COASTAL ENGINEERING ANALYSIS AND DESIGN OF A FETCH-LIMITED STORM-TRACKED LACUSTRINE MARINA

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A marina for small crafts is being planned to be built within Caliraya Lake situated at an elevation of 290m above Mean Sea Level (maMSL). Unlike sea-connected water bodies, the water level of Caliraya Lake is largely influenced not by tidal fluctuations, but by the operational water level requirements of the hydroelectric power plant that it caters to. Due to the large difference in the Normal High Water Level (NHWL) and Minimum Operating Level (MOL) of the lake of 2.5m, a floating pontoon marina with guide piles was contemplated to be used. The marina analysis and design approaches implemented in this study considered waves generated by prevailing winds and ship-generated wakes to assess the wave climate and tranquility within the marina. Since the project area is also frequently tracked by typhoons, wind- and pressure-driven storm surges were also used for the vertical siting of the guide piles. Lastly, based on the geographic appearances of the lake shoreline and with the small size of the lake, the fetch limitations resulted to very small wind-generated waves and wind setup considered as wind-driven storm surge components. In comparison to open seas where wind-driven storm surge accounts for approximately 95% of the total storm surge, the wind-driven storm surge components for the potentially critical historical typhoons which traversed within 200-km radius of the project area only generated 10-30% of the total storm surge considered for the vertical siting.

Keywords: Caliraya Lake; floating pontoon marina; ship-generated wakes; typhoons; fetch; storm surge

INTRODUCTION

A marina for small craft vessels is being proposed to be built in Caliraya Lake situated about 290m above Mean Sea Level (maMSL). The lake is primarily used as a reservoir for a pumped-storage hydroelectric power plant catering to Metro Manila and nearby provinces where numerous economic and government industries of the Philippines are located. Other uses of the lake include fishing and aquaculture, along with recreational activities such as swimming, watersports and boating. From Caliraya Lake, water is transported downstream to Laguna Lake (Figure 1) which has an average water surface elevation of 1maMSL. Eventually, Laguna Lake drains out to Manila Bay through Napindan Channel and Pasig River.

The water level of Caliraya Lake is not influenced by tidal fluctuations but instead by operational requirements of the hydroelectric power plant that it supplies. Hydrologic parameters such as rainfall, river runoff and evaporation also affect the lake water level. Moreover, hydraulic structures such as the Caliraya Dam – with crest elevation at +292maMSL – and Caliraya Spillway also help to regulate lake water levels. Based on the hydroelectric power plant operations, the normal high water level (NHWL) requirement of the power plant is published at 288maMSL while the minimum operating level (MOL) is set at 285.5maMSL. In conjunction with site development plan for a lake resort area, a lacustrine marina is contemplated. Due to the large water level fluctuation (2.5m), a floating marina structure instead of a bed-fixed type is proposed. The floating marina will consist of pontoon elements with guide piles to provide lateral stability to the overall structure.

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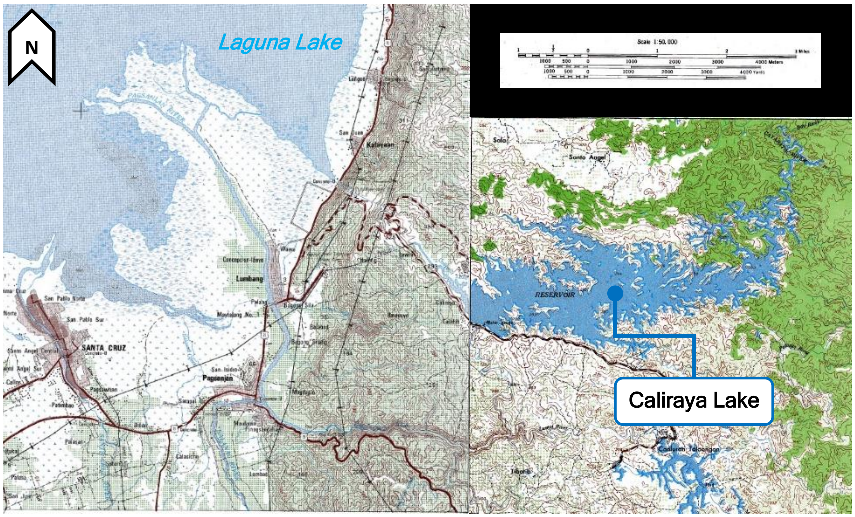

Figure 1. Vicinity and plan view of Caliraya Lake.

This paper presents the analyses and hydraulic design of a lacustrine marina primarily focusing on wave climate and vertical siting requirements. The topic of determining the marina depth to satisfy wave thresholds is also discussed.

MET-OCEAN DATA

Wind Fetch

Wind fetch is the effective stretch of water over which the wind blows at a certain speed and direction as it generates wind waves. For a given wind speed, longer fetch lengths are expected to generate higher wave heights. In open bodies of water, wind fetches can reach 300km and longer. However, due to the project area being located in a lake, and with the very complicated coastline of the lake, the fetch lengths needed to generate wind setup on the project area are also limited. As shown in Table 1, the fetch lengths for critical wind approaches are short, with the longest effective fetch only reaching 793m for winds coming in from the west direction.

Table 1. Effective fetch for multiple wind directions.

Direction	Fetch (m)	Remarks
N	305.7	Exposed
NNE	638.6	High Exposure
NE	384.6	Exposed
ENE	343.7	Exposed
E	178.8	Exposed
W	**792.7**	**Longest Fetch**
WNW	577.1	High Exposure
NW	322.8	Exposed
NNW	213.6	Exposed

Typhoons

The project site is frequented by storms emanating from the Pacific Ocean from the eastern coasts of the Philippines. Using available data from the Japan Meteorological Agency (JMA), historical typhoons from the 1950s to 2018 which tracked within a 200-km search radius from the project site were considered potentially critical.

The criteria in selecting these potentially critical typhoons included maximum wind speed (V_{max}), minimum central pressure (P_c), approximate distance from the project site (D), and whether it tracked north or south of the project coast. Shown in Figure 2 are the potentially critical typhoons which tracked within 200km radius of the project site. Based on these criteria, the typhoons that were considered for the marina analysis and design ranged from 1957 Typhoon Kit up to 2008 Typhoon Fengshen.

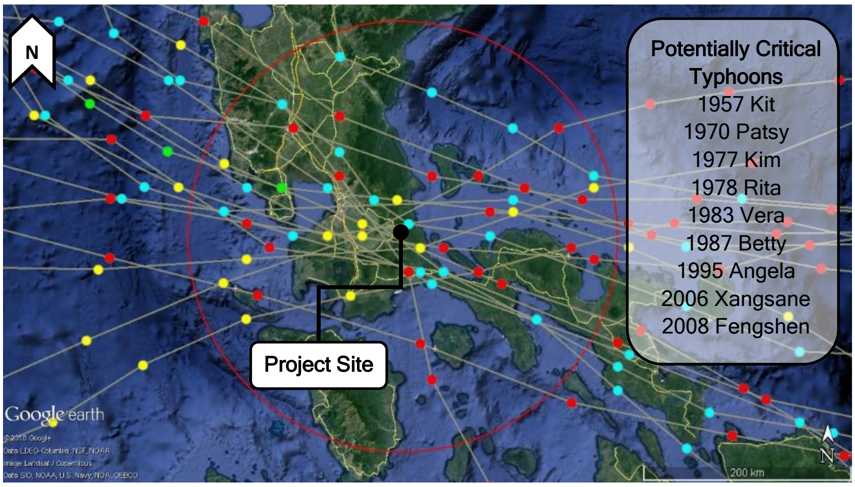

Figure 2. Tracks of historical typhoons that tracked within 200km radius of site from 1950 to 2018.

MARINA DESIGN

The marina has an initial layout based on coastal topography that allows access by 2 entrances. The vertical siting of marina boardwalk is dependent on the storm surge, as it is frequently tracked by typhoons. This study is also aimed at designing this marina for a lake that has a high water level fluctuation. The design conditions of the marina are as follows:

1. the deck of the boardwalk is designed as a floating dock system due to the high range of water level fluctuation (2.5m);
2. the deck structures are designed with floating pontoon elements guided by vertical piles to resist lateral movement;
3. wave conditions at the docks shall not exceed the wave height threshold for boat stability during prevailing, non-storm conditions; and
4. the pontoons shall be placed vertically to withstand the heaving induced by historical typhoons that tracked the project site.

MARINA LAYOUT

Several parameters were considered in the marina design, namely a) vessel draft and maneuvering, b) channel dimensions, c) berth dimensions, d) boat wakes, e) pontoon elements, and f) total storm surge.

The design vessel dimensions, such as beam width (B = 2.5m), length overall (Loa = 6.2m) and full-load draft (d_f = 1.5m), were derived from a list of potential vessels that are expected to use the marina. A limit speed of 4.75m/s was established at entrance locations for egress based on a maximum allowed Froude number of 1.0.

The design vessel's beam and length overall were used to define the turning basin size and the width of the access channel from the main lake into the marina. Berth and finger dimensions for the floating dock were also derived from the design vessel dimensions.

On the other hand, the depth of the channel was obtained based on an assumed minimum wave height within the marina of 0.6m (ASCE, 2012) and an under-keel clearance of 500mm for dredged channels consisting of hard materials as identified in the geotechnical study for the project area (AS, 2001). The interior channel of the marina was permitted to be shallower than the channel and the entrances in consideration of the effects of wave height reduction and wave transformation processes. Figure 3 shows the location of the 2 entrances A and B, the resulting marina layout and the dredged bathymetry. Dredging at entrances was permitted only through Entrance B as can be seen in the figure below. Ingress and egress through Entrance A are permitted only during high lake water level periods.

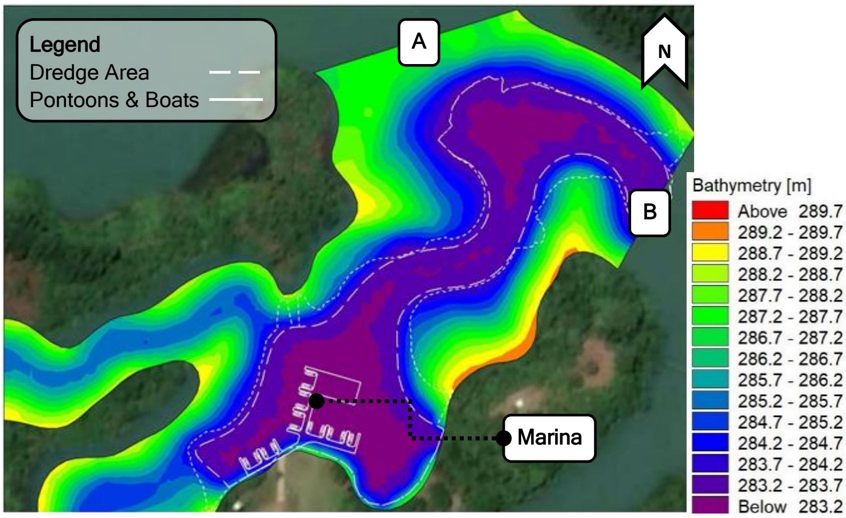

Figure 3. Dredged bathymetry and marina layout.

MARINA DESIGN ANALYSIS

The water depths in the marina during the lowest water level MOL is adequate to sustain the draft of the largest boat expected to enter if some dredging is done. However, due to wave transformations in the shallow interior, local waves may exceed the wave tranquility thresholds if the dredge depth is inadequate. Accordingly, it is necessary to determine an acceptable dredging depth that will satisfy this tranquility requirement. Considering the MOL, the draft and under-keel clearance of the largest boat, the locally dredged lake bed elevation was set at 283.2maMSL, which resulted in a marina depth of 2.3m. The simulative analyses carried out to confirm this dredge depth are discussed in the following.

The vertical siting of the marina boardwalk is based on the floating pontoon concept, namely, that the deck will heave with the effective water level during typhoons. The required height of the marine piles to support the heaving deck and withstand lateral forces is based on the total storm surge induced by the critical historical typhoons that tracked the project lake coast. The next section below discusses this analysis.

Boat Wake Waves

Vessels travelling along a sailing line create ship-generated wakes which cause transverse and diverging waves to form cusp lines of approximately 19°28 from the sailing line as shown in Figure 4. These secondary wave patterns propagate leeward of the vessel and undergo various wave transformations. Aside from waves generated by prevailing winds, ship-generated wakes are also considered in analyzing the wave tranquility of the interior, since marina vessels can tolerate wave heights of usually just 0.25m to 0.3m to be stable when docked at the fingers.

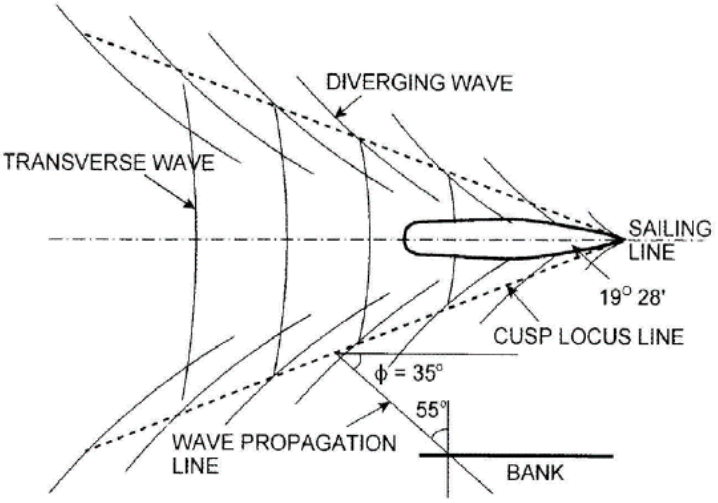

Figure 4. Secondary Wave Pattern (Schiereck, 2001).

Numerical simulations for wave penetration during prevailing wind conditions, as well as due to boat wake waves were carried out using MIKE21 spectral wave model SW. In the simulations, the partial reflectivity of the navigation channel banks is accounted for.

Boat wakes were modeled in SW as wave boundary conditions. The wave heights attributed to secondary waves generated by boat wakes, called transverse waves, were calculated using the limit egress speed, and a directional standard deviation of 19º was used to model the propagation of these secondary waves. The secondary wave height H at interference peaks generated by vessels in inland waterways is calculated from:

$$H = \zeta \cdot h \cdot Fr^4 \qquad (1)$$

where ζ is the ship geometry coefficient ($\zeta = 1.2$), h the channel depth, and Fr the dimensionless Froude number ($Fr \leq 1$) (Schiereck, 2001). The associated wave period T of the secondary wave is expressed as a function of the vessel limit speed v, shown in eq. (2), where g is the gravity acceleration.

$$T = 0.82 \cdot v \cdot \frac{2\pi}{g} \qquad (2)$$

The following boat egress operations were considered as simulation cases for boat wake waves. Table 2 identifies two (2) cases with Case 1 involving a single boat egress at each of the entrances. On the other hand, Case 2 considers a special scenario where there is a sudden boat egress or speeding up at the interior navigation channel of the marina. To allow for passage along both entrances, Case 1 was only simulated during a high-water level scenario which was assumed to be El. 289m. Case 2 is sudden boat egress that considered both high and low water level scenarios. The wave heights and wave periods shown in Table 2 were computed based on equations (1) and (2).

Table 2. Boat wake simulation cases.

Case	Description	Water Level	Wave Height (m)	Wave Period (s)
1	Single boat egress per entrance	El. 289m	2.40 (Entrance A) 1.35 (Entrance B)	2.33 (Entrance A) 2.63 (Entrance B)
2	Single boat egress at interior channel	El. 289m	1.35	2.63
		MOL	2.76	2.50

Within the marina interior, the penetrated wave heights caused by the prevailing winds and ship wakes were checked against the tranquility requirements of the berth and the durability requirements of the pontoon elements.

Storm Surge

Potentially critical typhoons, which tracked within 200-km radius of the project site that likely induced the critical combined wind and pressure storm surges, were considered for the determination of the vertical siting of the marina. The wind setup η_0 representing wind-driven storm surge is calculated via eq. (3),

$$\eta_0 = k \cdot \frac{F}{h} \cdot U^2 \qquad (3)$$

where k is the bay characteristic coefficient (equal to 0.048 from PPA, 2005), F is the fetch length (in km), h the channel depth, and U the typhoon sustained wind speed (in m/s). Pressure-driven storm surge, on the other hand, is equivalent to the water level rise Δh induced by the cyclone's central pressure difference Δp, where γ_w is the unit weight of lake water.

$$\Delta h = \frac{\Delta p}{\gamma_w} \qquad (4)$$

The combined wind and pressure storm surge effects shall be referred to as the total storm surge. The total storm surge is the primary component needed for the vertical siting of the pontoon and guide pile elements of the marina.

RESULTS

Boat wake-induced wave penetration

Due to the limited fetch lengths along the prevailing wind directions, the wave heights caused by prevailing wind conditions were deemed insignificant.

In order to satisfy marina tranquility requirements at the lowest lake levels, the required minimum dredge depth was determined by analyzing the penetrating waves due to ship wakes. The case for a single boat egress at either or both entrances (Case 1) resulted in highest ship-generated wave heights within the marina area of 0.75m (Figure 5). The block arrows marked at the entrances indicate propagation direction of secondary waves from exiting boats. Wave directions are indicated by the thin arrows in the interior.

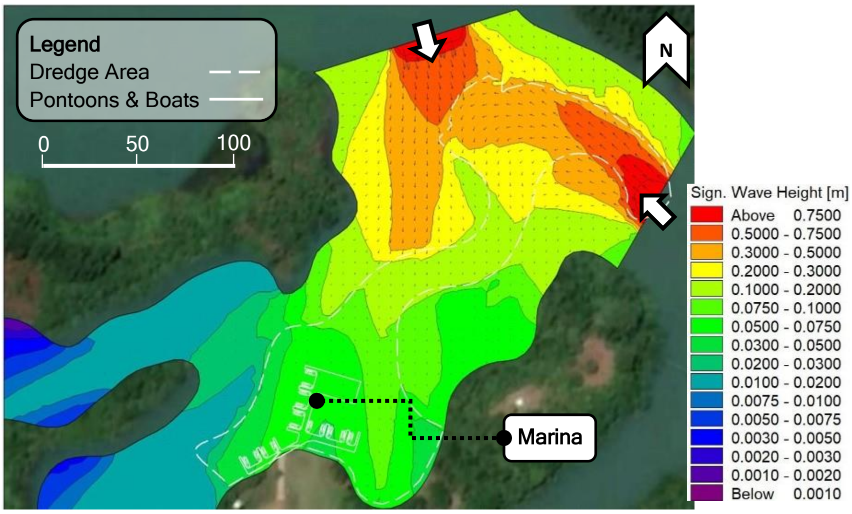

Figure 5. Simulated ship-generated wave heights (Case 1).

A special scenario of marina wave tranquility was also considered where a vessel suddenly goes off at full speed within the interior channels of the marina (Case 2). This resulted in higher maximum interior wave heights of 0.75m during high water levels due to the vessel wake waves (Figure 6), and wave heights of 0.5m during minimum operating level (Figure 7).

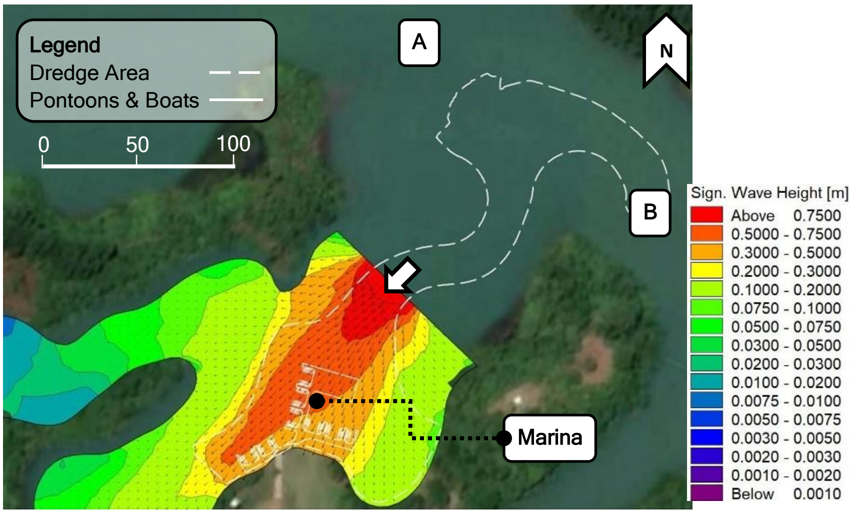

Figure 6. Simulated ship-generated wave heights (Case 2 – El. 289m).

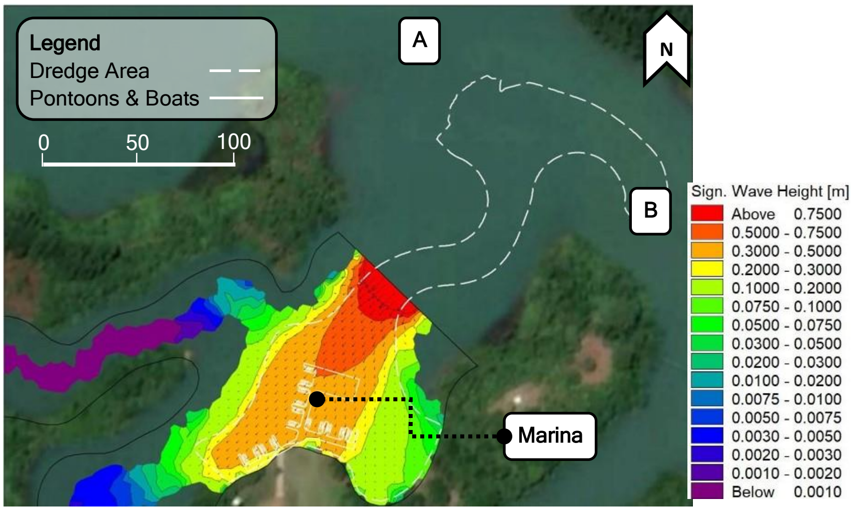

Figure 7. Simulated ship-generated wave heights (Case 2 – MOL).

The results of SW numerical simulation for vessel wakes were then compared to permissible wave heights of commercially-available floating pontoon elements. Under prevailing waves, considered normal operating conditions, typical pontoon elements can withstand wave heights of 1ft (~0.3m), while the threshold for sudden/extreme conditions is 3ft (~0.9m) wave heights. Hence, the simulations showed that the wave climate of the marina for a design dredge depth satisfies both tranquility requirements of the berth and durability requirements of the pontoon elements. Accordingly, a minimum dredging depth of 283.2maMSL was specified for the engineering design of the marina.

Vertical siting of guide piles from storm surge effects

Table 3 summarizes the combined wind- and pressure-driven storm surge values caused by the typhoons which were considered to be potentially critical based on their meteorological characteristics. The most critical typhoon (T. Patsy 1970) resulted in total storm surge of 0.65m. The minimum pile cutoff height as prescribed by design guidelines for floating walkways and pontoons is 2.5m above the high-water level (DTMR, 2015). Since the calculated total storm surge was much lower than the prescribed value, a minimum pile cutoff height of 2.5m above the NHWL was used for the marina design.

Table 3. Combined wind- and pressure-driven storm surge.

Typhoon	η_0 (cm)	Δh (m)	Total storm surge (m)
1957 Kit	2.13	0.11	0.14
1970 Patsy	21.12	0.44	0.65
1977 Kim	6.64	0.23	0.30
1978 Rita	4.25	0.19	0.23
1983 Vera	2.50	0.09	0.11
1987 Betty	1.03	0.15	0.16
1995 Angela	11.96	0.32	0.44
2006 Xangsane	4.02	0.20	0.24
2008 Fengshen	2.72	0.25	0.28

In open bodies of water, it is estimated that pressure-driven storm surge generally accounts for only 5% of the total storm surge (NOAA). However, due to the fetch limitations of Caliraya Lake, pressure-driven storm surge was found to be the more dominant surge component. From the tabulated storm surge results, it can be observed that wind setup, corresponding to wind-driven storm surge, only accounts for 10-30% of total storm surge.

CONCLUSION

From the results of the simulative analyses, the design of the marina, which includes the navigation channel, design dredge depth and pontoon elements, was found to be adequate in terms of the resulting wave climate as caused by boat-generated wakes for various boat egress and water level scenarios.

Moreover, in open bodies of water, it is estimated that pressure-driven storm surge generally accounts for only 5% of the total storm surge (NOAA). However, due to the fetch limitations of Caliraya Lake, pressure-driven storm surge was found to be the more dominant surge component. From the tabulated storm surge results, this component can be as much as 70-90% of the total storm surge.

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