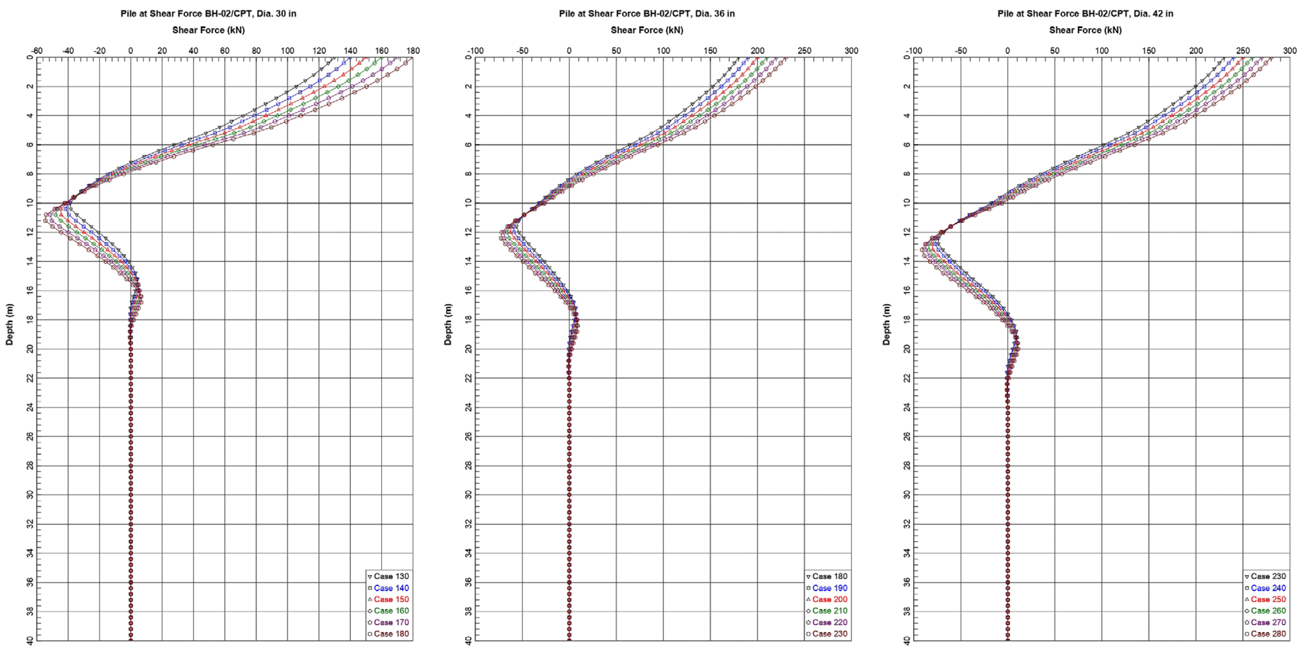
Figure 7 illustrates how the lateral deflection of the pile varies with depth and lateral load for different steel pipe pile diameters (0.762 m; 0.914 m; 1.067 m) at a particular drill hole location (BH-02), using data obtained from penetration cone test (CPT). The lateral loaded pile at BH-01/CPT-bending moment (kN-m) can be seen in **Figure 8**.

Figure 8 illustrates how the bending moment varies with depth for different steel pipe pile diameters (0.762 m; 0.914 m; 1.067 m) when subjected to lateral loads at a particular drill hole location (BH-01), based on data from the cone penetration test (CPT). The lateral loaded pile at bh-02/cpt-bending moment (kN-m) can be seen in **Figure 9**.



(a) (b) (c)

Figure 10: Pile at shear force BH-01/CPT; (a) diameter 0.762 m; (b): diameter 0.914 m; (c): diameter 1.067 m.



(a) (b) (c)

Figure 11: Pile at shear force BH-02/CPT; (a): diameter 0.762 m; (b): diameter 0.914 m; (c): diameter 1.067 m.

Figure 9 illustrates how the bending moment varies with depth for different steel pipe pile diameters (0.762 m; 0.914 m; 1.067 m) when subjected to lateral loads at a particular drill hole location (BH-02), based on data from the Cone Penetration Test (CPT). The pile at shear force BH-01/CPT can be seen in **Figure 10**.

Figure 10 illustrates how the shear force varies with depth for different steel pipe pile diameters (0.762 m; 0.914 m; 1.067 m) at a particular drill hole location (BH-01), using data obtained from the cone penetration test (CPT). The pile at shear force BH-02/CPT can be seen in **Figure 11.**

Figure 11 illustrates how the shear force varies with depth for different steel pipe pile diameters (0.762 m; 0.914 m; 1.067 m) at a particular drill hole location (BH-02), using data obtained from the cone penetration test (CPT). The lateral loaded pile at BH-01/CPT can be seen in **Figure 12**.

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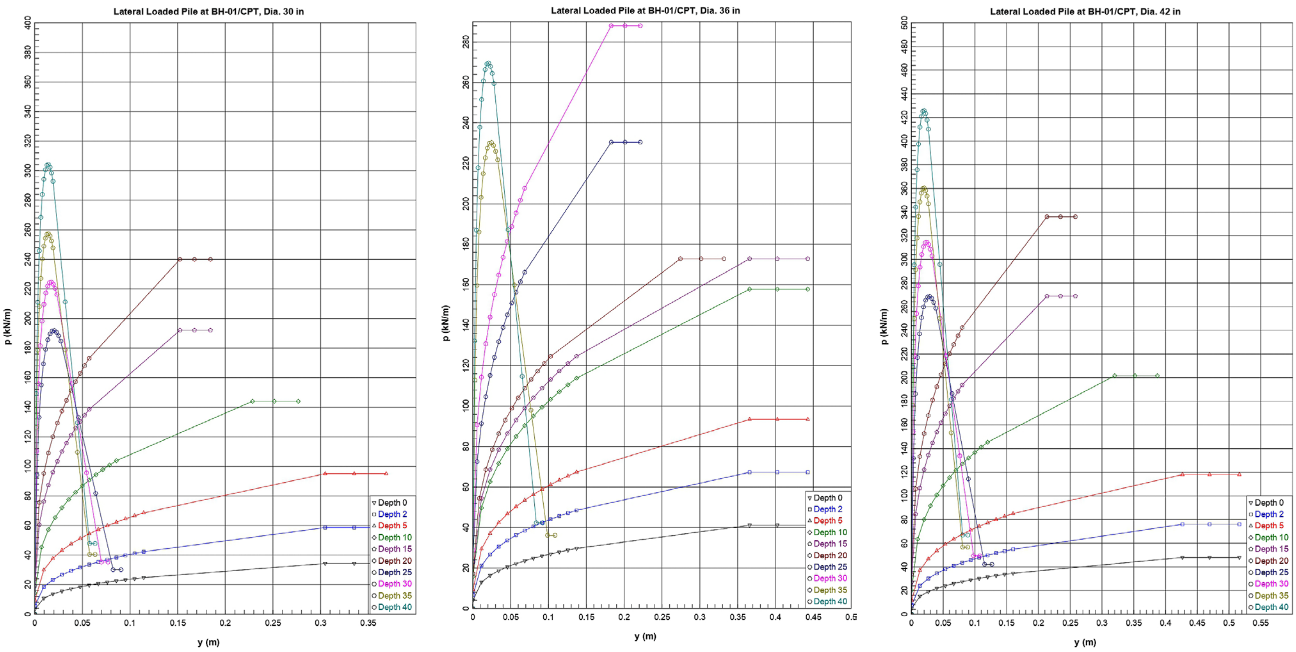
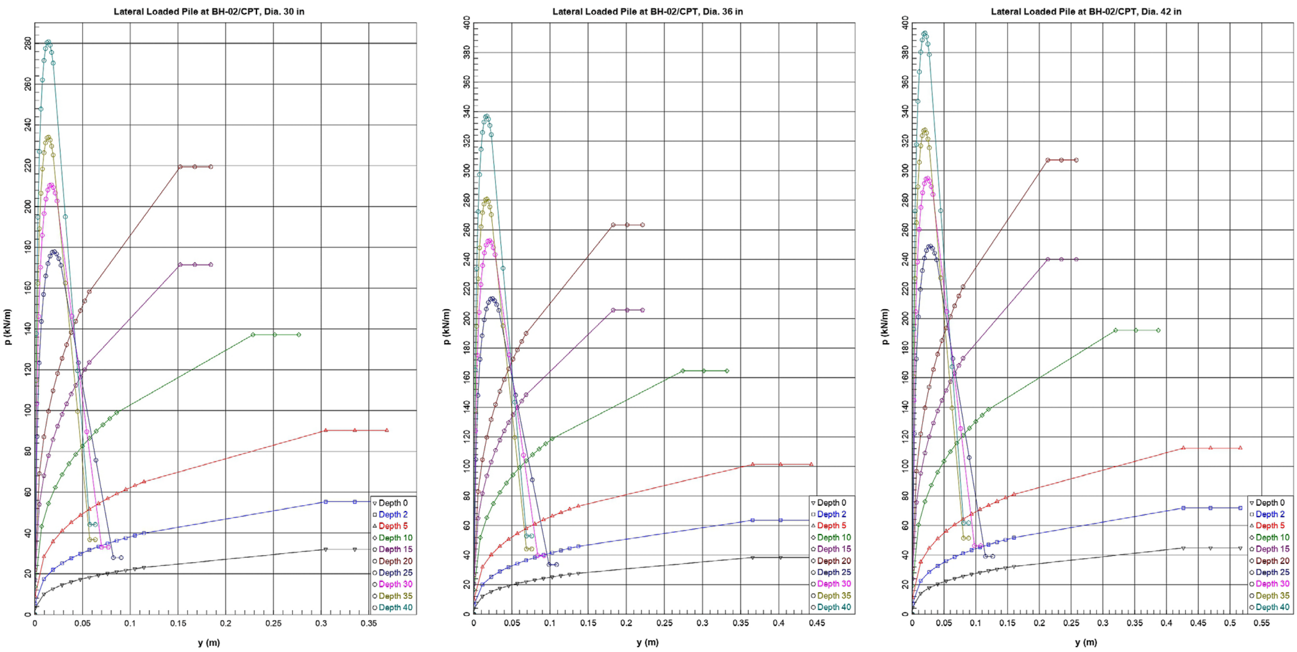


(a) (b) (c)

Figure 12: Laterally loaded pile at BH-01/CPT; (a): diameter 0.762 m; (b): diameter 0.914 m; (c): diameter 1.067 m.



(a) (b) (c)

Figure 13: Laterally loaded pile at bh-02/CPT; (a): diameter 0.762 m; (b): diameter 0.914 m; (c): diameter 1.067 m.

Figure 12 illustrates how lateral deflection varies with depth for different diameters of steel pipe piles (0.762 m; 0.914 m; 1.067 m) when subjected to lateral loads at a specific borehole location (BH-01), based on data from cone penetration tests (CPT). The lateral loaded pile at BH-02/CPT can be seen in **Figure 13**.

Figure 13 illustrates how lateral deflection varies with depth for different diameters of steel pipe piles (0.762 m; 0.914 m; 1.067 m) when subjected to lateral loads at a specific borehole location (BH-02), based on data from cone penetration tests (CPT). The soil-pile interaction is an important aspect of the analysis of offshore piles. This involves understanding how the pile and the surrounding soil respond to loads. Key factors include soil type, pile material, and installation method. Research has shown that the behavior of piles in cohesive soils is very different from the behavior of piles in granular soils.

4. Discussion

This research analyzes piles with three variations of offshore driving. Pile foundations with a diameter of 0.762 m exhibit lower axial and lateral capacities than larger diameter piles, but can still be used for lighter offshore structures or in locations with lower environmental loads. Recommendation: this diameter is suitable for applications where the environmental load is not too great or the soil depth is not too significant. A pile with a diameter of 0.914 m offers a greater capacity than a pile with a diameter of 0.762 m but is still below the performance of a pile with a diameter of 1.067 m. Recommendation: this diameter can be used in locations that require medium load capacity, such as areas with greater sea currents and wind loads, but still within moderate limits. The 1,067 m diameter pile exhibits the highest axial and lateral capacity, making it suitable for offshore structures experiencing the greatest environmental loads, such as wind turbines or oil platforms. The recommendation of this research is that diameter is ideal for locations with extreme environmental conditions, such as large waves, strong currents, or very high wind loads, as well as applications that require deeper installation depths for long-term stability. The choice of pile diameter must be adjusted to the environmental load conditions and the type of structure to be supported. Larger diameters provide better stability and load capacity, but at the expense of cost and suitability to project requirements.

This study provides comprehensive insight into the behavior of offshore pile foundations under various loading conditions, emphasizing the critical role of soil-pile interaction. The findings underscore the need for an integrated design approach that combines accurate geotechnical data, advanced modelling, and practical considerations to ensure the stability and longevity of offshore structures. This discussion offers valuable recommendations for improving pile foundation design through detailed analysis and real-world case studies, contributing to safer and more efficient offshore construction practices. This research resulted in an exploration of pile analysis in the offshore seabed environment, considering factors such as soil-pile interactions, loading conditions, and pile design that influence land displacement on the coast. Meanwhile, the analysis method utilizes the importance of accurate modelling to ensure the stability and longevity of offshore structures, resulting in the stability and longevity of offshore structures that are strong in the face of tides and tides. The implications of this research in theory can be used as a reference and additional reference by other researchers in the analysis of offshore seabed pile foundations, especially using soil-pile interactions, load conditions, and design recommendations. While carrying out this research in practice, it can be used as a reference for private parties in handling coastal abrasion by planning and repairing piles which are analyzed using soil-pile interaction analysis, load conditions, and design recommendations.

The maximum compression stress due to driving will be about 180 Mpa, less than the allowable stress of steel pipe of 280 Mpa. A bigger driving hammer Kobe K-80 which has 70% efficiency or its equivalent might be used as an alternative hammer to safely drive the proposed piles. The maximum compression stress due to driving will be about 210 MPa which is less than the allowable stress of steel pipe of 280 Mpa. Other studies for offshore well drilling look at expandable open hole liners, mono bore open hole liners, or mono bore open hole liners in good designs, streamlined hole designs can be achieved, undesirable situations that occur during offshore drilling can be overcome, and problem zones in the petroleum industry can be surmounted with minimal reduction and coverage of hole sizes (**Gaurina-Međimurec & Mesarić, 2022**). Safety factors and critical shear surfaces of underwater slopes at different times in one wave cycle, the stability of sensitive underwater clay slopes under various extreme wave parameters, and special cases with slope lengths of no more than one wavelength can hurt the stability of clay slopes that are sensitive to the seabed (**Zheng et al., 2019**).

This research combines geotechnical approaches, advanced numerical modelling, and environmental monitoring data for the first time to analyze the behavior of offshore pile foundations. This provides a deeper understanding of soil-pile interactions that have not been widely applied in previous offshore foundation designs. The novelty of this research is the use of direct tidal data in the pile design model, which allows for a more accurate assessment of the dynamic loads acting on the pile in changing sea conditions. The authors should highlight that this method provides advantages over conventional design approaches that often ignore the real impact of tides.

The limitations of this research include the type of load limitation, meaning that this research focuses on soil-pile interaction and certain load conditions, namely axial, lateral and moment loads. The effects of other loads, such as dynamic loads from very extreme waves and winds or seismic loads, may not be described in detail. This study may be limited to specific soil types at the selected offshore locations, which have unique characteristics, such as soft soils and marine sediment layers in Semarang. This means the results may not be directly applicable to other locations with different soil composition. The analysis uses numerical methods and certain model-based simulations, such as p-y curves and finite element analysis (FEA). These limitations include simplifications that may not capture the full complexity of soil-pile behavior in real environments, such as spatial soil variability. Environmental aspects such as climate change, sea level rise, and pile corrosion due to marine conditions may not be considered in pile design, which can affect the long-term durability and stability of the structure. The geotechnical data used may be limited to available field or laboratory test results. If the test does not cover the entire study area or depth variations, this may be a limitation in ensuring the accuracy of the model response to actual soil conditions. The design recommendations provided in this study may be very specific to applications in Semarang and may need to be adapted when applied in other areas with different environmental and geotechnical conditions.

5. Conclusions

This research can conclude that the performance analysis of pile foundations shows that piles with larger diameters and deeper depths have a better ability to withstand axial and lateral loads. This is very important to ensure the stability and safety of offshore structures. Meanwhile, for optimal design: to ensure optimal pile foundation design, it is necessary to pay attention to various factors, such as pile diameter, depth, soil type, and applied load. The use of numerical analysis and finite difference models helps in understanding the behavior of piles under different loads. Then regarding safety and stability seen from the integration of geotechnical data with advanced analysis models helps ensure that the pile foundation will be able to withstand the applied loads in the long term, which is very important for offshore structures such as wind turbines, oil platforms, and bridges. With comprehensive analysis, we can design safer and more efficient pile foundations for a variety of offshore applications, thus reducing the risk of structural failure and extending the service life of the structure. This research finds the importance of designing pile foundations that integrate geotechnical data, advanced modelling, and continuous monitoring to face the challenges of the seabed environment. Soil-pile interaction and robust design are critical to ensuring the long-term stability of offshore structures. This research produces an analysis of the behavior of pile foundations in offshore environments, taking into account factors such as soil-pile interactions, environmental load conditions, and variations in pile diameter. Piles with a diameter of 1.067 m demonstrate the highest axial and lateral capacities, making them ideal for more extreme environmental load conditions, such as strong ocean currents and high wind loads.

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SAŽETAK

Analiza temelja pilota u moru: interakcija tla i pilota i uvjeti opterećenja te preporuke za izgradnju

Temeljenje na pilotu u moru nužno je za potporne strukture kao što su vjetroturbine, naftne platforme i mostovi. Pri tome su važni čimbenici koji utječu na interakcije tla i pilota te procjena utjecaja različitih opterećenja okoliša, uključujući aksijalna, bočna i momentna opterećenja. Ova studija započinje opsežnim pregledom analitičkih i numeričkih metoda korištenih za analizu pilota. Cilj je istraživanja analizirati ponašanje pilota u okolišu morskoga dna uzimajući u obzir različite čimbenike kao što su interakcija tla i pilota, uvjeti opterećenja okoliša i izgradnja čvrstoga temelja pilota. Ova istraživačka metoda iskorištava važnost točnoga modeliranja kako bi se osigurala stabilnost i dugovječnost struktura u moru. Snaga i izvedba odobalnih struktura, kao što su vjetroturbine, naftne platforme i mostovi, uvelike ovise o čvrstoći temelja pilota. Ovo istraživanje donosi detaljnu analizu pilota u okruženjima morskoga dna naglašavajući važnost međudjelovanja tla i pilota, različitih uvjeta opterećenja i robusne izvedbe pilota. Nalazi naglašavaju potrebu za integriranim pristupom koji kombinira geotehničke podatke, napredno modeliranje i stalni nadzor kako bi se osigurala stabilnost i dugovječnost temelja pilota u moru. Ovo istraživanje daje temeljnu analizu ponašanja pilota u morskim okruženjima uzimajući u obzir čimbenike kao što su interakcija tla i pilota, uvjete opterećenja okoliša i varijacije u promjeru pilota. Piloti promjera 1,067 m pokazuju najveći aksijalni i bočni kapacitet, što ih čini idealnim za ekstremnije uvjete opterećenja okoliša, kao što su jake oceanske struje i velika opterećenja vjetrom.

Ključne riječi:
temeljenje na pilotima za konstrukcije u moru, interakcija tla i pilota, aksijalna nosivost, analiza bočnoga opterećenja, geotehničko inženjerstvo, uvjeti morskoga dna

Author's contribution

Edy Soesanto (PhD Candidate): compiler of all articles, author of the complete manuscript, and defined idea and wrote the manuscript. **Dicky Muslim** (Full Professor): idea generator and commentator on the review section related to the effective parameter in the implementation of this manuscript. **Evie Hadrijantie Sudjono** (Full Professor): idea generator and supervisor on the drafting section related to the implementation of this article. **Cipta Endyana** (Full Professor): directing and managing scientific work and providing input on English paraphase.