

Analysis of Jetty Structure Using the Fixity Point Method and Soil–Structure Interaction via the Spring Model

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Article Information	ABSTRACT
Article History Received : April 14, 2025 Revised : July 18, 2025 Published : July 26, 2025 Keywords: <i>Jetty;</i> <i>Soil Structure Interaction;</i> <i>Spring Model;</i> <i>Fixity Point;</i> <i>Steel Pile.</i>	A jetty is an essential element of port infrastructure yet remains vulnerable to lateral forces generated by waves, currents, berthing impact, and earthquakes, all of which can trigger structural failure. This study analyzes jetty performance by comparing two design approaches, soil-structure interaction (SSI) modeled with non-linear springs, and the conventional fixity-point method. A reinforced-concrete deck on steel pipe piles was modeled in SAP2000, with pile diameters of 24, 32, and 40 inches embedded in medium sand. Serviceability and ultimate load combinations followed BS 6349 and ASCE 7-10 provisions. The SSI analysis showed larger structural responses than the fixity-point approach, with peak deflection, bending moment, axial force, and shear force increasing by approximately 35 %, 21 %, 12 %, and 18 %, respectively. These differences arise because the fixity-point method considers soil stiffness only to the calculated fixity depth, potentially underestimating overall lateral demand. Both approaches indicate that a 40-inch pile driven no deeper than 30 m satisfies deflection criteria while limiting drive length, offering a balanced solution between safety and economy. Verifying fixity-point designs with detailed SSI analysis is therefore recommended for robust jetty construction.

INTRODUCTION

Jetty structures are critical components in port infrastructure, providing essential berthing facilities and serving as vital links between maritime operations and land-based logistics (Ajiwibowo, 2020; Koronides, Onoufriou, et al., 2024; Triatmodjo, 2009). These structures are continuously exposed to a variety of lateral loads. It includes wave forces, currents, wind, and seismic actions that will induce significant deflections and internal stresses (Han et al., 2021; Su et al., 2017). Consequently, the reliability and overall performance of these structures depend heavily on an accurate assessment of soil–structure interaction effects (Çetindemir, 2024).

Traditional design approaches often simplify analysis by assuming fixed base conditions for pile foundations, thereby neglecting the complex interaction between the pile and the surrounding soil (Burd et al., 2020; Gazetas, 2015; Meyerhof, 1959; Nair & Donovan, 1969). Such assumptions can underestimate bending moment and shear demand, particularly for long, slender piles embedded in soft or liquefiable soils. Recent studies demonstrate that non-linear spring models—expressed through p-y, t-z, and q-z curves—provide more realistic predictions of lateral behaviour than fixed-base approximations (Abdelaziz et al., 2021; F. Wahyuni, 2013; Fenu et al.,

2021). These advanced analytical methods thus facilitate a more comprehensive understanding of structural behavior under lateral loads, which is crucial for ensuring safety and durability (Kurniawan et al., 2025; Reese & Matlock, 1956; Taborda et al., 2020; Vytiniotis et al., 2019).

Focusing on the case study, the jetty analyzed in this research is located at the Port Project in Kolaka Utara, Southeast Sulawesi, where a vessel with a capacity of 1,000 DWT operates. The structure features a reinforced concrete superstructure coupled with a substructure comprising driven steel piles—a design commonly adopted in similar maritime facilities (C. Sriandini, 2016; Menteri Perhubungan, 2017). Notably, the jetty experienced significant settlement and lateral displacement, leading to structural failure that underscores the necessity for a detailed pile foundation analysis.

The primary objective of this study is to assess and compare the performance of jetty structures using both the conventional fixity point method and a soil–structure interaction approach based on the spring model (Jiunn-Shyang Chiou & Cheng-Hsing Chen, 2007; Wazeer Ali et al., 2018). Structural modeling was conducted with SAP2000 V22 while varying pile diameters (24, 32, and 40 inches) to evaluate their influence on overall structural response (American Petroleum Institute, 2014; Richards et al., 2021). This comparative analysis aims to provide deeper insights into how different foundation parameters affect the behavior of jetty structures subjected to lateral loading (Chopra, 2012; Suryasentana & Lehane, 2016). Accordingly, this study compares the fixity-point approach with a non-linear SSI spring model to quantify their influence on deflection, bending moment, axial force, and shear force, and to recommend an economical yet safe pile configuration for future jetty designs.

Despite the widespread use of both methods, a distinct gap remains in quantitatively benchmarking the simplified fixity-point approach against the more accurate non-linear SSI spring model for typical jetty structures. This study addresses this gap by directly comparing their resulting deflection, bending moment, axial force, and shear force. The findings are intended to provide clear, practical guidance on the potential margins of error in preliminary designs and to recommend an optimized pile configuration that balances safety and economy.

RESEARCH METHODS

This study utilizes data from the Port Project in Kolaka Utara, where a jetty structure is implemented. To analyze the behavior of the structure, two methods were employed, the fixity point method, and the soil–structure interaction (SSI) method (Abdelaziz et al., 2021; Coduto et al., 2016; Meyerhof, 1959). The jetty structure was modeled using SAP2000 software to analyze its structural response. In addition, LPILE software was used to calculate the lateral bearing capacity of the piles through p - y curves, while APILE was used to compute the axial bearing capacity. In this study three variations of pile with 24 inches, 32 inches, and 40 inches diameters were used and analyzed to examine their effects on structural behavior. The variables evaluated include deflection, moment, axial force, and shear force.

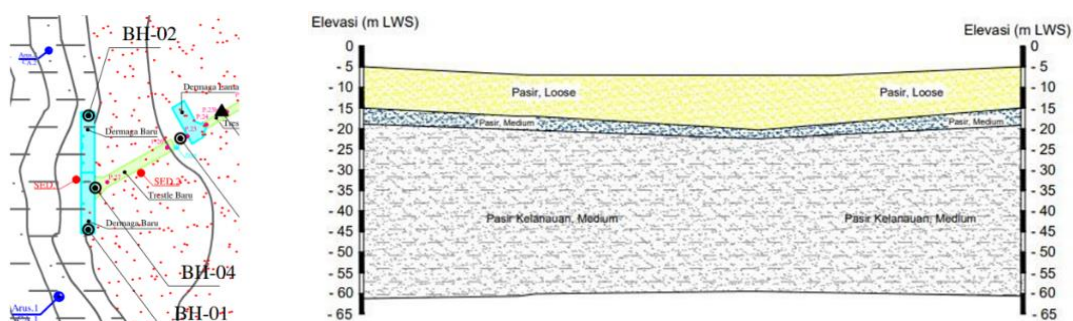


Figure 1. Boring Plan and Soil Stratigraphy of Jetty Project

There are three soil parameters used in this study: N_{60} , the internal friction angle (ϕ), and the unit weight (γ). The N_{60} value is obtained from SPT measurements with 60% energy efficiency as expressed in Equation (1). The internal friction angle (ϕ) is determined using Equation (2), in

which the relative density (D_r) is derived through interpolating SPT values based on Table 1. Meanwhile, the soil unit weight—both the saturated unit weight (γ_{sat}) and the dry unit weight (γ_{dry}), can be correlated with the bulk unit weight of the soil as shown in Table 2.

$$N_{60} = \frac{N_{SPT} \times \eta_S \times \eta_R \times \eta_B \times \eta_H}{60} \quad (1)$$

$$\phi = 28 + 0,15 D_r \quad (2)$$

η_S = Safety factor adjustment for SPT measurement

η_R = Rod length correction factor for the SPT test

η_B = Borehole diameter correction factor for the SPT test

η_H = Hammer drop height correction factor for the SPT test

Table 1. Correlation of N_{SPT} for Non-Cohesive Soil

Consistency	Relative Density (%)	N_{SPT}	ϕ (°)	γ_{sat} (kN/m ³)
Very Loose	0 – 15.0	0 – 4.0	28.0	11.0 – 16.0
Loose	16.0 – 35.0	5.0 – 10.0	28.0 – 30.0	14.0 – 18.0
Medium	36.0 – 65.0	11.0 – 30.0	31.0 – 36.0	17.0 – 20.0
Dense	66.0 – 85.0	31.0 – 50.0	37.0 – 41.0	17.0 – 22.0
Very Dense	86.0 – 100	51.0	41.0	20.0 – 23.0

Table 2. Correlation of γ_{sat} to γ_{dry}

γ_{sat} (kN/m ³)	γ_{dry} (kN/m ³)	w_{sat} (%)
12.840	4.9	163.0
13.530	5.880	129.60
14.12	6.86	105.8
14.70	7.84	88.0
15.39	8.82	74.1
15.98	9.80	63
16.57	10.78	53.9
17.25	11.76	46.3
17.84	12.74	39.9
18.43	13.72	34.4

The soil parameters obtained from equations (1) and (2) are presented in Table 3 below.

Table 3. Soil Parameter Design

Depth from seabed (m)		N_{60}	Dr (%)	γ_{sat} (kN/m ³)	γ' (kN/m ³)	γ_{dry} (kN/m ³)	γ_{unsat} (kN/m ³)	ϕ' (°)
Top	Bottom							
0	4	2	5.63	12.88	2.88	4.95	8.91	28.84
4	6	3	9.38	14.13	4.13	6.87	10.50	29.41
6	8	6	17.90	14.40	4.40	7.33	10.87	30.69
8	10	7	24.55	15.80	5.80	9.50	12.65	31.68
10	14	9	32.15	17.40	7.40	12.01	14.70	32.82
14	16	9	31.20	17.20	7.20	11.69	14.44	32.68
16	18	10	33.10	17.60	7.60	12.34	14.97	32.97
18	20	11	36.00	17.00	7.00	11.40	14.20	33.40
20	24	12	37.14	17.12	7.12	11.57	14.34	33.57
24	26	11	36.00	17.00	7.00	11.34	14.17	33.40
26	30	14	39.82	17.39	7.39	12.00	14.70	33.97
30	32	16	42.87	17.71	7.71	12.52	15.12	34.43

Depth from seabed (m)		N_{60}	D_r (%)	γ_{sat} (kN/m ³)	γ' (kN/m ³)	γ_{dry} (kN/m ³)	γ_{unsat} (kN/m ³)	ϕ' (°)
Top	Bottom							
32	34	19	47.45	18.18	8.18	13.31	15.75	35.12
34	36	20	50.12	18.46	8.46	13.77	16.12	35.52
36	38	19	48.21	18.26	8.26	13.44	15.85	35.23
38	40	21	50.88	18.54	8.54	13.90	16.22	35.63
40	42	20	50.12	18.46	8.46	13.77	16.12	35.52
42	46	21	51.26	18.58	8.58	13.97	16.27	35.69
46	48	25	56.99	19.17	9.17	14.95	17.06	36.55
48	52	26	59.28	19.41	9.41	15.34	17.38	36.89
52	54	27	60.42	19.53	9.53	15.54	17.53	37.06
54	58	28	61.57	19.64	9.64	15.74	17.69	37.23
58	60	29	63.86	19.88	9.88	16.13	18.01	37.58
60	62	32	67.25	17.33	7.33	11.89	14.61	38.09

The axial compressive capacity of a single pile is calculated as the sum of shaft friction capacity and tip bearing capacity, as expressed in Equation (3). Subsequently, the axial bearing capacities for single piles with various pile diameters were determined. The results of these calculations are presented in Figure 1.

$$Q_{ult} = Q_s + Q_p \quad (3)$$

$$Q_p = A_p \times q_p \quad (4)$$

$$Q_s = 2 \times N_{60} \times p \times L \quad (5)$$

where,

Q_{ult} = Ultimate axial bearing capacity (kN)

Q_s = Shaft friction bearing capacity (kN)

Q_p = Pile tip bearing capacity (kN)

q_p = Tip resistance in non-cohesive soil (t/m²)

A_p = Cross-sectional area of the pile (m²)

p = Perimeter of the pile (m)

L = Length of the considered soil layer (m)

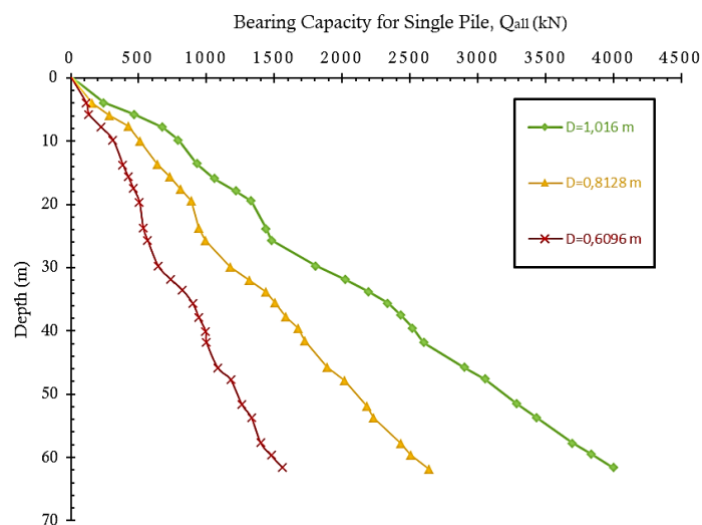


Figure 2. Axial Bearing Capacities For Single Piles With Various Pile Diameters

The figure illustrates the allowable axial bearing capacity (Q_{all}) of single piles at various depths for three different pile diameters, 1.016 m (green line), 0.8128 m (yellow line), and 0.6096 m (red line). As shown from the plotted graph, it can be interpreted that increases in pile diameter generally leads to higher bearing capacities at comparable depths. Additionally, the bearing capacity tends to increase with greater embedment depth because of the higher confining pressures and frictional resistance in deeper soil layers.

The jetty structure modeling was carried out using SAP2000 software with the material parameters listed in Table 4, while the frame and plate dimensions are presented in Table 5 and Table 6.

Table 4. Material Input Parameters in the Model

Material Type	Code	Strength	Input Parameter	Value	Description
Concrete	Concrete	30 MPa	f'_c	30 MPa	Beam and slab material
			E	25743000 kN/m ²	
Steel	Pile	ASTM A252	F_y	240 MPa	Steel pile material
			F_u	415 MPa	
Plain Steel Reinforcement	BjTP 24		F_u	380000 kN/m ²	Beam reinforcement material
			F_y	235000 kN/m ²	

Table 5. Frame Definition Parameters

Frame Code	Property	Material Code	Dimension (m)	
Longitudinal Beam	Rectangular	Beton	Width	0.450
		Tulangan	Height	0.7
Transverse Beam	Rectangular	Beton	Width	0.450
		Tulangan	Height	0.7
Pile	Pipe	Pile	Diameter	0.6090
			Thickness	0.012
Pile	Pipe	Pile	Diameter	0.8128
			Thickness	0.012
Pile	Pipe	Pile	Diameter	1.016
			Thickness	0.012

Table 6. Area Definition Parameters

Area Code	Property	Material Code	Thickness
Floor Slab	Shell-Thick	Concrete	0.250 m

The total length of the jetty structure used in this study is 86 meters, determined based on the Technical Standards and Commentaries for Port and Harbour Facilities in Japan (OCDI, 2002). Using Equation (6), which refers to this standard, the calculated jetty structure length is 82.5 meters. However, additional length is included due to two transverse beams spaced 4 meters apart and a cantilever slab extending 1.5 meters on both the right and left sides of the jetty, resulting in a total jetty structure length of 86 meters, as illustrated in Figures 5 and 6.

$$L = L_{OA} + (2 \times 0.5B) \quad (6)$$

$$L = \text{Jetty Length (m)}$$

$$L_{OA} = \text{Overall Length Of The Vessel (m)}$$

$$B = \text{Vessel Width (m)}$$

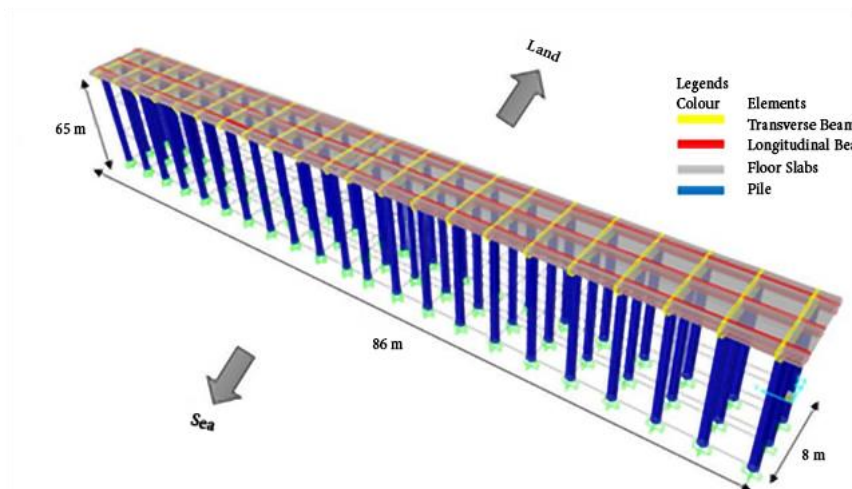


Figure 3. Fixity Point Method Jetty Structure Modeling using SAP2000

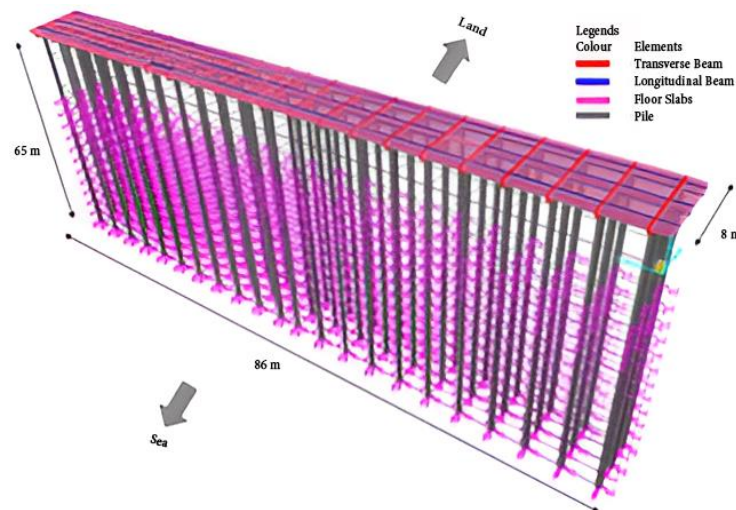


Figure 4. Soil Structure Interaction Method Jetty Structure Modeling using SAP2000

The pile length used in this study varies, as the jetty structure modeled using the fixity point method considers three different approaches: Nair's model, Lam's model, and the AASHTO method. These three models yield different fixity point depths (L_f), which represent the depth at which the pile behaves as if it is fully restrained against rotation. As a result, the modeled pile lengths also vary.

Nair's model simulates the flexibility of the pile head in a lateral soil system, where the equivalent length to the fixity point (Leq) is determined using the equation: $Leq = \frac{1}{\beta}$. The coefficient β represents the soil stiffness coefficient, which depends on soil properties and pile flexibility, and is calculated through Equation (7) (Abdelaziz et al., 2021). Meanwhile, Lam's model takes into account the stiffness of the pile head in the lateral soil system, where the fixity depth is obtained using the equation: $Leq = \frac{1.224}{\beta}$, with β determined using (8) (Abdelaziz et al., 2021).

In contrast, the AASHTO method assumes that embedded foundation elements and nonlinear soil reactions can be approximated as a homogeneous layer of sand or clay. The fixity point depth (L_f) for clay soil is determined using Equation (9), whereas for sandy soil, it is calculated using Equation (10), following the development by (Fenu et al., 2021; Possiel, 2008). These variations in fixity depth estimation influence the overall pile length required to achieve stability in lateral loading conditions.

$$\beta = \sqrt[4]{\frac{k_h \times D}{4 \times E \times I}} \quad (7)$$

$$\beta = \sqrt[4]{\frac{k_h \times D}{4 \times 0,612EI}} \quad (8)$$

$$L_f = 1,4 \left[\frac{E_p I_{py}}{E_s} \right]^{0,25}, \text{ Clay} \quad (9)$$

$$L_f = 1,8 \left[\frac{E_p I_{py}}{n_h} \right]^{0,20}, \text{ Sand} \quad (10)$$

where,

k_h = Horizontal subgrade modulus of the soil (kN/m³)

D = Diameter of the pile (m)

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

E_p = Young's modulus of the pile material (kN/m²)

E_s = Young's modulus of the surrounding soil (kN/m²)

I_{py} = Moment of inertia of the pile in lateral bending (m⁴)

n_h = Coefficient of subgrade reaction for sand (kN/m³)

Meanwhile, the jetty structure involving soil-structure interaction was modeled using spring elements, where the p-y curve was obtained through simulations using LPILE software, while the q-z and t-z curves were generated using APILE software. The values from these curves were then input into the link properties in SAP2000 software, which was used to model each pile depth as a spring element.

The model of Soil Structure Interaction on lateral, axial and pile tip with spring is illustrated as in Figures 5.

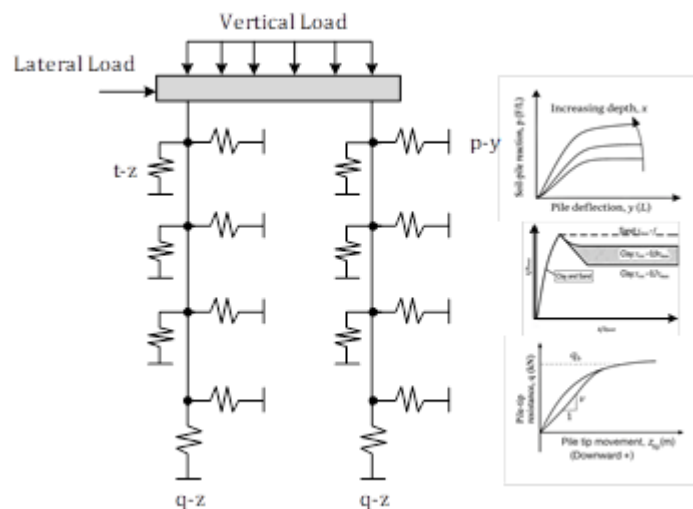


Figure 5. Modelling of Non-Linear Winkler Spring

The loads acting on the jetty structure refer to (British Standard, 2000; BSN, 2016, 2019; Elsebaey et al., 2025) and consist of horizontal and vertical loads. Horizontal loads include environmental forces such as wave, current, and seismic loads, as well as vessel impact forces during berthing (berthing force) and mooring forces caused by wind and currents. In addition to horizontal loads, the structure also experiences vertical loads, which include live loads such as uniform loads and lane load D, as well as dead loads, including the weight of bollards, fenders, and pile caps, along with uplift forces. To ensure that all structural components can withstand these loading effects, a combination of Serviceability Limit State (SLS) and Ultimate Limit State (ULS) load cases was used. These combinations were selected to assess the safety and performance of the structure, following the guidelines in Chapter 2 of ASCE Standard 7-10 (ASCE, 2022),

which establishes load requirements and performance limits for structures under operational and extreme load conditions

RESULTS AND DISCUSSION

Based on the calculated fixity point depths, the jetty structure analyzed using the fixity point method resulted in varying pile lengths, as shown in Table 7. Meanwhile, for the soil-structure interaction (SSI) method, the pile length was fixed at 65 meters. This selection of 65 meters was based on the results of LPILE software analysis, which indicated that the foundation element depth, where lateral deflection reaches zero, occurs at this depth, as referenced in (Parkes et al., 2018).

Table 7. Pile Lengths

Outer Diameter (m)	Pile Length (m)			SSI
	Fixity Point Methode			
	Nair's Model	Lam's Model	AASHTO Method	
0.6096	12	12.3	11.5	65
0.8128	12.5	12.8	12.5	65
1.016	13	13.3	13.1	65

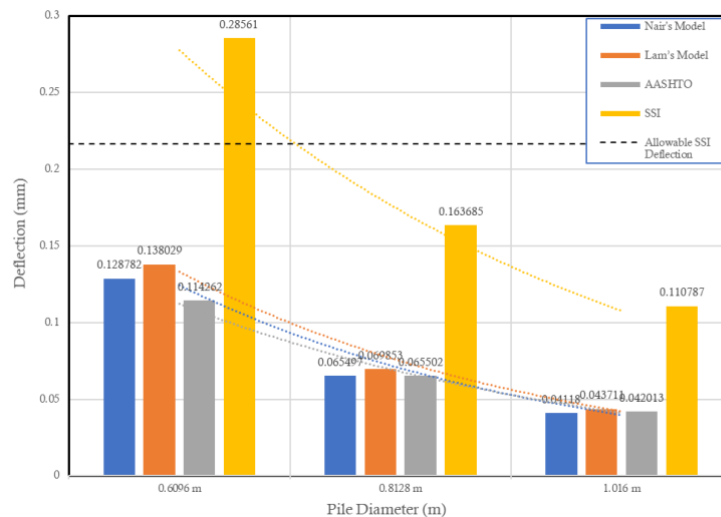


Figure 6. Comparison of Pile Deflection (mm) to Pile Diameter with different models output

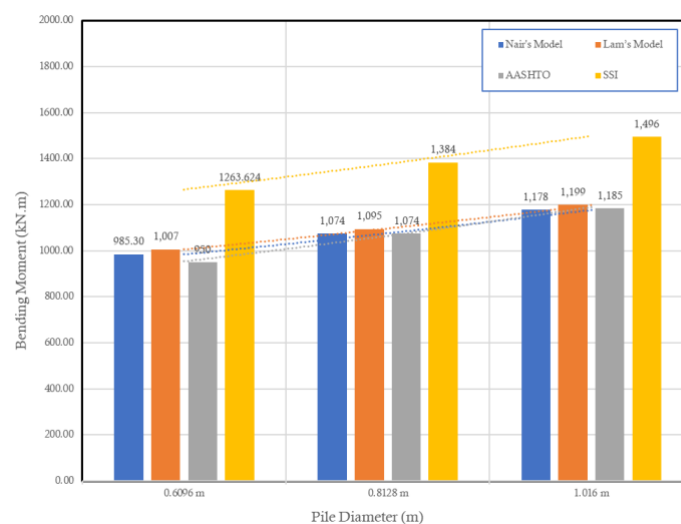


Figure 7. Comparison of Bending Moment on Pile (kN.m) to Pile Diameter with different models output

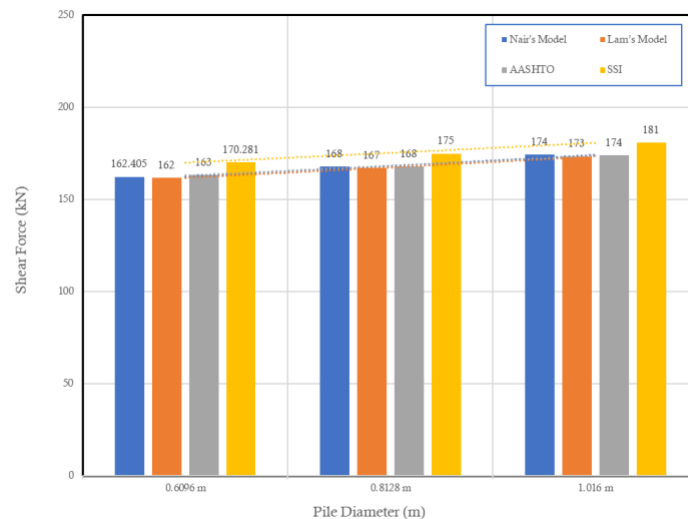


Figure 8. Comparison of Shear Force on Pile (kN) to Pile Diameter with different models output

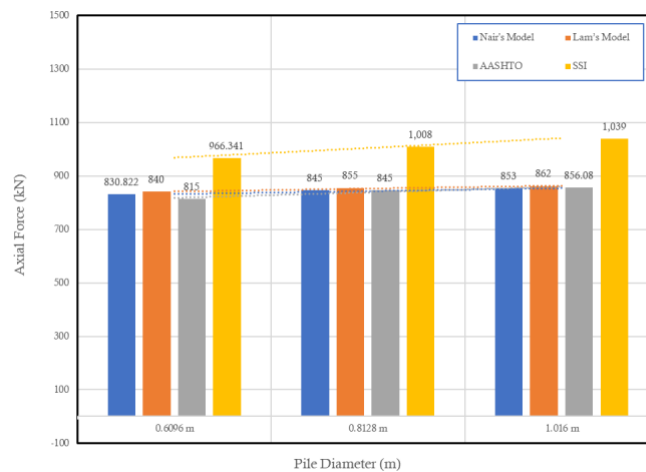


Figure 9. Comparison of Axial Force on Pile (kN) to Pile Diameter with different models output

Based on Figures 6 through 9, the deflection values for each analyzed method were obtained. The analysis results indicate that the largest deflection occurs in the pile with a diameter of 0.6096 m, followed by the pile with a diameter of 0.8128 m and then the pile with a diameter of 1.016 m. Additionally, among the fixity point methods, Lam's Model produces the highest deflection, followed by Nair's Model and the AASHTO method. This is attributed to the fact that Lam's Model results in the deepest fixity point depth. Deflection from every fixity-point run is smaller than that from the soil-structure interaction (SSI) analysis. A comparable trend was reported by Koronides et al. (2024), who found that omitting spring elements below the apparent fixity depth reduced lateral displacements of a marine jetty by about 30 % relative to a full SSI model. According to BS 6349-2:2010, the permissible deflection limit is less than $h/300$, as piles in jetty structures are assumed to function as columns (Boyke, 2024; British Standard, 2010). Based on this standard, the deflection in the fixity point method for piles with diameters of 0.6096 m and 0.8128 m does not meet the allowable criteria. Meanwhile, in the soil-structure interaction (SSI) method, the deflection exceeding the permissible limit occurs in the pile with a diameter of 0.6096 m.

Table 8. Pile Deflection

Methods		Pile Diameter (m)	Pile Length (m)	Allowable Deflection (m)	Pile Deflection (m)	Meets Requirement
Fixity Point Method	Nair's Model	0.6096	12	0.040	0.128782	No
		0.8128	12.5	0.042	0.065497	No
		1.016	13	0.043	0.04118	Yes
	Lam's Model	0.6096	12.3	0.041	0.138029	No
		0.8128	12.8	0.0427	0.069853	No
		1.016	13.3	0.0443	0.043711	Yes
	AASHTO Method	0.6096	11.5	0.0383	0.114262	No
		0.8128	12.5	0.0417	0.065502	No
		1.016	13.1	0.0437	0.042013	Yes
Soil-Structure Interaction		0.6096			0.28561	No
		0.8128	65	0.21667	0.163685	Yes
		1.016			0.110787	Yes

The moment analysis results presented in the comparison graph (Figures 4-7) show that among the fixity point methods, Lam's Model generates the largest bending moment, followed by Nair's Model and the AASHTO method. This occurs because Lam's Model assumes larger pile dimensions compared to the other models. The highest recorded moment occurs in the soil-structure interaction (SSI) method for a pile diameter of 1.016 m, with a maximum moment of 1495.5165 kN·m. A similar amplification was observed by Abdelaziz et al. (2021), who reported that including soil non-linearity deepened the plastic hinge and increased the maximum moment by roughly 20 % compared with equivalent-cantilever estimates. Koronides et al. (2024) likewise showed that full p-y, t-z, and q-z springs raise pile-head moments and trigger earlier steel yielding in jetty piles. Additionally, an evaluation of pile moment capacity was conducted to determine whether the piles can withstand the generated moments, following the applicable standards (BSN, 2020). The results, as shown in Table 9, indicate that the moments produced by both the fixity point and SSI methods remain below the maximum pile moment capacity, confirming that the piles can safely resist the applied moments.

Table 9. Pile Moment Capacity

Method		Diameter (m)	Mn (kN·m)	Moment (kN·m)	Meets Requirement
Fixity Point Method	Nair's Model	0.6096	4143.435	985.2975	Yes
		0.8128	7402.714	1073.8973	Yes
		1.016	11601.134	1178.487	Yes
	Lam's Model	0.6096	4143.435	1006.5362	Yes
		0.8128	7402.714	1094.5743	Yes
		1.016	11601.134	1198.6913	Yes
	AASHTO Method	0.6096	4143.435	949.7179	Yes
		0.8128	7402.714	1073.8908	Yes
		1.016	11601.134	1185.2309	Yes
Soil-Structure Interaction		0.6096	4143.435	1263.624	Yes
		0.8128	7402.714	1383.8942	Yes
		1.016	11601.134	1495.5165	Yes

Meanwhile, shear force and axial force follow a similar pattern as bending moments. Based on the comparison graph (figure 6 to 7), the largest shear force and axial force occur in the soil-structure interaction method for a pile diameter of 1.016 m, with values of 180.581 kN and

1039.313 kN, respectively. Thus, the highest moment, shear force, and axial force all occur in the 1.016 m diameter pile across all methods.

Table 10. Pile Penetration Depths

Pile Diameter (m)	Pile Length (m)			
	Nair's Model	Lam's Model	AASHTO Method	SSI
0.6096	50.58	54.58	48.58	56.58
0.8128	38.58	38.58	38.58	40.58
1.016	24.58	24.58	24.58	28.58

Aside from these structural parameters, an analysis of pile penetration depth was also conducted based on the axial bearing capacity of the pile, as presented in Table 10. The results indicate that piles with a diameter of 0.6096 m require the deepest penetration for all methods. This is due to the fact that smaller pile diameters correspond to lower bearing capacities, necessitating greater depths for stability. As a result, piles with a diameter of 0.6096 m require penetration depths exceeding 45 m, whereas piles with diameters of 0.8128 m and 1.016 m require penetration depths of less than 45 m. Field trials at Dunkirk reported by Taborda et al. (2020) reached a similar conclusion: increasing pile diameter from 0.75 m to 1.0 m reduced the required embedment by roughly one-third and shortened installation time by 40 percent. In this case, adopting the larger pile not only limits driving length but also provides greater corrosion allowance and fatigue capacity, which supports the final recommendation.

CONCLUSION

The structural behavior of the jetty (deflection, moment, shear force, and axial force) analyzed using the soil-structure interaction method for piles with diameters of 0.6096 m, 0.8128 m, and 1.016 m shows higher values compared to the fixity point method (Nair's Model, Lam's Model, and AASHTO Method) for the same pile diameters. However, this difference does not imply that the fixity point method is superior to the soil-structure interaction approach. This is due to the limitations of the fixity point method, which only analyzes the pile up to the fixity depth, whereas the soil-structure interaction method considers the overall stiffness of the surrounding soil. Therefore, the fixity point method requires additional verification through p-y curve analysis or soil-structure interaction modeling during the final design stage. Based on the analysis of the jetty's structural behavior, the most suitable pile foundation dimension for the Kolaka Utara Port jetty is a pile with a diameter of 1.016 m (40 inches) and a length not exceeding 30 m. This pile satisfies the deflection criteria while also requiring a shallower penetration depth compared to other pile diameters under both methods.

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