# ANALYSIS AND PRELIMINARY DESIGN OF A TANGENT BORED PILE WALL AS AN ALTERNATIVE TO CONVENTIONAL BREAKWATERS

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## INTRODUCTION

Based on existing construction practices, and the difficulty of sourcing rock armor materials in the Philippines, an alternative to conventional rubble mound breakwaters was considered for a beach resort development in Cebu, Philippines (Figure 1). A tangent bored pile wall, consisting of circular piles placed diametrically along a specified alignment, was analyzed and designed as a breakwater. It relies on pile embedment depth and soil friction for stability, unlike conventional breakwaters which rely on the weight of the armor rocks and the interlocking of individual armor units.



Figure 1 – Project site vicinity

## DESIGN CONCEPT

For simplicity of design, the structure was analyzed as a single bored pile unit (Figure 2). Rocks will be placed leeward of the pile wall to dissipate waves penetrating at the beachfront, and to serve as a softer landscape treatment from the beach.

Typhoon Rai 2021 was considered as the design typhoon as it was deemed as the most recent critical typhoon that traversed the area. To design economically by accounting the difference in coastal hazard loadings (dynamic wave and current pressure), the stretch of the bored pile wall was divided into trunk and head sections (Figure 3). The bored pile wall was designed by setting an individual pile diameter of 1.5 m and a pile crest elevation of 2.7 m above MSL based on the preliminary simulation of Typhoon Rai's storm tide level (STL). Coastal loadings and geotechnical parameters of the soil were used to design the embedment depth, diameter, and reinforcement detailing of the pile. Scour depth due to waves and currents, was also accounted for in the design.
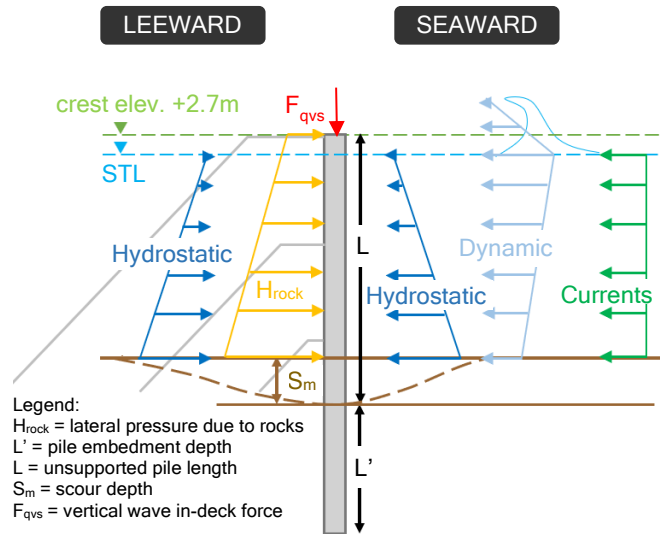


Figure 2 - Free body diagram of tangent bored pile wall

Legend:
$H_{rock}$ = lateral pressure due to rocks
L' = pile embedment depth
L = unsupported pile length
$S_m$ = scour depth
$F_{qvs}$ = vertical wave in-deck force

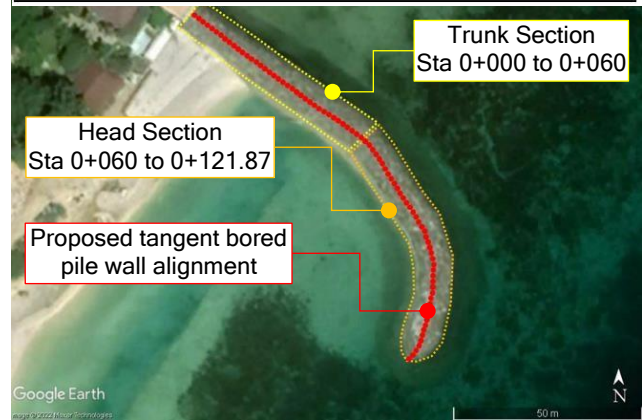| Section | Stationing | Design Significant Wave Height, $H_{s,max}$ (m) | Mean Wave Period, $T_{01}$ (s) | Storm Tide Level, $STL$ (m) | Current Speed, $U$ (m/s) |
|---|---|---|---|---|---|
| Trunk | 0+000 to 0+060 | 2.754 | 8.236 | 3.019 | 0.909 |
| Head | 0+060 to 0+121.87 | 4.319 | 7.437 | 2.654 | 1.785 |



Figure 3 - Trunk and head section stationing and their corresponding design wave parameters

## GOVERNING EQUATIONS

The loadings at the bored piles at the trunk sections were calculated based on the assumptions that the wave loading follows second-order Stokes theory (U.S. Army Corps of Engineers, 2011). Pressure loadings due to waves and currents were both assumed to be acting on a vertical wall.

The following equation gives the dynamic pressure at any distance z below the fluid surface as:

$$p(z) = \rho g \frac{H}{2} \frac{\cosh(2\pi(z+d)/L)}{\cosh(2\pi d/L)} \cos\theta +$$
$$\frac{3}{8}\rho g \frac{\pi H^2}{2} \frac{\tanh(2\pi d/L)}{\sinh^2(2\pi d/L)}\left(\frac{\cosh(4\pi(z+d)/L)}{\cosh(2\pi d/L)} - \frac{1}{3}\right)\cos 2\theta - \quad [1]$$
$$\frac{1}{8}\rho g \frac{\pi H^2}{2} \frac{\tanh(2\pi d/L)}{\sinh^2(2\pi d/L)}(\cosh(4\pi(z+d)/L) - 1)$$

where $\rho$ is the density of seawater (kg/m³), $H$ the design wave height (m), $D$ the design water depth (m), $L$ the design wavelength (m), and $\theta$ the wave phase angle. Drag force caused by currents acting on the bored pile is calculated by the following equation:

$$F_D = \frac{1}{2}C_D\rho U^2 \quad [2]$$

where $F_D$ is the drag force acting on the bored pile in the direction of the current (N), $C_D$ the drag coefficient, and $U$ the depth-averaged current (m/s).

WAVE AND CURRENT LOADINGS

Loadings at Trunk Sections
At these shallower trunk areas, the simulated maximum STL were found to be higher than the pile crest elevation of 2.7 m above MSL, which overtops pile wall section. Hence, the resulting pressure diagrams due to dynamic wave and current forcings, and their equivalent force components are as shown in Figure 4. It should be noted that the hydrostatic loadings are present on both sides of the pile element. In addition to lateral wave and current forces, wave in-deck forces ($F_{vqs}$) acting perpendicularly at the pile tip were considered (McConnell et al, 2004). An eccentricity equivalent to 10% of the pile diameter was assumed to derive the induced moment of the quasi-static vertical in-deck loads.
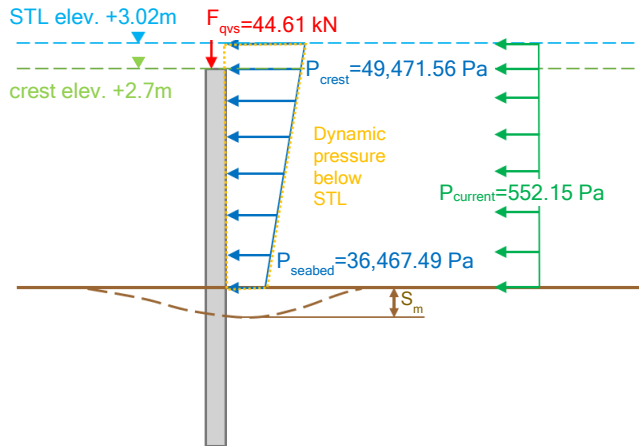


Figure 4 – Pressure diagrams due to dynamic wave and current forcings for the bored piles at trunk section

Loadings at Head Sections
Similar wave and current loading formulations were applied for the design of the bored piles at the head sections (Figure 5). However, for these areas, the STL simulated

were lower than the pile crest elevation (2.65 m above MSL). Hence, the dynamic wave components above the STL were considered in the analysis of loads.
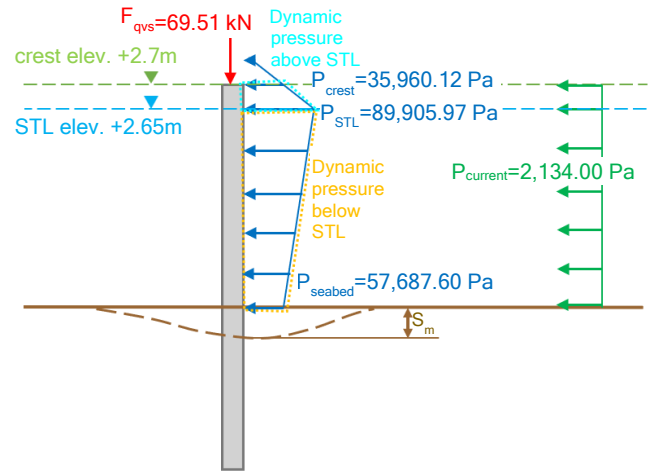


Figure 5 - Pressure diagrams due to dynamic wave and current forcings for the bored piles at head section

MATERIAL PROPERTIES
All materials are designed conforming to American Concrete Institute (ACI) 357R Standards (Guide for Design and Construction of Waterfront and Coastal Concrete Marine Structures) and Unified Facilities Guide Specifications (UFGS) for Marine Concrete. The minimum compressive strength for concrete shall be $f_c' = 35$ MPa (4,000 psi). Cement shall be Type V and sulphate-resistant (or any approved equivalent) in accordance with ASTM C150 (Standard Specification for Portland Cement). Reinforcing steel bars for the breakwater armor units shall be deformed billet steel bars Intermediate Grade 415 (Grade 60).

GEOTECHNICAL PARAMETERS
Geotechnical parameters used in the structural analysis and in determining the required minimum pile embedment depths were based on a geotechnical investigation campaign conducted in the site last July to August 2017. Considering the proximity and similarity in subsurface conditions for the alignment, one of the boreholes was used as reference to idealize the soil vertical profile (Table 1).

Table 1 - Idealized subsurface conditions based on reference borehole (depths reckoned from original seabed)

| Depth | Soil Classification (USCS) | SPT N-Value | Remarks (Relative Condition / Consistency) |
|---|---|---|---|
| 0.0 - 1.0 | Coral Stones | 'coring' | Very Dense |
| 1.0 -13.0 | SP / SM / SP-SM | 6 – 17 | Loose to Medium Dense |
| 13.0 - 15.0 | SP-SM | > 50 | Very Dense |

Liquefaction analysis was also carried out for the geotechnical investigation data, which identified below the Coral Stones layer to a depth of 2.5 m below original seabed as potentially liquefiable. Hence, geotechnical pile capacities from original seabed to 2.5 m below seabed were excluded.
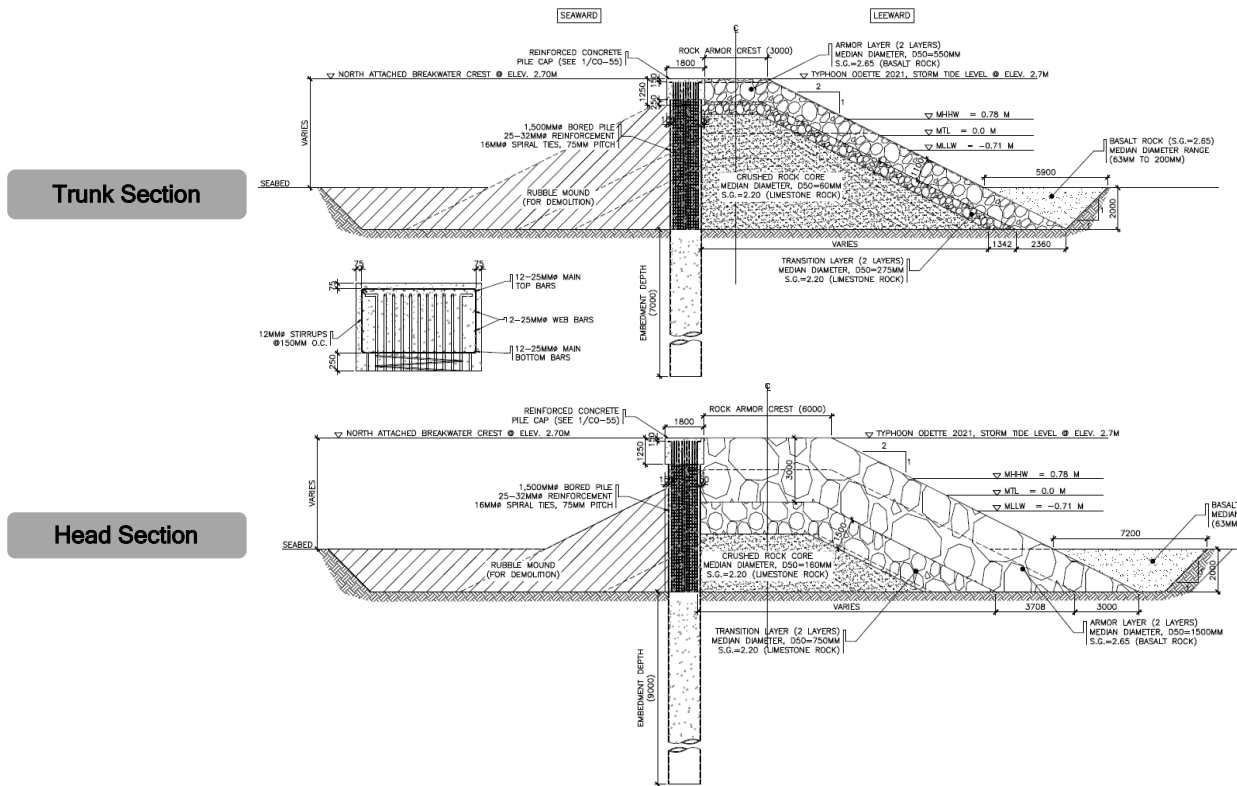
Figure 6 – Reinforced concrete bored pile wall design for NABW trunk and head sections

The recommended allowable axial pile capacities, and moduli of subgrade reactions for the reference borehole are summarized in Table 2. The indicated depths are reckoned from the original seabed. For the purposes of this analysis, only axial capacities starting from an assumed embedment depth of 10 m and below were considered.

Table 2 - Reference borehole geotechnical parameters

| Depth (m) | Allowable axial capacity, $q_{all}$ (kPa) | Modulus of Subgrade Reaction | |
| --- | --- | --- | --- |
| | | Vertical, $k_v$ (kN/m$^3$) | Lateral, $k_h$ (kN/m$^3$) |
| 9-10 | 789 | 94,600 | 25,140 |
| 10-11 | 1,005 | 120,600 | 28,290 |
| 11-12 | 1,155 | 138,600 | 31,430 |

STRUCTURAL ANALYSIS RESULTS

Based on the subsurface geotechnical parameters and the structural analysis of the bored piles at the trunk and head sections, the resulting preliminary design of the bored piles is summarized in Table 3. Minimum structural steel reinforcement was required as per the result of the analysis. Pile caps were supplementary designed to offer a larger area for the distribution of wave-in deck forces onto the piles (Figure 6). It is also found from the structural analysis that the size of the tangent piles is governed by the coastal hazard loadings during a storm, not during an earthquake, among the load combinations.

Table 3 - Structural design of 1.5-m diameter bored piles

| Section | Embedment Length | Reinforcement Details |
| --- | --- | --- |
| Trunk | 7 m below scoured seabed | 25-32 mm $\phi$ main reinforcement bars |
| Head | 9 m below scoured seabed | 16 mm $\phi$ spiral ties at 75 mm pitch |

CONCLUSIONS AND RECOMMENDATIONS

The concept of tangent bored pile wall as coastal protection structure was analyzed and designed based on wave and current loadings from Typhoon Rai simulation using a coupled hydrodynamic and spectral wave model. This can then be considered as an option in lieu of traditional rubble mound breakwaters if conditions will inhibit construction as such and if structural analysis considering coastal loadings and geotechnical parameters are found to yield a safe and economic design. Ideal assumptions were made such as isolating the bored pile wall as a single unit to simplify the analysis. Further methodologies should then be explored, and post-development analysis should be performed to assess the stability and strength of the structure to a typhoon prone area such as the Philippines.

REFEENCES

McConnell, K., Allsop, W. and Cruickshank, I. (2004): Piers, jetties, and related structures exposed to waves: Guidelines for hydraulic loadings, Thomas Telford Publishing, 1 Heron Quay, London.

U.S. Army Corps of Engineers. (2011): Coastal Engineering Manual, Washington, D.C. p. II-1-35.