

CASE STUDY OF THE EFFECT OF SOIL STRUCTURE INTERACTION ON MARINE JETTY PERFORMANCE SUBJECTED TO CORROSION

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ABSTRACT: This study investigates the combined impact of soil-structure interaction (SSI) and corrosion on the seismic performance of marine jetty systems, focusing on two locations in Indonesia with different soil conditions: sandy soil at Probolinggo and clayey soil at Gresik. Using numerical modeling and nonlinear static pushover analysis, the study evaluates the effects of 25 years of corrosion on the lateral resistance and displacement capacity of pile-supported jetties. The analysis revealed that while the jetty on sandy soil initially exhibited higher stiffness and lateral capacity, it was more susceptible to corrosion, resulting in a significant decrease in structural performance. Conversely, the jetty on clay soil showed more gradual degradation and better long-term ductility. The findings highlight the critical role of soil type and corrosion in influencing the performance and safety of marine jetties over time. These results provide valuable insights into the design and maintenance of similar coastal infrastructure, especially in seismically active regions with corrosive marine environments.

Keywords: Soil-Structure Interaction, Resilient Infrastructure, Seismic Performance, Pushover Analysis, Corrosion.

1. INTRODUCTION

Indonesia, as an archipelagic country with high tectonic activity, faces significant challenges in maintaining the reliability of its coastal infrastructure, particularly jetties. Jetties, as vital nodes in the national logistics chain, require comprehensive seismic performance evaluation, considering that 81% of Indonesia's territory is at high risk of earthquakes [1]. The phenomenon of corrosion on steel and concrete structural elements of jetties in coastal environments worsens this vulnerability, with corrosion rates reaching 0.5-2 mm/year in tropical regions [2]. Recent studies show that material degradation due to corrosion can reduce the flexural capacity of structures by up to 35% over 20 years [3]. Soil-structure interaction (SSI) is a critical phenomenon that can affect the dynamic response of structures, especially in coastal infrastructure like jetties. Research indicates that when SSI is considered, the dynamic response of jetties can vary by up to 25% [4]. Many operating jetties in Indonesia were designed using older versions of earthquake codes and ignoring the effect of SSI when performing structural analysis. Further, jetties in Indonesia often experience significant corrosion due to limited maintenance during their service life.

Several studies have underscored the importance of SSI in the seismic evaluation of coastal infrastructure. Su, Wan, Lu, Elgamal, and Arulmoli developed advanced three-dimensional finite element

models using the 'OpenSees' platform to evaluate the seismic performance of pile-supported wharves at varying hazard levels. Their findings showed that SSI significantly influences the structural response, with piles of shorter free lengths being more vulnerable to seismic damage [5]. Su, Wan, Dong, Frangopol, and Ling further explored the seismic fragility of large-scale pile-supported wharves, demonstrating that SSI influences the seismic vulnerability curves and overall structural performance under different damage states [6].

In recent years, the combined effect of corrosion and seismic loading on marine structures has gained increasing attention. Mirzaeefard, Hariri-Ardebili, and Mirtaheri conducted a study on the time-dependent seismic fragility of pile-supported wharves under chloride-induced corrosion. Their analysis revealed that corrosion reduces seismic performance due to both strength and ductility deterioration, potentially leading to brittle failure of the piles as the structure reaches the end of its service life [7]. Similarly, Darmawan, Bayuaji, Anugraha, Saputra, and Victoriawan conducted a case study on a 25-year-old reinforced concrete jetty in Indonesia, where chloride attack was identified as the main cause of corrosion in tropical marine environments. Their findings also highlighted that corrosion significantly reduced the safety factors of steel pipe piles, underlining the combined effect of material degradation and updated seismic design codes [8].

Recent methodological advances have enhanced

the framework for the seismic vulnerability assessment of pile-supported wharves. Huang, Zhang, Zhang, and Ai developed a comprehensive method for generating vulnerability curves for steel pipe pile-supported wharves that explicitly account for uncertainties in structural design and geotechnical parameters. Their approach employed a simplified mechanical model using the equivalent lateral stiffness method to efficiently generate vulnerability databases, while sensitivity analysis identified the axial compression ratio and length-to-diameter ratio as key vulnerability parameters. The study demonstrated that proper quantification and reduction of uncertainties through systematic classification enables accurate seismic resilience assessment, with validation results showing acceptable errors within 15% when compared to finite element analyses [9].

Complementing this framework, Refani and Nagao developed a simplified methodology for the nonlinear seismic response analysis of corroded pile-supported wharves using the frame analysis approach. Their research addressed the challenge of applying fiber-based finite element analysis in engineering practice by proposing a simplified method that accurately reproduces nonlinear seismic responses through the proper configuration of hinge properties. The study demonstrated that material property deterioration due to corrosion, including reductions in concrete compressive strength and prestressed steel yield strength, must be explicitly considered in seismic assessment. Their methodology enables the practical evaluation of corroded structures while maintaining computational efficiency suitable for design practice [10].

A parametric study by Khazi and Vazeer investigated the behavior of pile-supported wharves under liquefying soil conditions using nonlinear static pushover analysis. Their study showed that when soil was liquefied, base shear resistance dropped significantly, affecting the performance of the structure. The findings highlighted that pile yielding occurred at the interface between liquefied and nonliquefied soil layers [11].

Additionally, Bezih, Remadna, Remadna, and Demagh explored the reliability of reinforced concrete (RC) structures under variability in soil parameters, including soil stiffness and SSI. Their study demonstrated that soil stiffness variability significantly impacts the internal forces and deformations in RC structures, emphasizing the need for incorporating SSI and soil heterogeneity in structural reliability assessments. Their findings show that even minimal ground displacement can generate bending moments and shear forces that affect structural stability [12].

This study aims to address the gap in existing research by investigating the combined effect of SSI and corrosion on the seismic performance of steel pile jetties. Using numerical modeling and pushover

analysis, this paper evaluates the long-term performance of jetties located in two regions of Indonesia, Probolinggo (sand soil) and Gresik (clay soil), after 25 years of exposure to corrosion. The study considers both the initial and corroded conditions of pile foundations and aims to provide valuable insights into the design and maintenance of coastal infrastructure, particularly in seismically active and corrosive environments.

The remainder of this paper is organized as follows: Section 2 outlines the research significance and highlights the gap in understanding the combined effects of Soil-Structure Interaction (SSI) and corrosion on pile foundations. Section 3 details the methodology employed, including the geometric specifications of the jetty, distinct site conditions (sandy soil in Probolinggo versus clayey soil in Gresik), and numerical modeling techniques used for the nonlinear static pushover analysis. Section 4 presents the results and discussion, providing a comprehensive evaluation of the pushover response, degradation of pile capacity due to corrosion, global stiffness, moment-curvature relationships, structural ductility, and progression of failure mechanisms. Finally, the paper concludes with a summary of the key findings and their implications for the design and maintenance of marine infrastructure in seismically active and corrosive environments.

2. RESEARCH SIGNIFICANCE

The significance of this research lies in its ability to address the interaction between SSI and corrosion—two factors that have often been studied separately but not in tandem. Previous studies have shown that soil type plays a critical role in the behavior of pile foundations under lateral loads. This study provides new insights into how corrosion accelerates capacity degradation in sand-based pile foundations, whereas clay-based foundations exhibit more gradual degradation and superior long-term ductility, making them more resilient to corrosion-induced damage. These findings are particularly important for regions like Indonesia, where seismic activity and marine corrosion are prominent concerns.

3. METHODS

This research begins with a literature review aimed at establishing a theoretical foundation and understanding the fundamental concepts related to jetty structures, soil-structure interaction, degradation due to corrosion, and the evaluation of structural performance using the nonlinear static (pushover) analysis approach.

The next stage involves collecting existing jetty data, including geometric configuration, reinforcement details, material specifications, soil data, environmental conditions, and other relevant

information required for the numerical modeling of the structure.

The soil-structure interaction characteristics are then determined based on the available geotechnical data. These soil properties are integrated into the structural model to represent the actual response of the jetty to lateral loads, particularly those induced by earthquakes.

The numerical modeling of the jetty structure is conducted using FEA software (i.e. 'OpenSees'). The model aims to represent the global structural behaviors of the jetty and simulate the effects of corrosion on pile elements by considering the reduction in cross-sectional areas, material strength, and SSI. The Pushover Analysis is employed to evaluate the structural capacity under seismic loading. The modeling results are then validated against relevant literature and previous studies to ensure accuracy and consistency.

3.1 Jetty Specification

In this paper, a case study was conducted to model a single type of jetty structure in two different locations, Probolinggo [8] and Gresik [13], with distinct soil conditions. The analysis includes both initial (newly constructed) and corrosion-affected conditions over 25 years. The two jetties were modeled to compare their performance under different soil conditions and the impact of corrosion on their structural integrity.

The jetty under consideration has a dead weight tonnage (DWT) of 32,000, with a length of 180 meters and a width of 27 meters. The seabed depth is 18 meters, with soil conditions varying between the two locations; Location 1 features sandy soil, whereas Location 2 has clay soil. The structural sections of the jetty include a concrete slab with a rectangular shape, a depth of 400 mm, and a width of 1500 mm. The beam, also made of concrete, has a rectangular shape with a depth of 1700 mm and a width of 1500 mm. For the foundation, steel piles with a pipe shape, a depth of 1016 mm, and a thickness of 19 mm are used.

3.2 Site Conditions

Fig. 1 on the left side shows the jetty structure at Location 1, whereas on the right side shows the jetty located at Location 2. Both locations exhibit distinct soil conditions that will impact the behavior of the jetty.

At location 1 (left jetty), the soil composition consists mainly of sandy layers. The sand is divided into four strata: Sand-1 at a depth of 25.00 meters below the sea level with a unit weight of 19.1 kN/m³, Sand-2 at 31.00 meters with a unit weight of 17.3 kN/m³, Sand-3 at 33.00 meters with a unit weight of 19.3 kN/m³, and Sand-4 at 48.00 meters with a unit weight of 17.4 kN/m³. These sandy layers exhibit

varying degrees of cohesion (C) and friction angle (ϕ), with values ranging from 1 kPa to 1.3 kPa for cohesion and from 36.8° to 38° for the friction angle.

In contrast, location 2 (right jetty) has clayey soil layers, starting with Clay-1 at a depth of 25.00 meters with a unit weight of 15.5 kN/m³ and a cohesion of 6 kPa. The next layer, Clay-2, at 30.00 meters, has a unit weight of 16.5 kN/m³ and a cohesion of 18.5 kPa. Beneath these, at 40.00 meters, the soil transitions to a sand layer (Sand-1) with a unit weight of 21.6 kN/m³. The soils at this location exhibit varying unit weights, cohesion, and friction angles, influencing their behavior in the soil-structure interaction (SSI).

These distinct soil conditions will be used to calculate the $p - y$ curve, which is essential for determining the soil-structure interaction (SSI) and assessing the jetty's performance over time. The $p - y$ curve will help quantify the lateral resistance provided by the soil as the structure moves, which is critical for understanding the jetty's response to environmental loads and predicting its long-term behavior.

The $p - y$ curve is a crucial aspect of soil-structure interaction (SSI) analysis, representing the relationship between the lateral load (P) applied to a pile and its lateral displacement (Y). This curve helps evaluate the behavior of the jetty foundation under lateral forces, such as those caused by waves, seismic activity, or wind forces. The shape of the $p - y$ curve depends on the soil type, which significantly influences the pile's lateral resistance.

Fig. 2 illustrates the numerical idealization of the pile-soil system adopted in 'OpenSees'. The steel pipe pile is modeled as a vertical beam-column element subjected to axial load P_z , lateral load P_y , and bending moment M_b at the pile head, which produces a lateral displacement y at the seabed level. The lateral resistance of the surrounding soil is modeled as a series of non-linear springs distributed along the length of the embedded pile. These springs correspond to the depth-dependent $p - y$ curves and are implemented using *zeroLength* elements with the *ZeroLengthMaterial* definition in 'OpenSees'. Each spring is attached to the pile node and connected to a fixed reference node through restraint constraints, thereby simulating the relative pile-soil interaction at that depth.

The behavior of piles under various load conditions is critical for ensuring the stability and integrity of structures such as jetties. At the pile tip, a pinned boundary condition is frequently assumed in structural analyses. This assumption is grounded in the design principle that the pile has been driven to a sufficient depth within competent soil layers, thereby achieving optimal load transfer characteristics. In such scenarios, the pile base is located deep enough that it experiences minimal vertical settlement or rotational restraint, thereby allowing it to respond flexibly to applied loads.

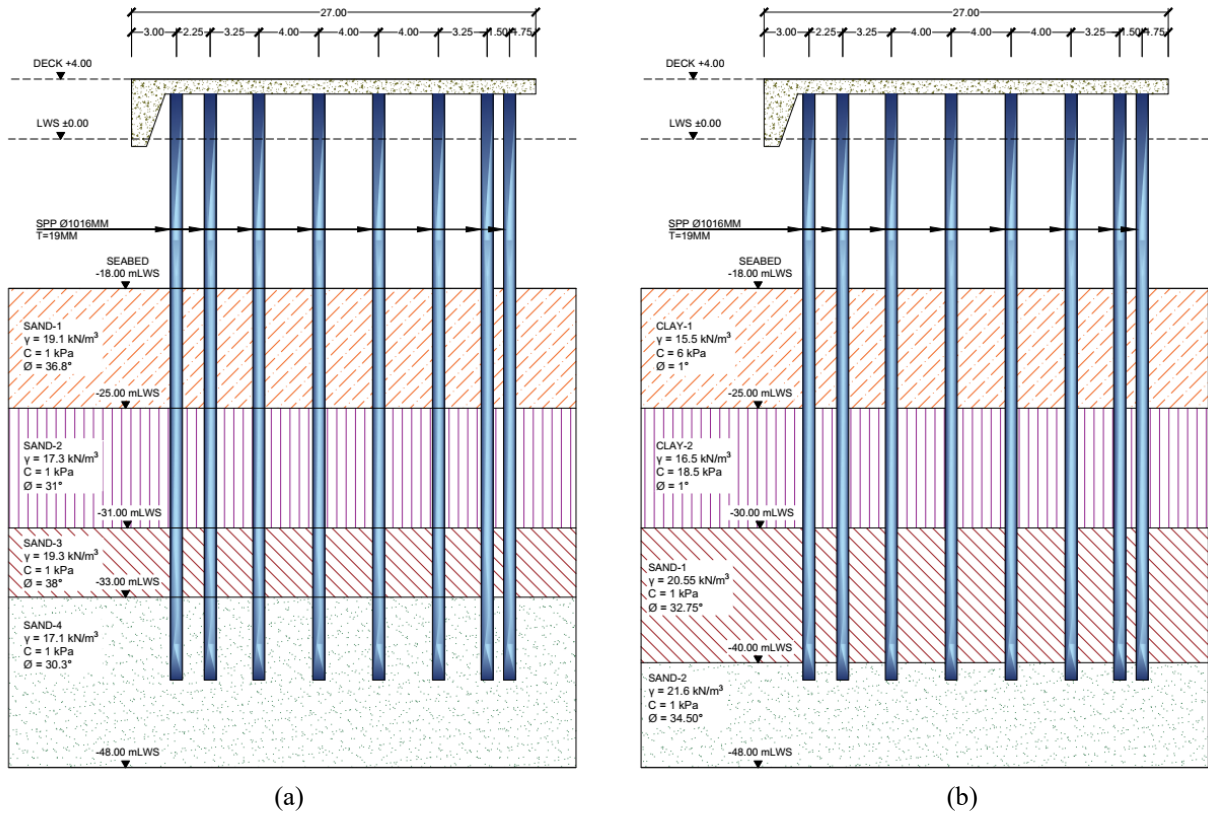


Fig. 1 Geometric jetty and soil condition of both locations of jetty: (a) location 1 and (b) location 2

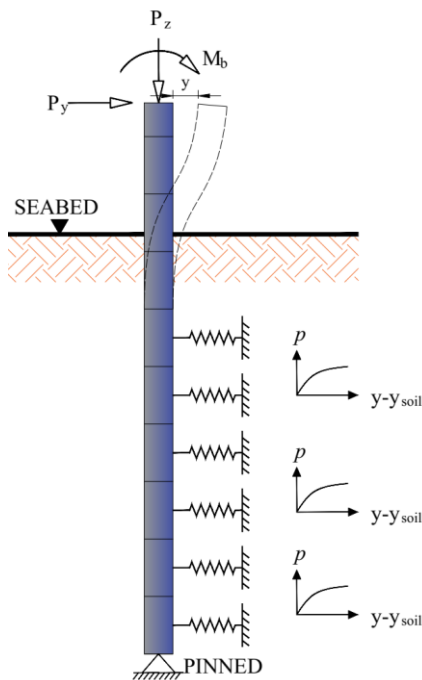


Fig. 2 Pile soil interaction

For the sandy soil at Location 1 (left jetty), the $p - y$ curve is derived using the American Petroleum Institute recommendations [14]. The API method, which is widely used for sandy soils, provides a

relationship between the modulus of subgrade reaction (k) and lateral displacement, with the $p - y$ curve initially steep, indicating high resistance at small displacements and then leveling off at larger displacements as the soil reaches its ultimate capacity. On the other hand, Location 2 (right jetty), characterized by clayey soils, uses Matlock's method [15], which is designed for cohesive soils. The $p - y$ curve for clay shows a more gradual increase in resistance with lateral displacement due to the role of cohesion and friction in the soil's resistance. The curve is typically more linear than sand, indicating a steady increase in resistance as the pile moves.

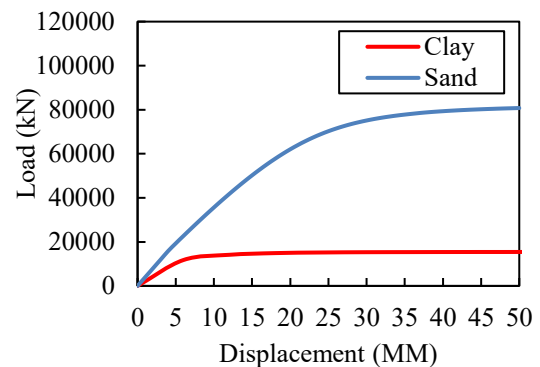


Fig. 3 $p - y$ curve existing soil

These curves were calculated using the L-PILE software [16], which models the non-linear behavior of piles under lateral loads. The results from L-PILE for both sandy and clayey soils are shown in

Fig. 3. The red line represents the $p - y$ curve for clay and the blue line represents the $p - y$ curve for sand. As can be seen, the $p - y$ curve for clay has a more gradual slope compared to sand, with sand showing higher resistance at larger displacements, reflecting the different behaviors of these soils under lateral loads.

The calculated $p - y$ curves are then integrated into the structural model to accurately simulate the soil-structure interaction. This allows for a better prediction of the jetty's long-term stability and safety under varying environmental conditions, ensuring that the jetty's design can accommodate the expected forces.

3.3 Structural Modeling of Jetty

In this study, a two-dimensional structural model of a jetty was developed to simulate the impact of corrosion on the cross-sectional area of the steel pipe pile foundation, capturing the nonlinear behavior of the pile foundation over time. The configuration, dimensions, and material specifications of the jetty are based on Darmawan, Bayuaji, Anugraha, Saputra, and Victoriawan [8]. The modeling process utilized the STKO program [17] as the pre-processor to set up the model and visualize the output, while 'OpenSees' [18] was used for the simulation, specifically for pushover analysis on the jetty structure.

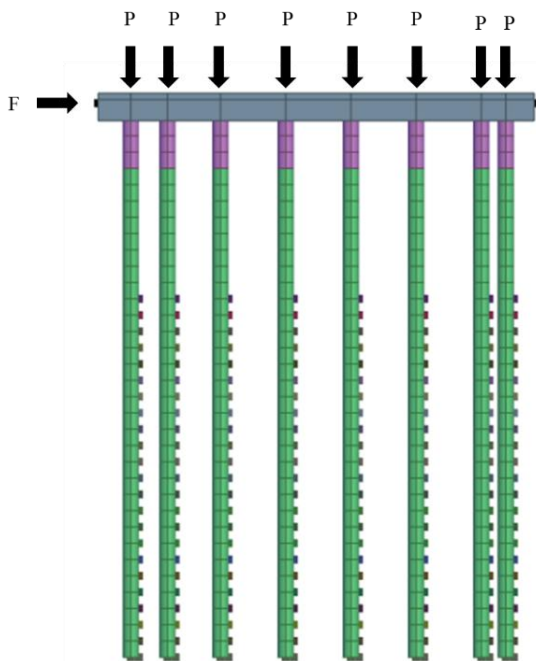


Fig. 4 Modeling of jetty structure

For the structural model, the deck was modeled as an elastic section, whereas the pile foundation was represented using fiber-based elements. Both the deck and pile components were discretized into 1-meter-long elements, with each element featuring a cross-section integrated at five points along its length. Nonlinear fiber displacement-based beam column elements were utilized through the STKO-'OpenSees' platform to accurately capture the nonlinear behavior of the piles and deck under various loading conditions [10], [17], [19], [20].

The analysis was carried out using a static solver with Newton's method with line search as the algorithm for nonlinear solution. The system used for the analysis was *UmfPack SOE*, which is suitable for solving large sparse systems [21]. The penalty method was used for constraint enforcement to handle boundary conditions accurately. The time step type was set as Adaptive Time Step with a maximum increment of 1000 to handle large displacements in the model. The adaptive control settings adjusted the step size based on the model's response, with a maximum factor of 1 and minimum factor of 1e-06, to ensure stability in the analysis. Additionally, wipe analysis was enabled to clear the previous analysis results and initialize new conditions for each calculation step.

To calculate the material response across each section, Gauss-Lobatto integration was used, providing a detailed and accurate representation of the pile's behavior [22]. The model was analyzed under two conditions: the initial state (new construction) and 25 years after construction to account for the effects of corrosion and the degradation of material properties over time.

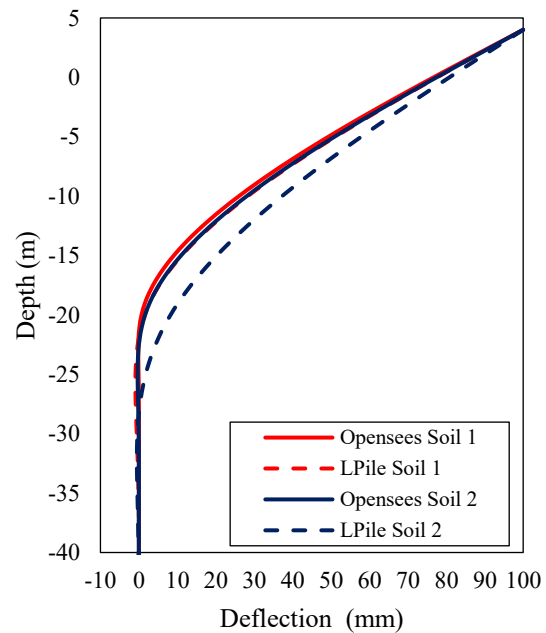


Fig. 5 Comparison lateral deflection 'OpenSees' with LPile

In Fig. 4, the jetty structure is subjected to vertical and lateral loads in the simulation. The vertical load denoted as P_a represents the combined dead load and live load of 100 kN applied to each pile, as shown in the diagram. The lateral force, labeled as F , represents the pushover load applied to the deck, simulating a lateral force incrementally increased until a displacement of 1 meter is reached. This pushover analysis allows the simulation to capture the nonlinear behavior of the pile foundation and deck under lateral forces, providing insights into the jetty's performance under seismic or other lateral loading conditions. The model incorporates both vertical and lateral forces to evaluate the interaction between the soil, piles, and superstructure under these loading scenarios.

Table 1 Material properties of the Jetty

| Symbol | Description | Value |
|-----------------|---|---------|
| f_c | Concrete compressive strength | 30 |
| ε_c | Strain at peak compressive strength of deck/infilled concrete | 0.00275 |
| f_{ypl} | Yield strength of the pile foundation (MPa) | 240 |
| f_{upl} | Ultimate strength of the pile foundation (MPa) | 415 |
| E_{spl} | Elastic modulus of pile foundation (MPa) | 190,000 |
| f_{yr} | Yield strength of concrete rebar (MPa) | 400 |
| f_{ur} | Ultimate strength of concrete rebar (MPa) | 620 |
| E_{sr} | Elastic modulus of concrete rebar (MPa) | 200,000 |

Table 1 presents the material properties used in the structural modeling of the jetty. The deck and infilled concrete are modeled using the *concrete02* material model in 'OpenSees' [23]. For concrete inside the core of a section, the Kent-Park model [24], [25] is used to simulate the uniaxial stress-strain behavior of unconfined concrete, whereas the modified Kent-Park model [26] is used for confined concrete. This allows for capturing the increase in strength and ductility because of the confining action imparted by the stirrups under axial loads [27]. On the other hand, concrete is modeled unconfined. For the pile foundation, the *steel02* material model is used for the steel pipe piles [23]. The constitutive relationship proposed by Menegotto and Pinto [28], [29] and modified by Filippou, Popov, and Bertero [30] is applied to simulate the uniaxial stress-strain characteristics of steel rebars. The steel reinforcement bars have a yield strength of 400 MPa, ultimate strength of 620 MPa, and an elastic modulus of 200,000 MPa. The material properties of the pile consist of a yield strength of 240 MPa, ultimate

strength of 415 MPa, and an elastic modulus of 190,000 MPa. These properties are crucial for precisely modeling the jetty's behavior under different loading conditions and for evaluating its structural performance over time.

Additionally, the two-dimensional models incorporate $p - y$ curves to simulate the interaction between soil resistance (p) and lateral displacement (y) at varying depths surrounding the piles. These curves are essential for capturing the soil-structure interaction (SSI) and play a critical role in determining the lateral resistance of the piles, thereby influencing the overall behavior of the jetty structure.

To validate the $p - y$ curve implementation adopted in the numerical SSI model, a single steel pipe pile with Diameter 1016 mm and thickness 19 mm was analyzed using two independent platforms: STKO-'OpenSees' [17], [19] and LPile [31]. The same pile section properties, loading scheme, and soil input parameters were used in both programs for two representative site conditions: Soil 1 (Probolinggo) and Soil 2 (Gresik). Fig. 5 compares the resulting lateral deflection profiles along depth. For Soil 1 the 'OpenSees' [19] and LPile [31] curves show nearly identical trends with slightly smaller deflections, reflecting the higher lateral confinement and stiffness mobilized by the sand profile. For Soil 2, both programs predict larger lateral deflections over a wider depth range, consistent with the more compliant soil behavior; the agreement between OpenSees [19] and LPile [31] remains strong, with only minor deviations in the mid-to-deep zone that can be attributed to differences in numerical discretization and soil spring implementation between the two solvers. Overall, the close correspondence for both sand and soft clay profiles confirms that the $p - y$ springs implemented in STKO-OpenSees [17], [19] can reproduce LPile [31] predictions with sufficient accuracy, supporting the use of the validated $p - y$ curve modeling approach in the subsequent global jetty pushover simulations.

This modeling approach allows for a comprehensive analysis of the jetty's performance under real-world conditions, accounting for both the initial design and long-term effects due to corrosion and environmental factors.

3.4 Corrosion Effect of the Pile Foundation

The corrosion effect on the steel pipe pile foundation is explicitly considered by modifying the pile wall thickness in the numerical model. The reference pile thickness at construction is 19 mm. The residual thickness at 25 years is determined from the assessment conducted by Darmawan, Bayuaji, Anugraha, Saputra, and Victoriawan [8], in which an average corrosion rate of 0.2 mm/year was adopted for the steel pipe piles in the marine environment. Based on this assessment, the effective wall thickness

of the pile at 25 years of service is taken as 16 mm.

In the structural analysis, two pile conditions are therefore modeled: (i) the initial (new construction) condition with a 19-mm wall thickness and (ii) the corroded condition at 25 years with a 16-mm wall thickness. The reduced thickness is implemented in the fiber-section definition of the pile elements, leading to a decrease in cross-sectional area and stiffness and allowing the pushover analysis to capture the degradation of the lateral and flexural capacity of the pile foundation due to corrosion.

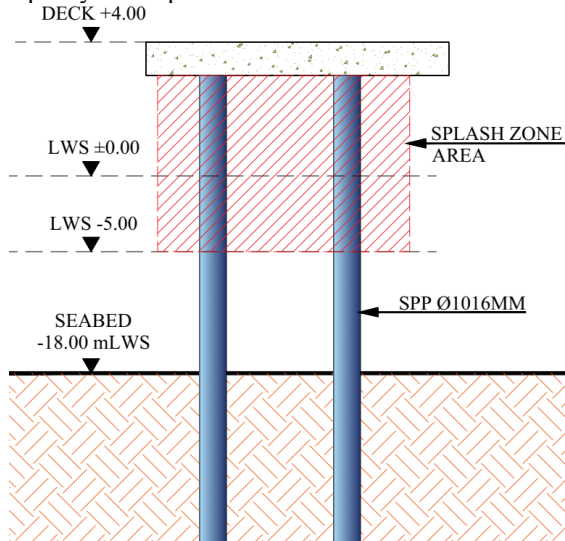


Fig. 6 Splash zone area of the jetty structure

In the modeling for the corrosion effect of the pile foundation, the corrosion is assumed to occur only in the splash zone area of the pile, as shown in Fig. 6. The splash zone is the portion of the pile exposed to the tidal range and is affected by seawater, leading to a higher rate of corrosion. In this model, the splash zone area is defined between the low water spring (LWS) at ± 0.00 mLWS and the area at -5.00 mLWS. This section of the pile is most vulnerable to environmental factors, such as seawater exposure, oxygenation, and chloride ions, which accelerate the corrosion process.

As depicted in Fig. 6, the pile foundation is modeled with the corroded portion of the steel pipe pile occurring only within the splash zone. The remaining pile sections, below the splash zone, are assumed to remain unaffected by corrosion, as these parts are submerged and protected from direct exposure to the fluctuating water level [32], [33]. This approach simplifies the modeling of corrosion by focusing on the most critical and exposed portion of the pile, which plays a significant role in the overall structural capacity of the jetty.

This method of corrosion modeling aligns with common engineering practices for marine structures, where corrosion is typically considered more severe in the splash zone due to its exposure to both air and seawater during tidal cycles.

3.5 Pushover Analysis

In this study, a nonlinear static pushover analysis was conducted to evaluate the lateral capacity and deformation demand of the jetty under increasing horizontal actions representing the combined effects of seismic loading and operational berthing forces. The analysis was performed in ‘OpenSees’ using the previously described two-dimensional jetty models for both locations and for two material states: initial (new construction) and after 25 years of corrosion. Gravity loads from the deck, superstructure, and permanent equipment were first applied and kept constant during the analysis. Subsequently, a monotonically increasing lateral load was imposed at the deck level in the longitudinal direction of the jetty until numerical instability or a clear strength degradation in the global capacity curve was observed. This procedure follows common practice for marine structures, where pushover analysis is employed to capture the nonlinear response of the soil–pile–structure system and ensure that its ultimate capacity exceeds the design lateral demand [6].

The pushover simulations explicitly incorporate soil–structure interaction through depth-dependent $p-y$ springs derived from the LPILE analysis, whereas the nonlinear behavior of the steel pipe piles is represented by fiber-based beam–column elements. The main outputs of the pushover analysis include global base shear versus deck displacement curves (capacity curves), distribution of bending moments and shear forces along the piles, evolution of curvature and plastic hinge formation, and the corresponding soil reaction profiles along the embedded pile length. For each location and corrosion scenario, the ultimate lateral capacity, displacement ductility, and sequence of damage in the pile foundation are extracted from these results, allowing a direct comparison between sandy and clayey site conditions as well as between intact and corroded piles. These comparisons are then used to quantify the reduction in strength and stiffness due to corrosion and discuss potential changes in the controlling failure mechanism of the jetty system.

4. RESULT AND DISCUSSION

4.1 Pushover Response of the Jetty Structure

The pushover curves in Fig. 7 compare the global base shear–deck displacement response of the jetty for the two initial soil conditions. The jetty founded on Soil 1 (sand, stiffer profile) exhibits a steeper initial slope, indicating a higher global stiffness of the soil–pile–structure system. The base reaction rapidly increases and reaches a peak of approximately 35×10^3 kN after which it stabilizes, reflecting a relatively rigid system with a rapid mobilization of lateral resistance. In contrast, the jetty on Soil 2 (clay, more

compliant profile) shows a more gradual increase in base shear, with a lower peak value of around 28×10^3 kN at a larger deck displacement. This confirms that the stiffer sand deposit can mobilize higher lateral resistance, leading to a larger peak base shear and higher force demands in the pile foundation.

From a deformation perspective, the structure on Soil 2 develops larger displacements before and around its peak strength, with a smoother, more extended post yield branch. This behavior indicates a more ductile global response for the clay site, where soil flexibility allows the system to dissipate energy over a wider displacement range. Conversely, the jetty on the stiffer Soil 1 demonstrates higher peak base shear and faster strength mobilization at relatively smaller displacements, reflecting a stiffer but slightly less ductile response. These results highlight the critical role of soil–pile–structure interaction: a stiffer soil profile increases lateral capacity but also amplifies internal forces in the piles, whereas a softer profile reduces peak shear demand while enhancing overall displacement ductility.

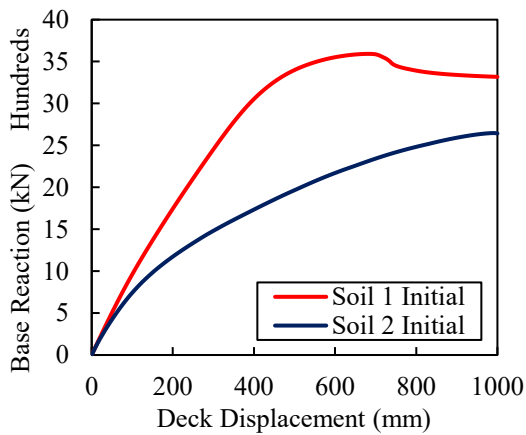


Fig. 7 Pushover curve of the initial condition for different soil conditions

These findings align with previous studies, such as the work by Su, Wan, Dong, Frangopol, and Ling. [6], which shows that soil-pile-structure interaction plays a significant role in the seismic performance of pile-supported structures. The interaction between the piles and the surrounding soil affects not only lateral resistance but also the overall stiffness and displacement response of the structure during seismic events.

4.2 Effect of Corrosion on Pile Foundation Capacity

The impact of corrosion on the pile foundation capacity is illustrated in the graphs above, which compare the base reaction (lateral resistance) versus deck displacement for both soil 1 (sand) and soil 2

(clay) under two conditions: initial (new construction) and after 25 years of corrosion.

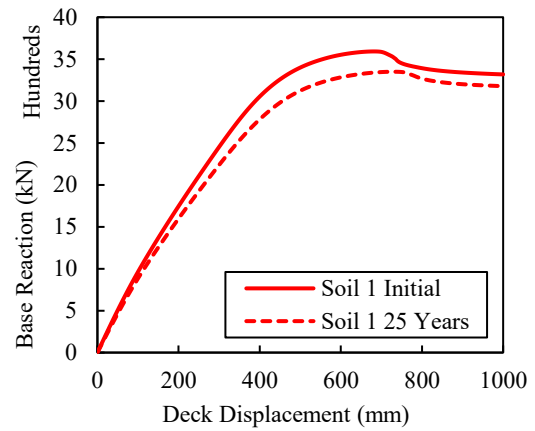


Fig. 8 Pushover curve for the Jetty on Soil 1 (Initial vs. 25 Years of Corrosion)

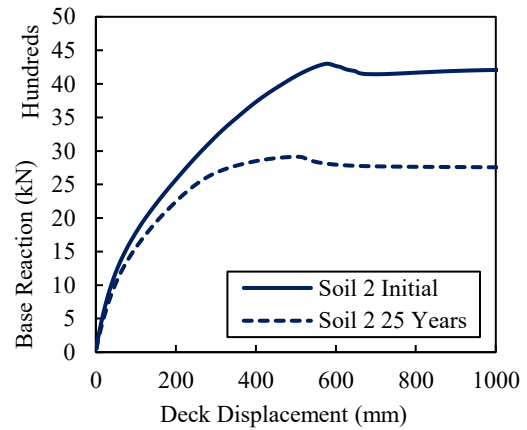


Fig. 9 Pushover curve for the Jetty on Soil 2 (Initial vs. 25 Years of Corrosion)

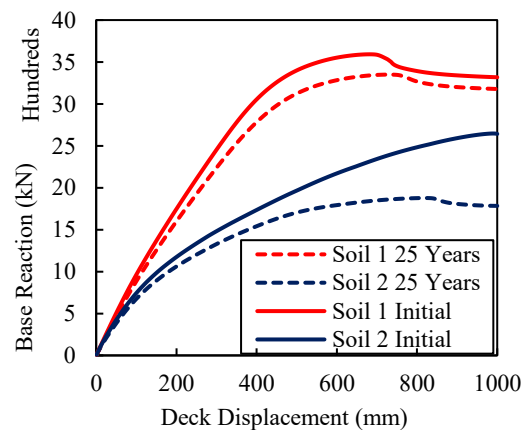


Fig. 10 Pushover curve for the Jetty on Soil 1 (sand) and Soil 2 (clay) at initial and 25 years of corrosion

For Soil 1 (sand), see Fig. 8 shows that the initial pile foundation (represented by the solid red line) exhibits a sharp increase in base reaction with

displacement, reaching a peak of approximately 35×10^3 kN. After 25 years of corrosion (represented by the dashed red line), the pile foundation exhibits a significant decrease in peak base reaction, dropping to around 30×10^3 kN. This reduction is a direct result of the loss of cross-sectional area due to corrosion, which reduces the pile's lateral load-carrying capacity. The curve for the corroded pile shows a similar shape but with a lower peak, indicating that the pile foundation is less stiff and more prone to larger displacements under the same applied loads.

In the case of Soil 2 (clay), shown in Fig. 9, the behavior is similar. The initial pile foundation (represented by the solid blue line) reaches a peak base reaction of 25×10^3 kN. After 25 years of corrosion (represented by the dashed blue line), the peak base reaction decreases to approximately 20×10^3 kN. The reduction in base reaction is less pronounced compared to Soil 1, reflecting the softer nature of clay soil, which allows for greater displacement and a more gradual increase in base reaction. However, the effect of corrosion still decreases lateral resistance and a more flexible foundation response.

Overall, these results highlight the significant impact of corrosion on pile foundation capacity. The reduction in pile stiffness due to corrosion leads to a decrease in lateral resistance, particularly evident in the pile foundations on Soil 1, which are stiffer than Soil 2. The corroded piles are more susceptible to larger displacements under lateral loading, which can affect the overall stability and serviceability of the jetty structure over time. These findings underscore the importance of considering corrosion in the long-term assessment of pile-supported marine structures, especially in aggressive environments like those found in ports and harbors.

4.3 Comparison of Jetty Performance under Sand and Clay Site Conditions

Fig. 10 compares the base reaction (lateral resistance) versus deck displacement for the jetty under two soil conditions: soil 1 (sand) and soil 2 (clay), both at initial (new construction) and after 25 years of corrosion.

For Soil 1 (sand), the graph shows that the jetty initially exhibits a steep increase in base reaction with displacement, reaching a peak of approximately 34×10^3 kN before gradually stabilizing at higher displacement values. However, after 25 years of corrosion (dashed red line), the peak base reaction drops to about 31×10^3 kN, indicating a reduction in lateral resistance due to the loss of cross-sectional area from the corrosion of the steel pipe pile. The curve for the corroded condition shows a more gradual increase in resistance and a lower peak value, suggesting that the pile foundation has become less

stiff and more prone to larger displacements under the same applied loads.

In Soil 2 (clay), the initial curve (solid blue line) shows a similar trend, with a more gradual increase in base reaction as the deck displacement grows, peaking at about 28×10^3 kN. After 25 years of corrosion (dashed blue line), the peak base reaction drops to 25×10^3 kN, again reflecting the reduction in pile stiffness due to corrosion. The jetty in clay soil shows more displacement for the same load compared to sand soil, which can be attributed to the greater flexibility of the clay profile.

When comparing the performance between Soil 1 and Soil 2, the jetty on Soil 1 (sand) initially exhibits higher lateral resistance but experiences a more significant reduction in peak base reaction after 25 years of corrosion. The jetty on Soil 2 (clay) demonstrates a more gradual increase in base reaction with displacement, which remains lower overall than the sand-based jetty, but the impact of corrosion on lateral resistance is less pronounced. This behavior shows that soil stiffness significantly affects both the maximum base shear and the displacement capacity of the pier structure. In stiffer soils (sand), the jetty reaches higher lateral resistance but becomes more sensitive to corrosion. In softer soils (clay), the jetty is more flexible and less impacted by corrosion in terms of peak resistance, but it tends to undergo larger displacements.

These findings are consistent with the results of previous studies on soil-pile-structure interaction, which show that stiffer soils tend to increase lateral capacity but also amplify the effects of corrosion on pile performance, whereas softer soils reduce peak shear demand and improve the overall displacement ductility of the structure [4, 8].

4.4 Global Stiffness of the Jetty Structure

The comparison of stiffness versus deck displacement for Jetty 1 and Jetty 2, shown in Fig. 11, provides valuable insights into how corrosion impacts the structural performance of the jetties under different soil conditions. Initially, Jetty 1, founded on sand, exhibits a higher stiffness than Jetty 2, which is supported by clay. This is due to the stiffer nature of sand, which provides greater lateral resistance. However, as time progresses and corrosion takes effect, the stiffness of Jetty 1 decreases significantly, especially at larger displacements, as seen in the dashed red line representing the corroded pile (29). This shows that corrosion on pile foundations in the splash zone has a greater impact on stiffness in sand than in clay.

On the other hand, Jetty 2 shows a more gradual reduction in stiffness over time. While it starts with lower stiffness compared to Jetty 1, the reduction in stiffness after 25 years of corrosion is more gradual (as seen in the dashed blue line). The clay soil in

Gresik is more flexible, allowing the structure to absorb more displacement without significant stiffness degradation, even after 25 years of corrosion.

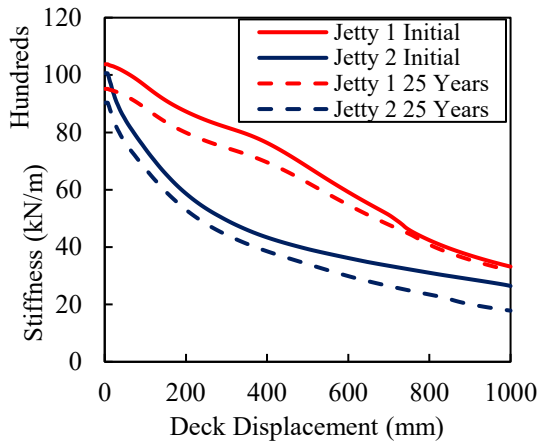


Fig. 11 The stiffness versus deck displacement for Jetty 1 and Jetty 2

These findings suggest that while Jetty 1 initially performs better in terms of stiffness due to the stiffer soil at Probolinggo, it is more susceptible to the effects of corrosion over time, leading to a more pronounced decrease in stiffness. Conversely, Jetty 2 benefits from the flexibility of clay, which provides better long-term performance under corrosion, with a more gradual reduction in stiffness and a higher overall resilience to displacement (30). This highlights the importance of considering both soil properties and the long-term effects of corrosion when evaluating the performance of pile-supported structures in marine environments.

4.5 Moment–Curvature Results for the Steel Pipe Pile Foundation

Fig. 12 presents the moment-curvature relationship for Jetty 1 and Jetty 2, showing both the initial conditions and after 25 years of corrosion. The moment-curvature curve is crucial for assessing the bending behavior of the pile and its capacity to resist lateral forces.

For Jetty 1, represented by the solid red line for initial conditions and the dashed red line for the corroded pile after 25 years, the pile exhibits a higher moment capacity at lower curvatures compared to Jetty 2. This indicates that the pile foundation in Probolinggo, with a sandy soil base, has a greater initial resistance to bending. However, after 25 years of corrosion, the curve shifts downward, showing a noticeable reduction in moment capacity. This loss is attributed to corrosion in the splash zone of the pile, which reduces its cross-sectional area over time, reducing bending resistance.

In contrast, Jetty 2, depicted by the solid blue line for initial conditions and the dashed blue line for the corroded pile, shows a more gradual increase in moment capacity with respect to curvature. Although the initial moment capacity is lower than that of Jetty 1, the pile in Gresik, supported by clay soil, exhibits a more gradual reduction in moment capacity after 25 years of corrosion. The decrease in moment capacity at Jetty 2 was not as significant as at Jetty 1, showing that the more flexible clay soil in Gresik allowed the piles to adjust to greater shifts without significant performance degradation [34].

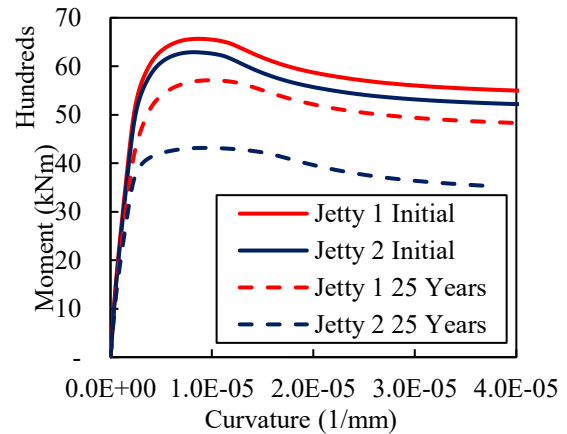


Fig. 12 Moment-curvature relationship for Jetty 1 and Jetty 2

These results highlight that Jetty 1, while initially stronger, suffers a greater reduction in moment capacity due to corrosion over time. On the other hand, Jetty 2 shows better long-term performance, with a more gradual reduction in moment capacity, reflecting the resilience of the pile foundation in Gresik. This behavior indicates that clay soil provides better long-term flexibility and ductility than stiffer sand soil in Probolinggo, which worsens the effects of corrosion on the pile’s performance [35]. These findings emphasize the critical role of soil type and corrosion in determining the long-term structural behavior of pile foundations.

4.6 Ductility of Structure

Table 2 summarizes the ductility of the jetty structures under different conditions, showing the displacement at ultimate capacity (Δ_u), displacement at yield (Δ_y), and the resulting ductility factor (μ) for both Jetty 1 (Probolinggo) and Jetty 2 (Gresik) at initial conditions and after 25 years of corrosion.

The ductility factor (μ) is calculated using the following formula:

$$\mu = \frac{\Delta_u}{\Delta_y} \quad (1)$$

Where Δ_u is the ultimate displacement, corresponds to the point where the jetty reaches its maximum lateral capacity. Δ_y is the yield displacement, where the structure starts to experience significant non-linear behavior and permanent deformations.

Table 2 Ductility reduction after corrosion of structure

| Study | Initial Ductility | Ductility After Corrosion | Reduction |
|--|-------------------|---------------------------------|-------------|
| Jetty 1 (Sand) Steel Pipe Pile | 6.19 | 5.98 (25 years) | 3.40% |
| Jetty 2 (Clay) Steel Pipe Pile | 13.2 | 12.22 (25 years) | 7.40% |
| Chen and Jiang RC Frames [36] | 4.04 | 3.69 (~10% corrosion) | 8.70% |
| Banayan-Kermani, Bargi, Heidary-Torkamani Wharf Piles [37] | Baseline | Reduced at 25, 50, and 75 years | Progressive |

For Jetty 1, under initial conditions, the ductility factor is 6.19, with an ultimate displacement of 681 mm and a yield displacement of 110 mm. This indicates a moderate level of ductility for the structure under normal conditions, meaning that the jetty can undergo a significant amount of displacement before reaching its ultimate capacity. However, after 25 years of corrosion, the ductility factor slightly decreases to 5.98, with the ultimate displacement increasing to 729 mm and the yield displacement rising to 122 mm. While there is a decrease in ductility, the structure still maintains a relatively high capacity for displacement before significant failure, though it is less flexible than it initially was.

For Jetty 2, the initial ductility is notably higher, with a factor of 13.20. The ultimate displacement for Jetty 2 is 990 mm, whereas the yield displacement is 75 mm, indicating that the structure is much more flexible and able to withstand larger displacements without a drastic loss in lateral resistance. After 25 years of corrosion, the ductility factor decreases to 12.22, with an ultimate displacement of 819 mm and a yield displacement of 67 mm. Despite this decrease, Jetty 2 retains a significant level of ductility, demonstrating better long-term performance in terms of flexibility and resilience to corrosion.

Jetty 2 (Gresik) demonstrates superior ductility compared to Jetty 1 (Probolinggo), both initially and after 25 years of corrosion. This is due to the more flexible response of Jetty 2, supported by clay soil, which allows the structure to withstand larger displacements before failure. Jetty 1, while initially stiffer, experiences a greater reduction in ductility over time due to the loss of capacity from corrosion, particularly in the sand soil at Probolinggo. The decrease in ductility in Jetty 1 after corrosion

indicates that the structure becomes less able to resist larger displacements without significant degradation, whereas Jetty 2 retains better resilience to corrosion and displacement, making it more ductile in the long term.

Based on the data presented in Table 2, both Jetty 1 and Jetty 2 exceed the minimum ductility requirement of 5, as set by ASCE 7 [38] and ASCE 61 [39] for pile-supported marine structures, ensuring that the jetties maintain adequate seismic resilience even after 25 years of exposure to corrosion. For Jetty 1 (Probolinggo), the initial ductility ratio of 6.19 decreases to 5.98 after corrosion, still surpassing the minimum requirement and demonstrating that the pile foundation can absorb seismic energy and prevent brittle failure. Jetty 2 (Gresik) shows an even higher initial ductility ratio of 13.20, which drops to 12.22 after 25 years of corrosion, remaining well above the minimum. This indicates that the structure, supported by clay soil, retains high ductility and can undergo significant displacement without experiencing failure. These results highlight the importance of both soil type and corrosion management in determining the long-term performance and seismic resilience of marine structures. The fact that both jetties maintain ductility above the required minimum ensures they are designed to withstand seismic events effectively, absorbing energy without catastrophic failure, and underscores the need for regular maintenance to preserve structural integrity over time.

A directly relevant study by Banayan-Kermani, Bargi, Heidary-Torkamani, assessed the seismic performance of pile-supported wharf structures at initial conditions ($t = 0$ years) and after corrosion at $t = 25, 50,$ and 75 years. This study developed fragility curves using displacement ductility factor (μ) as the engineering demand parameter. The results showed a steady increase in seismic vulnerability over the structure's lifespan due to corrosion, highlighting the significant effect of deterioration on the structural behavior. The study confirms that corrosion significantly affects the displacement ductility and overall performance of pile-supported wharves over time, which aligns with your observation that both jetties experienced ductility factor reductions after 25 years [37].

An experimental study by Chen and Jiang on corroded RC moment-resisting frames provides valuable quantitative data on the degradation of ductility due to corrosion [36]. The study shows a reduction in the displacement ductility ratio (μ) with increasing corrosion levels, from 4.04 (non-corroded) to 3.77 at an average corrosion level of 6.7%, 3.69 at 9.2% corrosion, and 3.64 at 9.4% corrosion. The ductility reduction was 6.7% at 6.7% corrosion, increasing to 8.7% at 9.2% corrosion and 10.0% at 9.4% corrosion. The ultimate displacement also decreased from a range of 73–76 mm in the non-corroded state to 57–66 mm at the highest corrosion

level. Similarly, the yield displacement was reduced, showing a range of 13–24 mm in the non-corroded state to 12–20 mm at the highest corrosion level [36].

These findings demonstrate that Jetty 2 (clay) demonstrates superior long-term ductility despite its initially larger displacement capacity. These findings align with existing research showing that more flexible soil conditions provide better resilience against the combined effects of corrosion and loading. Conversely, the higher initial stiffness of Jetty 1 (sand) correlates with studies indicating that stiffer soil conditions can intensify the harmful effects of corrosion on structural performance. These results are consistent with the behavior observed in Jetty 1, where the ductility factor decreased from 6.19 to 5.98 after 25 years of corrosion, highlighting a similar pattern of ductility degradation over time. Experimental data, such as the study by Chen and Jiang and Banayan-Kermani, Bargi, Heidary-Torkamani [36], [37], reinforce the importance of considering corrosion effects on structural ductility, particularly in long-term performance analysis of structures like reinforced concrete, where corrosion progressively reduces ductility, as seen in Jetty 1 and other studies.

4.7 Depth of Fixity Point

The Depth of Fixity Point is a critical factor influencing the performance of the jetty under lateral loading. As shown in Fig. 13, the maximum moment distribution along the pile is determined by the location of the fixity point, where the pile is assumed to be fully restrained. In this study, pushover analysis was conducted up to 1000 mm of displacement to simulate the pile's behavior under large lateral forces, considering both the initial and corroded conditions.

For Jetty 1 in Fig. 13 (a), the fixity point is located at a depth of 30 meters from the top of the deck, as indicated in the model. This means that the pile foundation is fully fixed at this depth, resulting in a concentrated maximum moment distribution at this location. The deeper the fixity point, the more resistant the pile is to bending forces and the greater the distribution of moment along the pile, leading to improved structural performance.

For Jetty 2, as illustrated in Fig. 13(b), the fixity point is strategically located at a depth of 32 meters from the top of the deck. This deeper fixity point is significant because it contributes to a more stable moment distribution throughout the pile compared to Jetty 1, where the fixity is situated at a shallower depth. By being anchored deeper within the soil, Jetty 2's piles are better equipped to withstand higher bending moments, particularly during conditions of increased lateral displacement, such as those caused by seismic events. The greater depth of fixity in Jetty 2 promotes a more evenly distributed moment along the length of the pile.

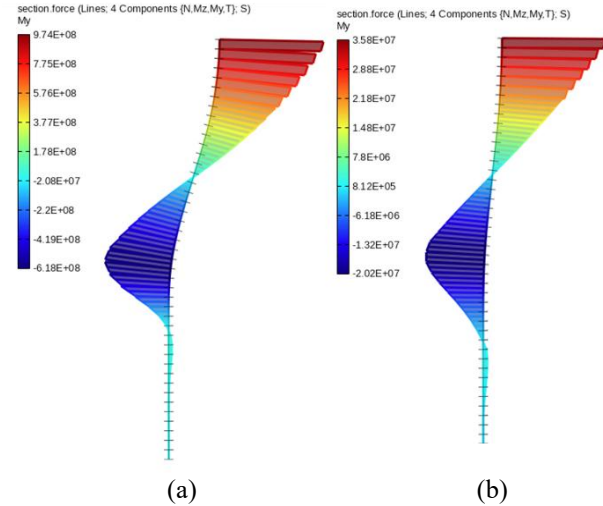


Fig. 13 Maximum Moment in the Pile Jetty

These findings align with those of Su, Wan, Dong, Frangopol, and Ling [6], who demonstrated that a deeper fixity point provides better load distribution, a more uniform moment-curvature response, and greater overall resistance to lateral forces. Their study found that deeper fixity points in pile foundations result in more stable and durable structures by improving the resistance to bending and enhancing the performance of the pile in sustaining long-term seismic and operational loads. Similarly, the deeper fixed points on Jetty 2 demonstrate superior long-term performance, especially when subjected to large lateral shifts, compared to Jetty 1, which has shallower fixed points.

The depth of fixity significantly influences the distribution of bending moments along the pile, as well as the overall stability and resilience of the jetty structure. The deeper fixity point in Jetty 2 provides improved moment distribution and better long-term resistance than Jetty 1, highlighting the importance of considering the fixity depth in pile foundation design for marine structures. Additionally, this deeper fixity reduces the concentration of moments at the pile head, thus distributing forces more evenly throughout the pile, which contributes to the structure's overall durability and ability to withstand dynamic loading conditions such as seismic forces and long-term environmental exposure.

4.8 Failure Mechanism and Damage Progression of the Jetty System

The progression of failure and damage in the jetty system is clearly illustrated by analyzing the deformation patterns and the corresponding data analysis over time, specifically when comparing the initial and 25-year conditions for Jetty 1 and Jetty 2. This extensive analysis highlights how environmental factors and load conditions influence the structural integrity of each jetty.

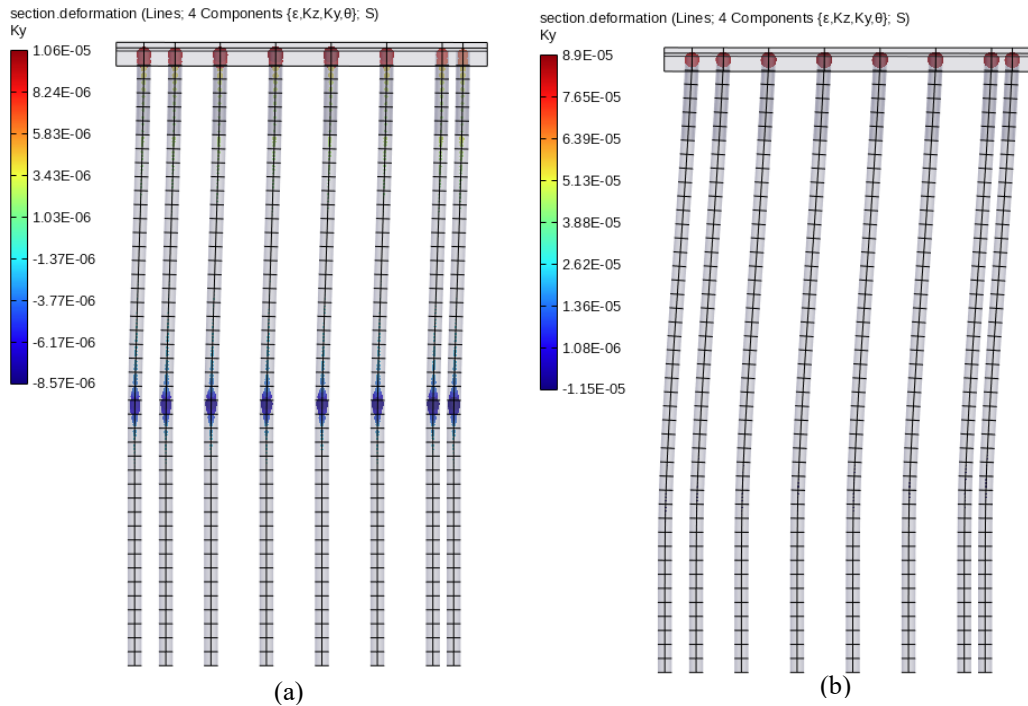


Fig. 14 Deformation and Damage Progression of Structure: (a) Jetty 1 and (b) Jetty 2

At the initial condition for both jetty systems, the deformation values are minimal and consistent, as evidenced by the color distribution in the deformation plots. For Jetty 1, as shown in Fig. 14 (a), the maximum displacement at 1000 mm is associated with a k_y value of $1.06E-05$ (1/mm) and a moment of $5.12E + 09$ Nmm. Jetty 2, shown in Fig. 14 (b), exhibits a slightly higher k_y value of $8.90E-05$ (1/mm), indicating a more flexible behavior at the start, with a moment of $5.41E + 09$ Nmm. These values show that both piers are operating within their elasticity limits in the early stages, with no indication of imminent failure.

As the system ages and undergoes 25 years of corrosion, significant changes in the deformation and structural behavior become evident. For Jetty 1, the k_y value decreases to $4.16E-05$ (1/mm), indicating a reduction in the structure's ability to resist deformation, with the moment increasing slightly to $5.35E + 09$ Nmm. The deformation map for Jetty 1 clearly shows localized regions with larger deformations, reflecting the onset of damage and the potential formation of plastic hinges in areas affected by long-term corrosion. This indicates the onset of inelastic behavior and a reduction in the jetty's load-bearing capacity.

Jetty 2, after 25 years, shows even more significant deterioration, with the k_y value dropping to $3.80E-05$ (1/mm), and the moment decreasing to $3.71E + 09$ Nmm. The deformation map for Jetty 2 illustrates a more pronounced curvature, with deformation spreading across more of the structure. The reduced moment and k_y values confirm the

damage progression, where the structure has experienced a more severe degradation due to corrosion over the years.

The failure mechanism of both jetties progresses from initial elastic behavior to localized plasticity, as seen in the increase in displacement and decrease in stiffness (k_y value). Jetty 1, despite showing some damage, retains a higher resistance to deformation than Jetty 2, which has experienced a more severe decline in capacity. The plastic hinge formation and overall reduction in structural stiffness are the primary indicators of failure. This transition from elastic to plastic behavior is driven by the cumulative effects of corrosion, leading to a reduction in the cross-sectional area and the ultimate bearing capacity of the piles.

In conclusion, the analysis of deformation, k_y values, and moments over time highlights the importance of regular monitoring and maintenance to mitigate the impact of corrosion on the structural integrity of jetty systems. The progression from elastic to plastic behavior, with the formation of plastic hinges, marks the transition toward failure, emphasizing the need for timely intervention to prevent catastrophic failure.

4.9 Comparative Discussion

The results of this study align with and extend the findings of previous research on corroded pile-supported marine structures. The observed 10%–20% reduction in lateral capacity after 25 years of corrosion is consistent with the range reported by Mullins, Sen, Stokes, and Scott [33], who

documented 15%–25% strength loss in corrosion-damaged pile bents under lateral loading. Furthermore, the disparate impact of corrosion depending on soil type—where the stiffer sand profile exhibited a more pronounced degradation in both stiffness and peak strength than the clay profile—corroborates the findings of Sharma, Dasgupta, and Dey [23]. Their work on soil-pile-structure interaction elucidates how stiffer soil conditions amplify the harmful effects of pile section loss on the global system's force-resisting mechanism. This soil-dependent vulnerability is a critical consideration for lifecycle assessments. The overall behavioral trend, where corrosion flattens the pushover curve and increases displacement demand, resonates with the numerical observations of M. Koronides, Michailides, and Onoufriou [40] for marine jetties and the simplified seismic assessment methodology proposed by Refani & Nagao [10]. Collectively, these studies underscore a consensus: ignoring the synergistic effects of long-term corrosion and site-specific soil-structure interaction can lead to a significant overestimation of the lateral capacity and a mischaracterization of the failure mechanism for aging marine infrastructure.

5. CONCLUSION

This study offers a comprehensive investigation into the combined effects of soil-structure interaction (SSI) and corrosion on the seismic performance of marine jetty systems, a critical aspect of coastal infrastructure in seismically active regions. Through detailed numerical modeling and nonlinear static pushover analysis, we examined the structural integrity of jetties located in two distinct environments: Probolinggo, characterized by sandy soil, and Gresik, with clayey soil. The evaluation spanned 25 years, with a focus on corrosion impacts on the pile foundations of the jetties.

Our findings highlight key differences in the performance of jetties supported by different soil types. The jetty located in sandy soil (Probolinggo) exhibited higher initial stiffness and lateral resistance, which are typical of stiffer soils. However, after 25 years of corrosion, the jetty experienced a substantial reduction in its structural performance, specifically in lateral capacity and stiffness. The corrosion-induced degradation of the pile foundations increased the vulnerability to lateral displacements, which could compromise the long-term serviceability of the structure.

In contrast, the jetty supported by clayey soil (Gresik) demonstrated more gradual degradation with better long-term ductility. The flexibility provided by the clay soil allowed the jetty to absorb larger displacements without significant loss of lateral resistance. This result underscores the importance of soil flexibility in mitigating the adverse effects of

corrosion, particularly in environments exposed to aggressive marine conditions.

The study also emphasizes the significance of incorporating soil-structure interaction in the design and analysis of marine jetties. SSI plays a crucial role in influencing the overall stiffness, lateral resistance, and displacement capacity of the structure. Furthermore, the long-term effects of corrosion, particularly in the splash zone of the piles, have a profound impact on the pile's capacity to resist lateral forces. These findings highlight the importance of regular maintenance and corrosion monitoring to maintain the structural safety and longevity of jetties in marine environments.

Overall, the research contributes to the understanding of how corrosion and soil-structure interaction jointly affect the seismic performance of aging marine jetties. The insights gained from this study can guide the design, assessment, and retrofitting of jetties and other pile-supported structures in similar coastal regions. It also highlights the need for further studies that integrate corrosion and SSI effects to improve the resilience of critical infrastructure despite both environmental degradation and seismic hazards. Moreover, this research underscores the importance of incorporating long-term maintenance and monitoring strategies to mitigate the impact of corrosion over time and ensure the continued safety and functionality of marine infrastructure in the face of evolving environmental challenges.

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