

Residual Structural Performance of Spun Pile-Supported Wharves under Long-Term Marine Corrosion: A Multi-Parameter Assessment

Kohar Yudoprasetyo ^{1✉}, Afif Navir Refani ²

(1,2) Department Civil Infrastructure Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

Abstract: Long-term marine corrosion can progressively reduce the strength, stiffness, and deformation capacity of prestressed-concrete spun piles, but individual material or global-response parameters do not by themselves provide a complete condition assessment of aging pile-supported wharves. This study develops a multi-parameter residual-performance assessment by re-analyzing previously established corrosion-dependent material models and nonlinear pushover results for two representative wharf configurations: PSW-A with vertical Ø700 mm spun piles and PSW-B with vertical and batter Ø600 mm spun piles. Three exposure states were considered: 0, 50, and 75 years, corresponding to corrosion degrees of 0, 12.20, and 18.56%. At 75 years, the reported cover-concrete strength, core-concrete strength, and PC-bar yield strength retained approximately 40.21%, 82.87%, and 91.64% of their initial values. The effective pile stiffness factors decreased to 0.789-0.799, while lateral capacity decreased by approximately 25-28%. Ductility retention was only 0.667 for PSW-A and 0.660 for PSW-B. The comparison shows that the batter-pile system can retain relatively high peak-displacement and stiffness ratios while still experiencing greater lateral-capacity loss and strain concentration. The proposed normalized assessment provides a practical screening framework for inspection and maintenance prioritization, while remaining a deterministic, model-based preliminary approach requiring field validation.

Article history:

Received: 30 August 2026

Revised: 19 September 2026

Accepted: 21 September 2026

Published: 02 October 2026

Keyword:

corrosion, spun pile, pile-supported wharf, residual performance, pushover analysis

This is an open-access article under the [CC-BY-SA License](#).



How to cite: Yudoprasetyo, K., & Refani, A. N. (2026). Residual Structural Performance of Spun Pile-Supported Wharves under Long-Term Marine Corrosion: A Multi-Parameter Assessment. *RESWARA: Jurnal Riset Ilmu Teknik*, 4(4), 1361-1372. <https://doi.org/10.70716/reswara.v4i4.856>

INTRODUCTION

Pile-supported wharves are critical components of port infrastructure because they support berthing operations, cargo transfer, and access to coastal logistics networks. Prestressed-concrete spun piles are widely used for these structures because they provide high axial capacity, rapid construction, and good initial durability in marine applications. Nevertheless, continuous exposure to chloride-rich seawater, tidal wetting-drying cycles, and salt spray can initiate reinforcement corrosion and progressively reduce the mechanical performance of the pile system (Michalek & Gago, 2024; Refani & Nagao, 2023b). Recent depth-dependent corrosion modelling further shows that deterioration can vary significantly across atmospheric, splash, tidal, and submerged exposure zones, with the splash zone often becoming the most vulnerable because of combined transport and wetting-drying effects (Sannasiraj et al., 2026).

Corrosion deterioration is not limited to steel section loss. The expansion of corrosion products generates internal pressure, promotes cracking and spalling of the cover concrete, weakens the bond between steel and concrete, and reduces the strength and ductility of the reinforcing or prestressing steel. Numerical and experimental studies have shown that corrosion morphology and corrosion degree can significantly affect stress-strain response, ductility, and failure mechanisms (Liu et al., 2025;

Ou et al., 2016; Xi et al., 2018; Zhu et al., 2017). These effects are particularly relevant for spun piles because the hollow circular section, high-strength concrete, prestressing bars, and transverse reinforcement create a deterioration mechanism that differs from that of conventional reinforced-concrete members.

At the structural level, the seismic performance of pile-supported wharves depends on the interaction between degraded pile properties, pile configuration, deck restraint, and soil-pile response. Previous research has demonstrated that soil-structure interaction and pile arrangement can modify displacement, force demand, and damage concentration under lateral loading (Darmawan et al., 2026; Kumar et al., 2026; Zhao et al., 2023; Feng & Gao, 2022; Su et al., 2021). More recent studies have expanded this perspective toward resilience-based evaluation, showing that liquefaction, isolation systems, aging, and climate-modified chloride corrosion can substantially change damage probabilities, post-earthquake recovery, and long-term wharf resilience (Cui et al., 2025; Mirzaeefard, 2026; Zhang et al., 2026). Recent work also shows the strong influence of soil classification on structural displacement and drift response, supporting the broader need to interpret seismic performance together with foundation and site conditions (Zebua et al., 2026).

A sequence of previous studies established the numerical basis used in the present paper. Refani and Nagao (2023a) quantified corrosion-dependent changes in cover concrete, core concrete, PC-bar strength, and bond behavior using three-dimensional finite-element analysis. Refani and Nagao (2023b) then incorporated deterioration-dependent section properties into nonlinear analyses of spun pile-supported wharves. More recently, Refani et al. (2026) evaluated material strains, ductility degradation, and corrosion-adjusted performance limits for vertical-pile and vertical-batter-pile wharf configurations. These studies provide detailed component-level and system-level information, but their outputs are expressed in different response quantities and are therefore not immediately comparable for practical condition screening.

For asset management decisions, an engineer often needs to answer a simpler question: how much of the original structural performance remains after a given corrosion exposure? A single parameter may be misleading. For example, a system may retain a relatively high displacement at peak force while having already lost substantial lateral resistance or ductility. Likewise, local material degradation may be severe even when a global stiffness indicator remains comparatively high. Therefore, normalized residual ratios can provide a transparent way to compare material degradation, stiffness, capacity, and deformation response on a common scale.

Although previous studies have quantified corrosion-dependent material deterioration and nonlinear seismic response of spun pile-supported wharves, the resulting parameters have generally been interpreted separately. Consequently, the relationship between material deterioration, residual stiffness, lateral resistance, and deformation capacity is not readily expressed on a common scale for comparative condition assessment. The present study addresses this gap through a secondary numerical re-analysis that transforms previously established component- and system-level results into dimensionless residual-performance indicators. The novelty lies in the cross-scale integration of material degradation and global structural response and in demonstrating that stiffness, strength, ductility, and peak-displacement retention may evolve at different rates depending on pile configuration.

Accordingly, this study aimed to (1) establish traceable links between corrosion-induced material degradation and residual structural response; (2) quantify normalized stiffness, lateral capacity,

ductility, and peak-displacement retention; and (3) compare the deterioration patterns of vertical and vertical-batter spun pile wharf systems.

RESEARCH METHOD

Study Design and Data Provenance

The present work is a secondary numerical assessment based on two previously published modeling frameworks. Material deterioration relationships were taken from the three-dimensional finite-element study of corroded spun pile materials by Refani and Nagao (2023a), while the global structural response data were obtained from the fiber-based nonlinear wharf model reported by Refani et al. (2026), which itself adopted the structural configuration and deterioration modeling strategy of Refani and Nagao (2023b). The current analysis introduces new normalized residual-performance ratios and a cross-scale comparison rather than repeating the original stress-strain or strain-limit objectives.

Three exposure conditions were retained because exact structural-response data were available at these states: 0 years (uncorroded), 50 years (12.20% corrosion degree), and 75 years (18.56% corrosion degree). The corrosion model is deterministic and represents seawater-induced chloride corrosion. Soil-induced corrosion of embedded pile segments, probabilistic chloride transport, climate-change scenarios, and record-to-record earthquake variability are outside the scope of the present assessment.

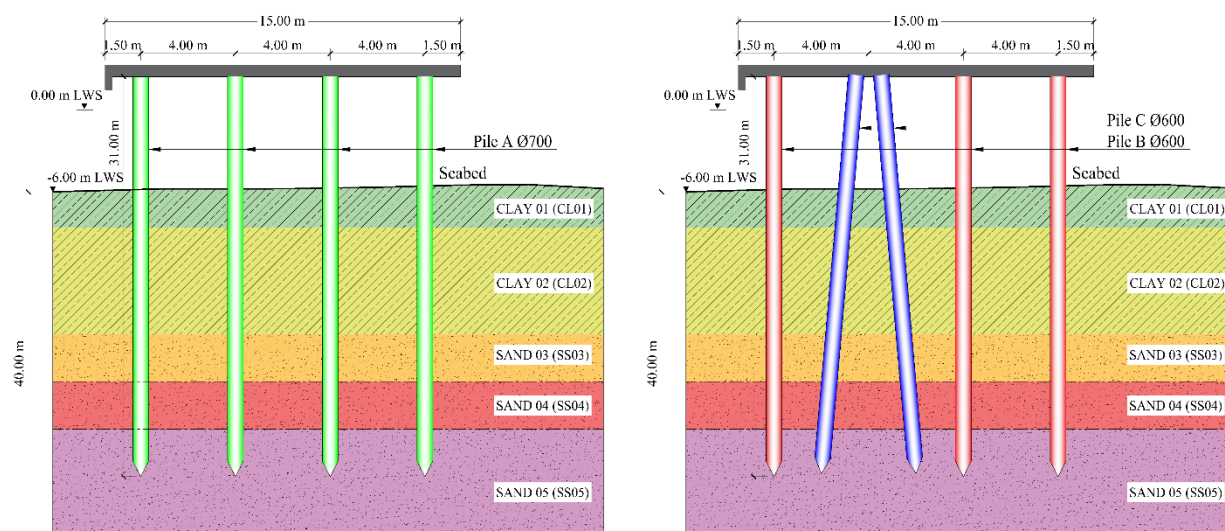


Figure 1. Geometry of the analyzed pile-supported wharf configurations: (a) PSW-A and (b) PSW-B.
Reproduced from Refani et al. (2026).

Table 1. Main characteristics of the analyzed pile-supported wharf configurations.

Parameter	PSW-A	PSW-B
Pile configuration	Vertical piles	Vertical + batter piles
Main spun-pile diameter	700 mm	600 mm
Batter angle	-	5°
Pile-head infill	Top 2 m concrete infill	Top 2 m concrete infill
Crown elevation	+3.00 m relative to LWS	+3.00 m relative to LWS
Corrosion states	0, 50, 75 years	0, 50, 75 years

Corrosion-Dependent Material Properties

The mechanical deterioration relationships were adopted from Refani and Nagao (2023a). The corrosion degree, ψ , represents the relative loss of PC-bar area and is expressed as a decimal fraction in the equations. The fitted relationships used to describe the reduction in cover-concrete strength, core-concrete strength, and PC-bar yield strength are:

$$f_{c,corr} = \left(0.25 \tan^{-1} \left(\frac{0.149 - \psi}{0.025} \right) + 0.65 \right) f_{c,0} \quad (1)$$

$$f_{cc,corr} = \left(0.14 \tan^{-1} \left(\frac{0.17 - \psi}{0.1} \right) + 0.848 \right) f_{cc,0} \quad (2)$$

$$f_{y,corr} = (1 - 0.4448\psi) f_{y,0} \quad (3)$$

The continuous equations are used in this paper only to visualize the material-retention trend. For the 75-year condition, the reported finite-element retention values are retained directly: 40.21% for cover-concrete compressive strength, 82.87% for core-concrete compressive strength, and 91.64% for PC-bar yield strength. This avoids implying that the fitted equations are universal corrosion laws.

Table 2. Exposure states and material-retention ratios used in the present re-analysis.

Exposure	Corrosion degree ψ	Cover concrete	Core concrete	PC-bar yield
0 years	0.00%	1.000	1.000	1.000
50 years	12.20%	0.856	0.911	0.946
75 years	18.56%	0.402	0.829	0.916

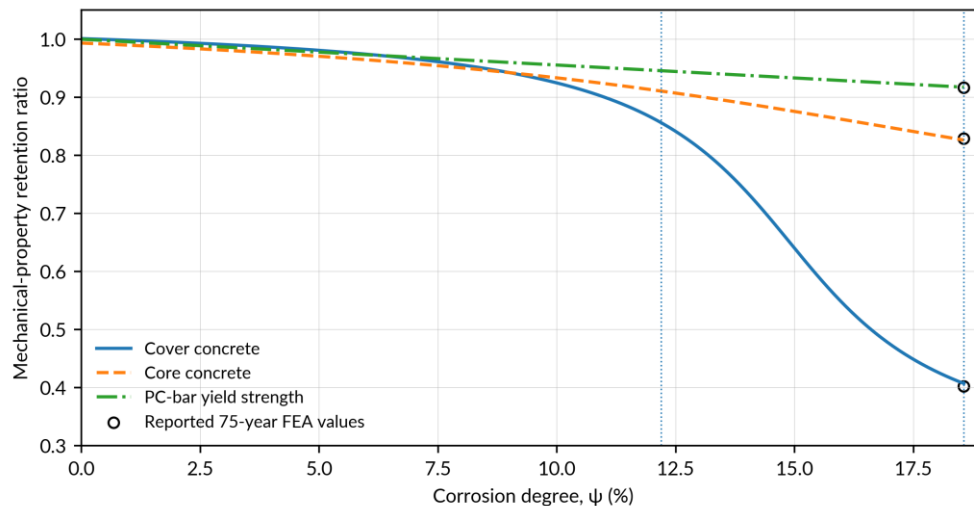


Figure 2. Corrosion-dependent material-retention trends derived from the published equations, with reported 75-year FEA endpoints shown for reference.

Nonlinear Structural Model

The structural response was based on two-dimensional fiber-based finite-element models developed in STKO-OpenSees. Deck and pile members were discretized using displacement-based

beam-column elements, with 1 m element lengths and five section integration points. Material nonlinearity was represented through fiber sections for cover concrete, confined core concrete, PC bars, and infilled concrete. The soil-pile interaction was represented using nonlinear p-y springs calibrated from the geotechnical profile adopted in the original model.

The nonlinear static pushover analysis applied a constant gravity load and incrementally increased lateral displacement at the deck. The original analysis used displacement control to trace the response beyond yielding and into the post-peak range. The reported displacement values in the hundreds of millimeters are therefore control displacements used to investigate nonlinear damage progression and should not be interpreted as allowable service displacements.

Table 3. Representative soil parameters retained from the published PSW numerical model.

Layer	Soil type	Representative N-SPT	Thickness (m)	Unit weight, γ (kN/m ³)	Friction angle (°)	Cohesion (kPa)
CL01	Very soft clay	3	3	10.07	6	41.19
CL02	Soft clay	5.5	9	10.33	7	42.22
SS03	Silty sand	15	4	10.75	22	-
SS04	Medium sand	30.5	4	11.09	30	-
SS05	Dense sand	47.5	20	11.89	34	-

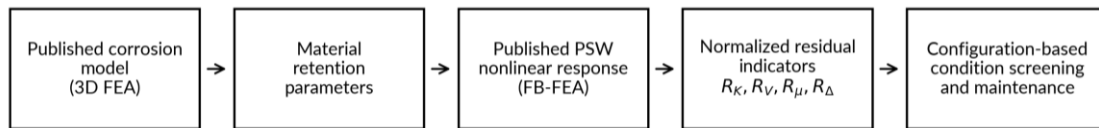


Figure 3. Cross-scale analysis framework adopted in the present study.

Residual Performance Indicators

Four dimensionless ratios were used to express the remaining response relative to the uncorroded condition. The stiffness ratio, lateral-capacity ratio, ductility ratio, and peak-displacement ratio were defined as:

$$R_K = \frac{K_t}{K_0} = \frac{\eta_t}{\eta_0} \quad (4)$$

$$R_V = \frac{V_{max,t}}{V_{max,0}} \quad (5)$$

$$R_\mu = \frac{\mu_t}{\mu_0} \quad (6)$$

$$R_\Delta = \frac{\Delta_{peak,t}}{\Delta_{peak,0}} \quad (7)$$

where the subscript t denotes the corrosion-exposure condition and the subscript 0 denotes the uncorroded state. These indicators are not acceptance limits. They are normalized comparison

parameters used to identify whether the two pile configurations lose stiffness, strength, or deformation capacity at similar or different rates.

RESULTS AND DISCUSSION

Material Degradation under Long-Term Corrosion

The corrosion-dependent material response shows a markedly different degradation rate among the components. At 50 years, corresponding to $\psi = 12.20\%$, the fitted relationships indicate that the cover concrete retains approximately 85.6% of its original compressive strength, the core concrete about 91.1%, and the PC-bar yield strength about 94.6%. The effect becomes substantially more severe for the concrete cover between 50 and 75 years. At 75 years, the reported FEA retention values are approximately 40.21% for cover concrete, 82.87% for core concrete, and 91.64% for PC-bar yield strength (Refani & Nagao, 2023a).

This divergence is mechanically consistent with the nonuniform corrosion mechanism. Rust expansion develops close to the outer pile surface, leading to interconnected cracking and eventual cover spalling. The confined core is less directly affected and therefore retains a much larger fraction of its initial strength. The original 3D FEA also showed that bond stress at 75 years decreased to about 31.3% of the initial value, confirming that interface deterioration can be more severe than the reduction in PC-bar yield strength. Similar studies on corroded reinforced-concrete members have reported that corrosion morphology and confinement conditions strongly influence the resulting strength and strain degradation (Fernandez et al., 2016; Ma et al., 2022; Liu et al., 2025). Recent marine-pile studies further demonstrate that depth-dependent corrosion and exposure-zone variability can materially alter long-term stiffness, displacement, and service-life predictions, indicating that uniform corrosion assumptions may mask critical local deterioration (Sannasiraj et al., 2025, 2026).

Residual Pile Stiffness

The published stiffness reduction factors provide the first link between material deterioration and global response. Pile A, representing the $\varnothing 700$ mm vertical-pile system, decreases from $\eta = 1.000$ to 0.885 at 50 years and 0.789 at 75 years. Piles B and C maintain a higher stiffness factor at 50 years (0.950) but decline to 0.799 at 75 years. Thus, the two systems converge to a similar residual stiffness level after prolonged exposure even though their intermediate degradation paths differ.

At 75 years, the stiffness-retention difference between the two pile groups is only about one percentage point (0.789 versus 0.799). This result is important because stiffness alone would suggest nearly equivalent residual condition. The subsequent capacity and ductility indicators, however, show that the global systems do not degrade identically. Therefore, stiffness reduction should be used together with force and deformation measures rather than as a stand-alone condition indicator.

Global Pushover Response and Peak Displacement

The nonlinear pushover curves show a systematic reduction in lateral resistance with increasing corrosion degree. At $\psi = 18.56\%$, the reported peak lateral load decreases by approximately 25% for PSW-A and 28% for PSW-B. The larger capacity loss in PSW-B occurs despite its stiffness factor being slightly higher at the same exposure state. The source analysis attributes this behavior to the combined axial-flexural demand attracted by the batter piles, which promotes earlier strain concentration and local stiffness degradation.

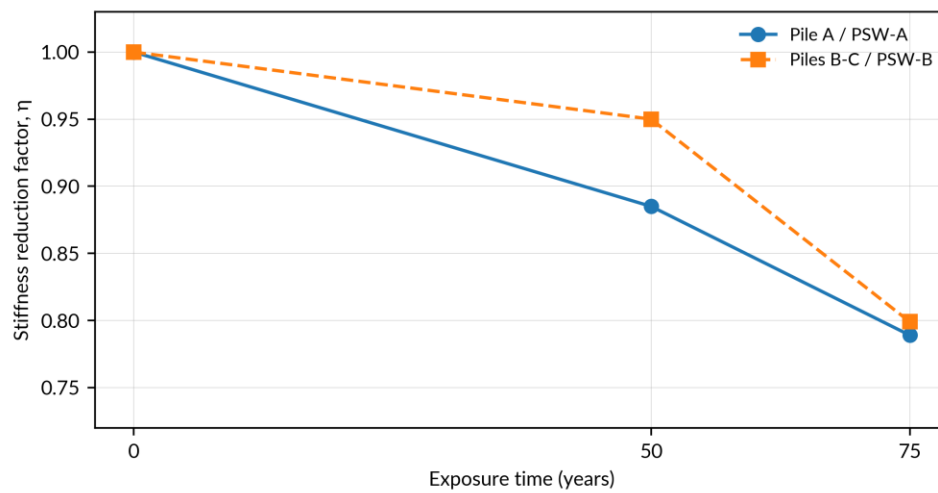


Figure 4. Stiffness reduction factors of the analyzed spun piles at the three exposure states.

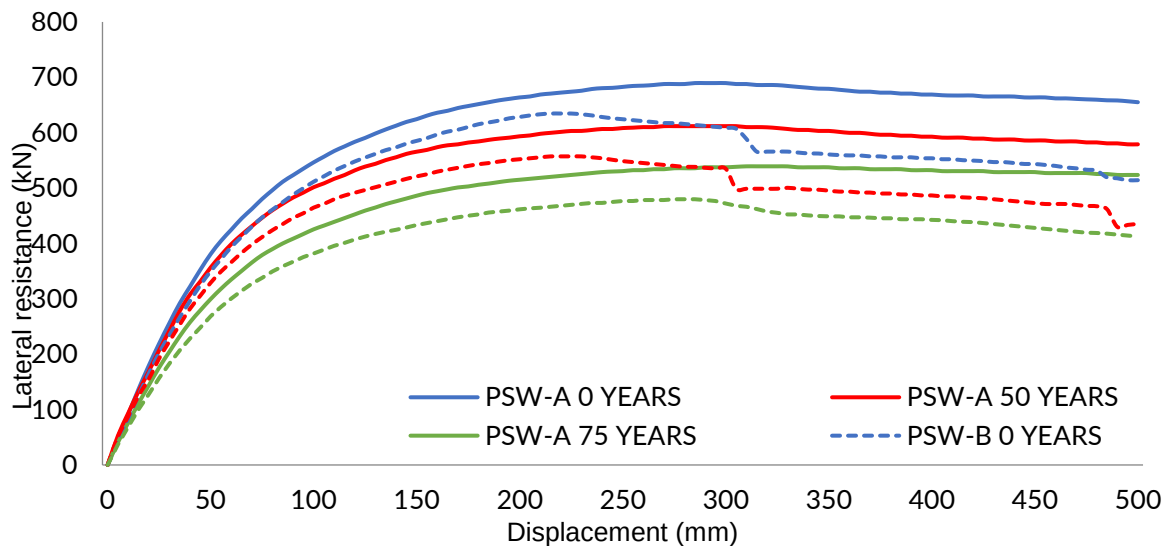


Figure 5. Nonlinear pushover response of PSW-A and PSW-B at 0, 50, and 75 years.

Table 4. Peak-response parameters reported for the two PSW configurations.

System	Exposure (years)	ψ (%)	Δ_{peak} (mm)	PC-bar strain, ϵ_{sp} (mm/mm)	Concrete strain, ϵ_c (mm/mm)
PSW-A	0	0.00	413	0.022	0.023
PSW-A	50	12.20	385	0.020	0.021
PSW-A	75	18.56	372	0.018	0.020
PSW-B	0	0.00	336	0.035	0.025
PSW-B	50	12.20	329	0.032	0.023
PSW-B	75	18.56	324	0.030	0.022

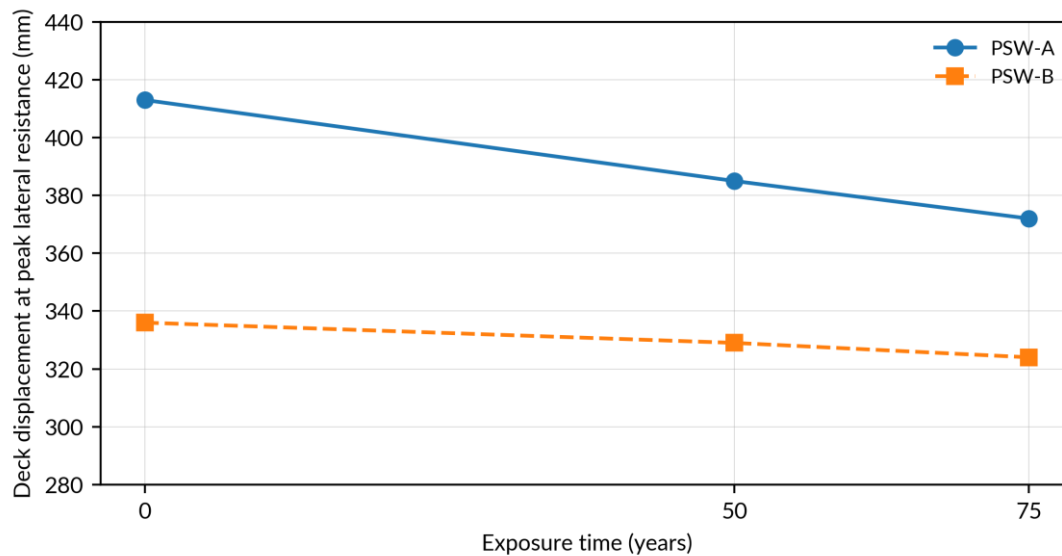


Figure 6. Deck displacement corresponding to peak lateral resistance.

The peak-force displacement decreases from 413 to 372 mm in PSW-A and from 336 to 324 mm in PSW-B over 75 years. The corresponding retention ratios are 0.901 and 0.964, respectively. These relatively high ratios should not be interpreted as evidence that PSW-B remains less damaged. The source strain analysis shows that PSW-B develops higher local strains at smaller displacement because the batter piles introduce combined axial and bending actions. This illustrates why a displacement-only condition assessment may understate deterioration in configurations where load path and local strain concentration change with corrosion.

Ductility Degradation

The ductility ratio was defined in the source analysis as $\mu = \Delta u / \Delta y$ using a yield displacement of 100 mm. PSW-A decreased from $\mu = 4.50$ in the uncorroded condition to 3.00 at 75 years, while PSW-B decreased from 4.70 to 3.10. The corresponding ductility-retention ratios are 0.667 and 0.660. Thus, both systems lose approximately one-third of their initial deformation capacity by the 75-year exposure state.

Table 5. Endpoint ductility and normalized global-response indicators.

System	μ_0	μ_{75}	R_μ	$R_{K,75}$	$R_{V,75}$	$R_{\Delta,75}$
PSW-A	4.50	3.00	0.667	0.789	0.750	0.901
PSW-B	4.70	3.10	0.660	0.799	0.720	0.964

Figure 7 provides the principal new interpretation of the present study. No single indicator ranks the two configurations consistently. PSW-B retains slightly more pile stiffness (0.799 versus 0.789) and a larger fraction of its displacement at peak force (0.964 versus 0.901), yet it retains less lateral capacity (0.720 versus 0.750) and slightly less ductility (0.660 versus 0.667). This mixed response confirms that residual condition cannot be represented reliably by a single scalar parameter without introducing additional assumptions regarding weighting and acceptance thresholds.

From an engineering perspective, the most important finding is the mismatch between apparently favorable displacement or stiffness retention and less favorable capacity or local-strain behavior. Batter piles can limit global lateral displacement because of their axial contribution, but this

mechanism simultaneously increases axial-flexural interaction and promotes strain concentration. Therefore, condition assessment of corroded wharves containing batter piles should include local pile-deck and in-ground hinge demands in addition to deck displacement.

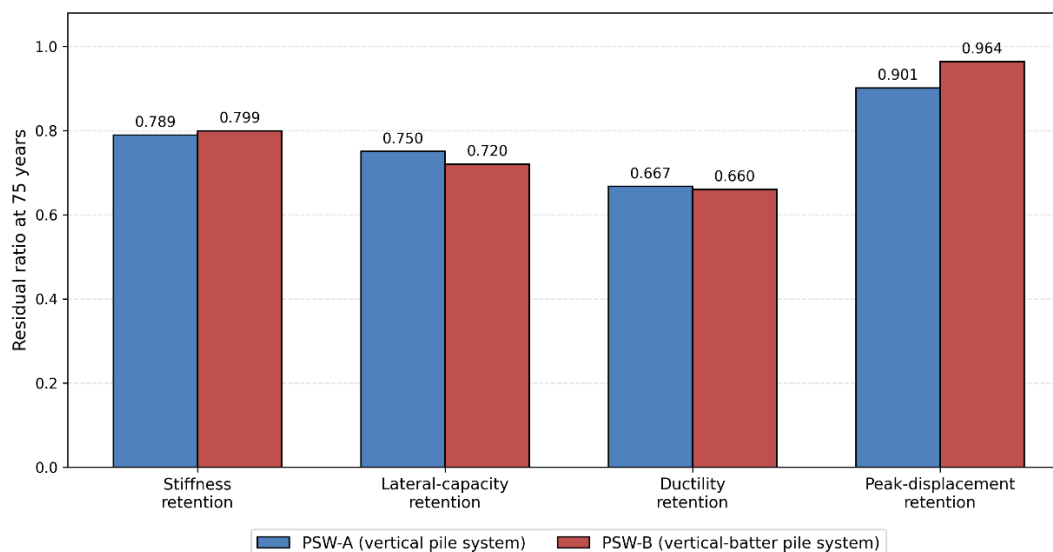


Figure 7. Normalized residual performance indicators at 75 years. Lateral-capacity ratios are based on the reported approximate reductions of 25% and 28%.

The normalized ratios can provide a comparative screening basis for identifying response dimensions that may warrant more detailed inspection or structural assessment. A marked reduction in material strength should trigger targeted inspection of the splash and tidal zones, while reductions in R_K , R_V , R_μ can identify the need for progressively more detailed structural assessment. This interpretation is consistent with recent resilience-oriented wharf studies, which emphasize that aging and corrosion should be translated into condition-, recovery-, and life-cycle-based decision variables rather than being treated only as end-of-life strength reductions (Mirzaeefard, 2026; Zhang et al., 2026). The indicators are intended to organize evidence rather than prescribe intervention thresholds. Any decision on repair, strengthening, or replacement should incorporate site-specific inspection data, measured corrosion, operational loading, geotechnical condition, and applicable port-performance criteria.

Mechanistic Link between Material Degradation and Residual Structural Performance

The results demonstrate a progressive cross-scale deterioration mechanism rather than a set of independent response reductions. Chloride-induced corrosion first produces section loss in the PC bars and expansive corrosion products around the reinforcement. The resulting internal pressure causes cracking and eventual spalling of the cover concrete and reduces the steel-concrete bond. At the 75-year condition ($\psi=18.56\%$), the cover-concrete compressive strength retains only 40.21% of its initial value, whereas the core concrete retains 82.87% and the PC-bar yield strength retains 91.64%. The previous material-level analysis further showed that bond strength decreases to approximately 31.3% of its initial value, indicating that cracking and interface deterioration develop more rapidly than PC-bar strength loss.

These material-level changes reduce the effective flexural stiffness of the spun piles. At 75 years, the normalized stiffness factors decrease to 0.789 for Pile A and 0.799 for Piles B/C. The loss of effective stiffness modifies the force–displacement relationship and promotes earlier nonlinear response. Consequently, peak lateral resistance decreases by approximately 25% for PSW-A and 28% for PSW-B.

The deterioration is also reflected in deformation capacity. The ductility ratio decreases from 4.50 to 3.00 for PSW-A and from 4.70 to 3.10 for PSW-B, corresponding to residual ductility ratios of 0.667 and 0.660, respectively. Thus, approximately one-third of the initial deformation capacity is lost after the modeled 75-year exposure.

The relationship is not purely proportional, however. PSW-B retains slightly greater normalized pile stiffness than PSW-A at 75 years but experiences a larger lateral-capacity reduction. This apparent mismatch is associated with pile configuration. The batter piles provide additional axial resistance that limits global displacement, while simultaneously attracting combined axial and flexural actions. As a result, strain concentration and nonlinear damage can develop earlier despite comparatively favorable global stiffness or peak-displacement retention. Therefore, corrosion-induced deterioration should be interpreted through multiple response dimensions rather than through a single stiffness or displacement parameter.

Limitation of the Study

The present study has several limitations that should be considered when interpreting the results. First, the investigation is based on secondary numerical data obtained from previously developed corrosion and structural-response models; therefore, no new experimental testing or field measurements were conducted. Second, the residual-performance indicators represent normalized comparative measures and should not be interpreted as direct predictions of the remaining capacity of a specific existing wharf. Third, the underlying nonlinear static pushover analysis does not explicitly account for cyclic loading effects, ground-motion duration and frequency content, record-to-record variability, or fully dynamic soil–pile–structure interaction. In addition, soil-induced corrosion and exposure-zone-dependent deterioration were not modeled independently. Consequently, the proposed residual-performance assessment should be regarded as a model-based comparative framework within the investigated corrosion range. Future work should validate the framework using field inspection data, material testing, monitoring records, or laboratory experiments and extend the structural analysis using nonlinear time-history procedures.

CONCLUSION

This study performed a secondary numerical re-analysis to investigate the residual structural performance of two spun pile-supported wharf configurations subjected to long-term corrosion. Previously established material-degradation and nonlinear structural-response data were transformed into normalized indicators representing stiffness retention, lateral-capacity retention, ductility retention, and displacement retention at peak lateral resistance.

At the 75-year corrosion condition ($\psi=18.56\%$), the degradation of material properties was non-uniform. The cover-concrete compressive strength decreased substantially, whereas the core concrete and PC-bar retained larger proportions of their initial strengths. These material-level changes were accompanied by reductions in effective pile stiffness and global structural performance.

For the structural response, the stiffness-retention ratios at 75 years were 0.789 for the PSW-A pile system and 0.799 for the PSW-B piles. The original nonlinear numerical outputs showed approximate lateral-capacity reductions of 25% and 28%, corresponding to residual lateral-capacity ratios of approximately 0.750 and 0.720 for PSW-A and PSW-B, respectively. The ductility ratios decreased from 4.50 to 3.00 for PSW-A and from 4.70 to 3.10 for PSW-B, corresponding to residual ductility ratios of 0.667 and 0.660. Meanwhile, the displacement-at-peak-force ratios were 0.901 for PSW-A and 0.964 for PSW-B.

The comparison demonstrates that corrosion-induced performance degradation cannot be represented adequately by a single structural parameter. PSW-B retained slightly higher normalized stiffness and peak-force displacement but exhibited a larger reduction in lateral capacity and a slightly lower ductility-retention ratio than PSW-A. This difference is associated with the distinct load-transfer mechanisms of the vertical and vertical-batter pile configurations.

The findings should be interpreted within the limitations of the underlying numerical datasets. The proposed indicators provide a normalized basis for comparing deterioration trends but have not yet been validated against field measurements or experimental results and should not be interpreted as direct estimates of the remaining capacity or service life of an existing wharf. Further validation using field or experimental data and nonlinear dynamic analysis is therefore required before the framework is applied for quantitative condition assessment.

REFERENCES

- Cui, Y., Ur Rehman, S., Wang, Z., Cui, Y., Ali, A., & Faisal, M. S. (2025). Seismic fragility and resilience assessment of pile-supported wharves with isolation systems in liquefied soil. *Ocean Engineering*, 340, 122317. <https://doi.org/10.1016/j.oceaneng.2025.122317>
- Darmawan, M. S., Yudoprasetyo, K., Refani, A. N., Rosyidi, M. F., & Irwansyah. (2026). Case study of the effect of soil structure interaction on marine jetty performance subjected to corrosion. *International Journal of GEOMATE*, 30(141), 40–55. <https://doi.org/10.21660/2026.141.5385>
- Feng, Y., & Gao, S. (2022). Seismic fragility analysis of concrete pile-supported wharves based on single-degree-of-freedom model. *SN Applied Sciences*, 4, 248. <https://doi.org/10.1007/s42452-022-05129-2>
- Fernandez, I., Bairán, J. M., & Marí, A. R. (2016). Mechanical model to evaluate steel reinforcement corrosion effects on stress-strain and fatigue curves: Experimental calibration and validation. *Engineering Structures*, 118, 320–333. <https://doi.org/10.1016/j.engstruct.2016.03.055>
- Kumar, S., Sarkar, R., & Nainegali, L. (2026). Seismic fragility of pile groups with batter piles in slope: A three-dimensional finite element investigation. *Probabilistic Engineering Mechanics*, 84, 103937. <https://doi.org/10.1016/j.probengmech.2026.103937>
- Liu, Y., Miao, Z., Jiang, C., & Lu, Y. (2025). Effects of non-uniform rebar corrosion on the seismic behaviour of RC columns. *Engineering Structures*, 328, 119748. <https://doi.org/10.1016/j.engstruct.2025.119748>
- Ma, J., Yu, L., Li, B., & Yu, B. (2022). Stress-strain model for confined concrete in rectangular columns with corroded transverse reinforcement. *Engineering Structures*, 267, 114710. <https://doi.org/10.1016/j.engstruct.2022.114710>
- Michalek, J., & Gago, F. (2024). Service life of pre-tensioned concrete structures in a chloride environment on the example of an aluminium foundry building. *Materials*, 17(12), 2985. <https://doi.org/10.3390/ma17122985>

- Mirzaeefard, H. (2026). Time-dependent seismic resilience assessment of pile-supported wharves under climate-modified chloride-induced corrosion. *Soil Dynamics and Earthquake Engineering*, 210, 110512. <https://doi.org/10.1016/j.soildyn.2026.110512>
- Ou, Y. C., Susanto, Y. T. T., & Roh, H. (2016). Tensile behavior of naturally and artificially corroded steel bars. *Construction and Building Materials*, 103, 93–104. <https://doi.org/10.1016/j.conbuildmat.2015.10.075>
- Refani, A. N., & Nagao, T. (2023a). Corrosion effects on the mechanical properties of spun pile materials. *Applied Sciences*, 13(3), 1507. <https://doi.org/10.3390/app13031507>
- Refani, A. N., & Nagao, T. (2023b). Simplified method for nonlinear seismic response analysis of corroded pile-supported wharf. *Applied Sciences*, 13(19), 10936. <https://doi.org/10.3390/app131910936>
- Refani, A. N., Yudoprasetyo, K., Arkani, M. I., & Dewata, J. V. (2026). Performance-based strain limits for aging spun pile-supported wharves under long-term corrosion and seismic loading. *Civil and Environmental Engineering*. <https://doi.org/10.2478/cee-2027-0007>
- Sannasiraj, R. D. A., Shi, S., Liu, X., Gryllias, K., Vandepitte, D., Chronopoulos, D., & Zhang, L. (2025). A fully coupled depth-dependent corrosion model for reinforced concrete piles under marine environmental conditions. *Construction and Building Materials*, 472, 140795. <https://doi.org/10.1016/j.conbuildmat.2025.140795>
- Sannasiraj, R. D. A., Shi, S., Liu, X., Gryllias, K., Vandepitte, D., Chronopoulos, D., & Zhang, L. (2026). Structural stability and service life assessment of marine RC piles subjected to depth-dependent corrosion under lateral impacts. *Ocean Engineering*, 359, Part 2, 125972. <https://doi.org/10.1016/j.oceaneng.2026.125972>
- Su, L., Wan, H.-P., Lu, J., Ling, X., Elgamal, A., & Arulmoli, A. K. (2021). Seismic performance evaluation of a pile-supported wharf system at two seismic hazard levels. *Ocean Engineering*, 219. <https://doi.org/10.1016/j.oceaneng.2020.108333>
- Xi, X., Yang, S., & Li, C. Q. (2018). A non-uniform corrosion model and meso-scale fracture modelling of concrete. *Cement and Concrete Research*, 108, 87–102. <https://doi.org/10.1016/j.cemconres.2018.03.009>
- Zebua, D., Laia, B., Giawa, J. F. K., & Mendrofa, K. B. (2026). Analysis of the effect of soil classification on displacement and inter-story drift of reinforced concrete buildings. *RESWARA: Jurnal Riset Ilmu Teknik*, 4(3), 398–410. <https://doi.org/10.70716/reswara.v4i3.665>
- Zhang, X., Yang, M., Liu, H., Man, X., Yang, J., & Cui, J. (2026). Seismic resilience assessment of pile-supported wharves in liquefiable sites considering recovery path diversity and failure probability. *Engineering Structures*, 359, 122580. <https://doi.org/10.1016/j.engstruct.2026.122580>
- Zhao, X., Liao, X., Hu, Z., Li, X., Nie, Y., Liu, J., & Xu, Y. (2023). Seismic fragility analysis of steel pipe pile wharves with random pitting corrosion. *Buildings*, 13(10), 2619. <https://doi.org/10.3390/buildings13102619>
- Zhu, W., François, R., Poon, C. S., & Dai, J. G. (2017). Influences of corrosion degree and corrosion morphology on the ductility of steel reinforcement. *Construction and Building Materials*, 148, 297–306. <https://doi.org/10.1016/j.conbuildmat.2017.05.079>