Seismic lateral pile capacity analysis in marine soils: Philippine practices with open-source frameworks

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ABSTRACT

A new extradosed bridge is being constructed in the Philippine province of Pangasinan, supported by concrete drilled piles in a seismically active region. Concerns have been raised regarding its lateral load capacity under seismic loading. The bridge foundation, situated in stratified marine deposits composed of loose sand and soft clay, presents challenges in accurately modelling soil-pile interaction under liquefied conditions. This paper compares the current practice in the Philippines for lateral pile capacities using the COM624P algorithm as the benchmark with a contemporary Python-based framework utilizing the open-source OpenPile package. Various pile geometries with soil-specific p-y curves under static and seismic conditions are evaluated. For seismic conditions involving liquefaction, the analysis compares the current practice of reducing soil strength parameters in affected layers using p-y curves tailored for such conditions. Results indicate agreement between the current practice and OpenPile for sandy marine soils under static and seismic conditions. However, significant differences are observed in the shear profile produced by OpenPile for marine clays under seismic conditions compared to the profile produced by the current practice. These findings highlight the advantages of using an open-source framework for integrating updated methods and research. This study emphasizes the importance of adopting appropriate soil-pile interaction models, particularly for earthquake-induced liquefaction, to ensure accurate assessment of pile capacities for deep foundations in offshore conditions.

1 INTRODUCTION

The construction of new bridges aims to boost the local economy by improving transportation safety and reliability while providing critical support during emergencies. However, designing foundations for bridges in marine environments in seismically active regions presents significant challenges, necessitating robust geotechnical and structural considerations. A new extradosed bridge is set to be constructed in Pangasinan, Philippines, located within 100 km of significant seismic features, including the Manila Trench (M_w 8.0), the East Zambales Fault (M_w 7.4), and the Agno Fault (M_w 6.8) (Japan International Cooperation Agency

[JICA], 2004). Additionally, the bridge piers are situated in a site where marine sands and clays dominate the subsurface conditions. Given these considerations, in addition to historical evidence, liquefaction potential is possible and should be considered in the seismic design of the proposed bridge. The collapse of the Dagupan Bridge during the M_w 7.8 Luzon Earthquake in 1990 highlights the necessity of improving geotechnical design for seismic conditions. Liquefaction-induced loss of soil resistance could critically undermine the stability and lateral capacity of the deep foundations. Furthermore, the current guidelines in the Bridge Seismic Design Standards of the Department of Public Works and Highways [DPWH-BSDS] (2013) implement constant spring values for piles, thus excluding the nonlinear behavior of soils at larger strains, which is critical for addressing liquefaction scenarios effectively.

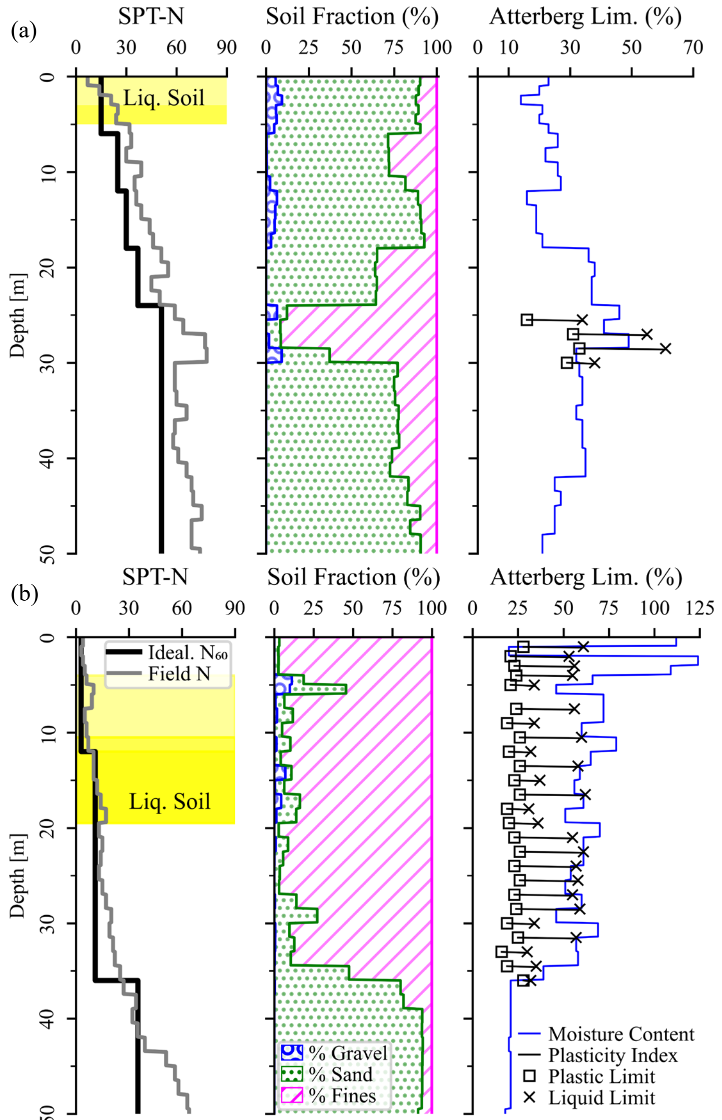
To bridge this design gap for lateral analysis, the COM624P algorithm (Wang & Reese, 1993), as implemented in the AllPile v7.1 commercial software package, may be used to develop p-y curves for specific soil types in lieu of constant spring values. Reduction coefficient D_E is implemented to shear strength parameters to account for shear strength degradation under seismic loading. However, these methods are limited when addressing p-y curves for liquefied soils. As an alternative, this study employs the hybrid p-y curve model developed by Franke and Rollins (2013), which integrates liquefied sand (Reese et al., 2005), and residual shear strength of soils applied to Matlock (1970) soft clay p-y curves. This methodology is implemented in the open-source Python software package OpenPile v0.7.0 (Guillaume, 2023) to assess soil-pile interaction under seismic loading. These liquefied p-y curves are recommended by Brown et al. (2018). Pile head lateral capacity and reaction profiles are compared between AllPile and OpenPile, highlighting their application to routine geotechnical analysis of bridge foundations of two piers.

2 SUBSURFACE CHARACTERIZATION

Site characterization involves identifying the distribution of materials and assessing their physical and engineering properties. Following this, soil layer idealization is used to simplify geometry and material variations for numerical analysis. This process is influenced by computational analysis constraints, including dimensionality and the number of layers.

The project area consists of clays, silts, and sand layers, each exhibiting different consistencies and densities. Two piers of the bridge alignment are selected for foundation analysis, both situated in offshore conditions. Typically, a stable bearing layer of very dense sands with a high degree of compaction/relative density is found below 30 meters in both piers. Pier 1 primarily consists of cohesionless soils with a thin stratum of hard clay, while Pier 3 consists mainly of marine clay soils in the upper half of the profile and a dense layer of clean sands in the lower half. The idealized soil profiles, including measured SPT-N values, particle size distribution (classified using the Unified Soil Classification System), consistency limits, and adopted geotechnical parameters, are presented in Figure 1.

It is important that the reported SPT N-values correspond to field recordings. A donut-hammer manual rope-and-pulley, without sample liners, was used to obtain SPT-N blow counts. Geotechnical parameters, such as those for undrained shear strength (S_u) and friction angle (ϕ) under static conditions are correlated from Bowles (1997) and Look (2014), using energy-corrected SPT N-values (N_{60}).



Depth (m)	Pier 1 Soil Properties
0 - 3 [LIQ.]	S_r=28.6kPa, ε_{50}=0.56%, ϕ=30°, γ_{sat}=17kN/m³, D_e=0.10
3 - 5 [LIQ.]	S_r=36.7kPa, ε_{50}=0.055% ϕ=31°, γ_{sat}=18kN/m³, D_e=0.17
5 - 6 [SAND]	ϕ=31°, γ_{sat}=18kN/m³
6 - 12 [SAND]	ϕ=35°, γ_{sat}=18kN/m³
12 - 18 [SAND]	ϕ=36°, γ_{sat}=18kN/m³
18 - 24 [SAND]	ϕ=37°, γ_{sat}=19kN/m³
24 - 30 [CLAY]	S_u=192kPa, ε_{50}=0.32% γ_{sat}=20kN/m³
30 - 50 [SAND]	ϕ=39°, γ_{sat}=19kN/m³

Depth (m)	Pier 3 Soil Properties
0 - 4 [CLAY]	S_u=12kPa, ε_{50}=2.65%, γ_{sat}=13kN/m³
4 - 10.5 [LIQ.]	S_r=22.1kPa, ε_{50}=0.88%, γ_{sat}=14kN/m³ S_u=18kPa, D_e=0.10
10.5 - 12 [LIQ.]	S_r=15.6kPa, ε_{50}=1.05%, γ_{sat}=14kN/m³ S_u=24kPa, D_e=0.33
12 - 19.5 [LIQ.]	S_r=30.0kPa, ε_{50}=0.49%, γ_{sat}=14kN/m³ S_u=44kPa, D_e=0.33
19.5 - 36 [CLAY]	S_u=70kPa, ε_{50}=0.80%, γ_{sat}=17kN/m
36 - 50 [SAND]	ϕ=37°, γ_{sat}=18kN/m³

Figure 1: (a) Pier 1 and (b) Pier 3 profile visualization and adopted geotechnical parameters.

3 LIQUEFACTION HAZARD

Liquefaction occurs in loose, saturated, cohesionless soils subjected to undrained loading, leading to increased pore water pressure. Under poor drainage conditions, the effective soil strength diminishes as excess pore pressure approaches the confinement pressure, causing the soil to exhibit fluid-like behaviour with near-zero shear resistance (steady-state shear strength). Liquefaction is also manifested in cohesive soils through cyclic softening. Generally, liquefaction causes large strains and material degradation. Capturing soil-pile interactions in seismic conditions requires identifying liquefiable soil layers.

Liquefaction susceptibility was first established using the screening criteria of JRA (2002)/DPWH-BSDS (2013) and Pehlivan (2009). Upon screening, factors of safety (F.S.) against liquefaction are evaluated using the Boulanger and Idriss (2014) simplified approach to identify soil layers that will undergo liquefaction. The peak ground acceleration (PGA) used for liquefaction triggering is set at 0.58g for both piers. The PGA was obtained from a site-specific Seismic Hazard Analysis (SHA) study for the proposed bridge. From the de-aggregated hazard, a magnitude (M_w) of 7.4 was set considering the potential rupture of the East Zambales Fault. The hazard level for PSHA to meet a Level II earthquake performance objective 1,000 years. Figure 1 highlights the liquefiable layers in the profile of SPT-N.

Reduction coefficients (D_E) to shear strength parameters in JRA (2002)/DPWH-BSDS (2013) are based on case histories and testing from the 1995 Great Hanshin Earthquake. D_E factors are obtained as a function of F.S. against liquefaction using the simplified method of Boulanger and Idriss (2014). D_E factors are applied to the shear strength parameters to consider the loss of strength, following the design recommendations in the DPWH-BSDS 2013. These are incorporated into the input shear strength parameters of the COM624P algorithm implemented in AllPile. D_E factors range from 0.10 to 0.17 for Pier 1 and 0.10 to 0.33 for Pier 3 at the liquefied layers as listed in Figure 1.

In contrast, the Franke and Rollins (2013) hybrid p-y curves for liquefied soils are directly implemented in OpenPile. This hybrid p-y curve implements residual shear strength (S_r) and strain parameters (ε_{50}) obtained from clean-sand corrected N-values from Seed and Harder (1990) and Franke and Rollins (2013), respectively. Initial subgrade modulus of reactions (k) is internally implemented in both commercial and open-source software packages but are generally functions of N-values and friction angle ϕ.

It is important to note that the liquefaction analysis in this study is limited to depths of up to 20 meters and water levels near the ground surface, based on available case histories and empirical relationships. A site-specific ground motion response analysis incorporating excess pore water pressure generation, complemented by laboratory testing, would be necessary to verify liquefaction potential at greater depths. Nevertheless, the methods employed in this study are considered adequate for routine geotechnical analysis.

4 PILE CAPACITIES

The axial and lateral pile capacities are calculated using geotechnical properties estimated directly from the in-situ data along with correlated parameters from Section 2 of this paper. The pile geometries selected range from 1.5 m to 2.5 m in diameter and 30 m to 50 m pile embedment lengths. The piles are designed with a concrete compressive strength of 28 MPa. The loading is set at the pile head to determine the axial and lateral capacities. The pile head is positioned at the waterline level, with a fixed support at the head and pin support at the pile end bearing. These pile properties are typically available construction templates in the Philippines.

4.1 Axial Pile Capacity

The requirement to evaluate the axial pile capacity is to consider the p-delta effect on lateral capacities. The factored axial pile capacities are then set as the full axial load. The calculation of axial pile capacities employs the semi-empirical soil mechanics approach following the α-method and β-method for skin friction resistance (q_s) evaluation for cohesive and cohesionless soils, respectively, with SPT-N correlations of drilled shaft load tests and bearing capacity theory for evaluating pile tip resistance (q_p)—consistent with the procedures described in the American Association of State Highways and Transportation Officials [AASHTO] Load Resistance and Factor Design [LRFD] Bridge Design Specifications (2020). Liquefaction-induced downdrag forces are considered by negating the skin friction at the bottom interface of the deepest liquefied layer up to the seabed under seismic conditions (including non-liquefied layers above liquefying zones) and reducing the corresponding shear strength parameters of the liquefied soils by the D_E factor. A limiting skin friction of 120 kPa for clay, 150 kPa for sand, and a tip resistance limit of 3,000 kPa are applied as recommended in Tomlinson and Woodward (2008). Figure 2 illustrates the factored axial pile capacities in hollow bars, with orange representing static conditions (no downdrag) and blue representing seismic conditions (with downdrag) for each pier.

Notice that Pier 1 has greater axial capacities, reflected by the higher skin friction and end-bearing tip resistance. This illustrates that clay profiles (Pier 3) generally have weaker resistances than sand profiles (Pier 1). Likewise, zones of liquefaction negate any positive skin friction. Notably, there is a great difference in axial capacity below and above 35m pile lengths for Pier 3, highlighting the need to reach greater depth resistance to minimize the effects of liquefaction-induced loss of confining support and downdrag.

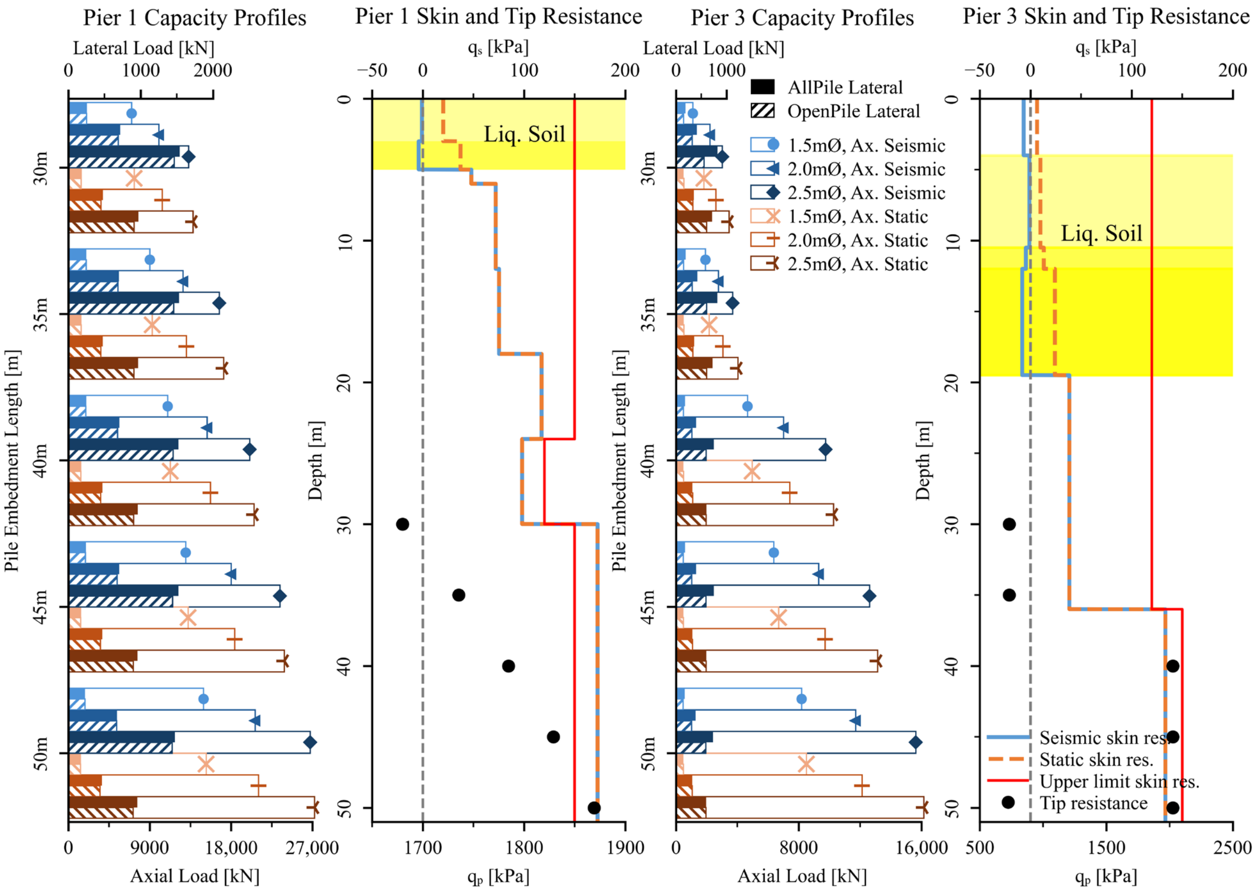


Figure 2: Pier 1 and Pier 3 capacity and axial resistance profiles.

4.2 Lateral Pile Capacity

Lateral pile capacity is analyzed through the Beam-Winkler formulation in a single pile geometry and by utilizing soil-pile interaction p-y springs. This study employs two soil-pile interaction frameworks: (a) the COM624P algorithm (Wang and Reese, 1993) calculated in the commercial software AllPile (CivilTech Inc., 2011) and (b) the American Petroleum Institute [API] (2000) framework through the Python-based package OpenPile (Guillaume, 2023). Much of the empirical relationships of the p-y curves are similar in static conditions between the COM624P algorithm and the API framework, with the latter expanding the sand database from COM624P pile testing for its correlations. The COM624P algorithm accounts for the loss of resistance to earthquake loading under seismic conditions by applying D_E factors to reduce shear strength parameters from their static values. In contrast, the Franke and Rollins (2013) hybrid p-y curves for analysis of liquefied soils are employed through the object-oriented functional form in OpenPile. Deformation limits of 25mm and 50mm are set for the static and seismic conditions, respectively, at the pile head for both piers based on recommendations in Bozozuk (1978). This is to anchor the lateral capacity of the bridge by maintaining operational capacity immediately after a Level II earthquake as its performance objectives set in DPWH-BSDS 2013.

It is also noted that layering correction is implemented in both software packages as recommended in Georgiadis (1983) where the integration of the maximum soil resistance is equal at the soil interfaces by adjusting any depth variables in the empirical equations of each p-y curve not related to overburden stress.

However, layering correction is not implemented to the liquefied p-y curves in OpenPile due to the depth limitation of the pile testing in its database.

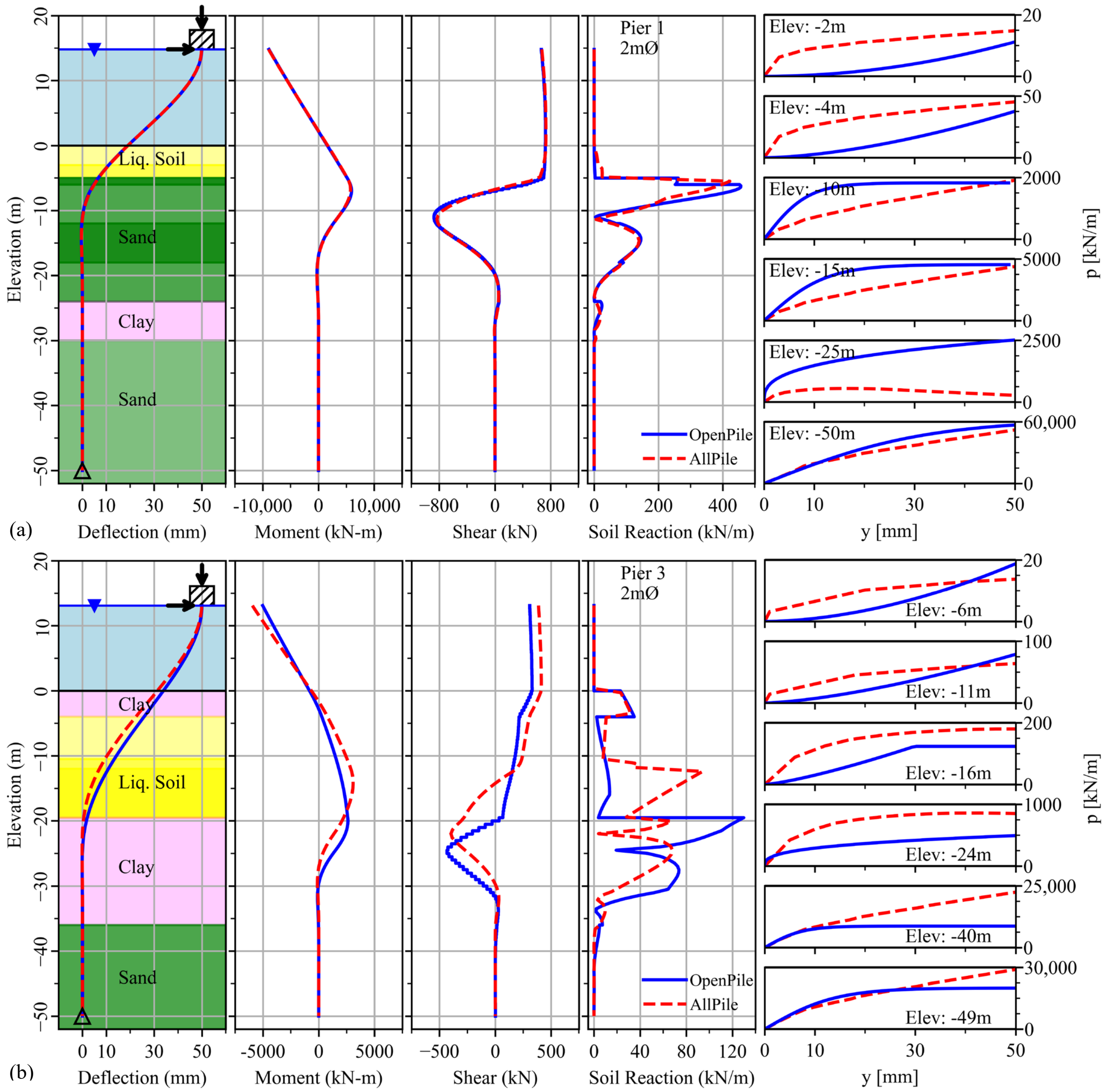


Figure 3: (a) Pier 1 and (b) Pier 3 force profiles and developed p-y curves between AllPile and OpenPile.

Figure 2 illustrates the lateral capacity at the pile head at the corresponding deformation limit for static and seismic conditions. Solid bars indicate the lateral capacity evaluated from AllPile, whereas diagonal hatch bars indicate the lateral capacity from OpenPile. The lateral bars, contained within hollow axial bars corresponding to their axial load, integrate axial loads into lateral analyses to account for p-delta effects. Orange bars indicate static conditions, while blue bars correspond to seismic conditions. In general, lateral capacities are greater under seismic conditions, given they have greater deformation limits. It is observed that there is minimal difference in lateral capacity evaluated from the two software packages for Pier 1 under static and seismic conditions. This is due to the similar soil reaction profiles and p-y curves for sand profiles in both loading conditions. In pier 3, however, there are noticeable differences where OpenPile provides lower lateral pile capacity results under seismic conditions than AllPile.

To illustrate further for seismic conditions, Figure 3 shows the deflection, moment, shear, soil reaction, and developed p-y curves of a 2mØ pile at 50m length at both piers. Notice that for Pier 3, the soil reaction profile under seismic conditions varies greatly than Pier 1. This is due to the differing p-y curves between the COM624P algorithm in AllPile and the API framework in OpenPile. The evaluated soil reaction for Pier 3 at the liquefied zone is much lower at 10m to 20m depths, which reflects the hyperbolic concave upward shape of the hybrid p-y model than the reduced shear strength parameters implemented to the p-y curves in COM624P.

The magnitude of the peak shear stress calculated in OpenPile for Pier 3 is also much higher and its location is shifted lower along the pile compared from AllPile. It is observed that for relatively homogenous soils such as Pier 1, the shear profiles are similar between analysis frameworks than composite soil profiles of sands and clays. The location of maximum shear and moment is also crucial for reinforcement detailing. However, one methodology does not supersede the other, but allows for multiple analyses and considerations into both model situations that can help a designer incorporate either methodology.

5 CONCLUSIONS

This study evaluates the current engineering practice in the Philippines for determining lateral pile capacities using the COM624P algorithm as a benchmark, comparing it with the open-source OpenPile Python package. The analysis highlights how these methods address soil-pile interactions for marine sandy and clayey soils under static and seismic conditions. Results show agreement between the COM624P algorithm implemented in AllPile and the API framework with the Franke and Rollins (2013) hybrid p-y curves implemented in OpenPile for sandy marine soils under both loading conditions. However, significant differences emerge for marine clays under seismic conditions, with OpenPile producing distinct soil reactions and shear profiles. These differences are attributed to the application of p-y curve methods in liquefied p-y curves and D_E-reduced shear strength parameters. OpenPile predicts lower lateral pile capacities than AllPile capacities for liquefiable clay profiles due to reduced soil reactions from liquefied p-y curves.

This study highlights the importance of correctly identifying liquefiable soil layers and using appropriate soil-pile interaction curves, as these factors significantly impact pile capacities for critical infrastructure. OpenPile also demonstrates the potential of open-source tools to democratize pile design calculations, making them accessible for open review and use by a broader engineering community. The findings are limited by the databases from which empirical p-y curves are derived, particularly for pile geometries and depths. The simplified liquefaction analysis, which is constrained to 20-meter depths, reflecting the limited range of existing empirical relationships. Additionally, few studies address liquefaction with high total overburden stress from deep marine sites. Future work should verify OpenPile's predictions with actual pile test data, integrate p-y curves calibrated from new test data, and expand its capabilities to include pile groups, batter angles, porewater pressure generation to identify liquefied soils, and stochastic simulation of geotechnical parameters as a measure of reliability on pile capacities.

The reference data and code are available in this GitHub repository:
https://github.com/emabcede30/openpile/tree/nzsee2025-ema

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