Proceedings of the 7th International Conference on Asian and Pacific Coasts (APAC 2013) Bali, Indonesia, September 24-26, 2013

HIGH WAVE HAZARDS ON A SEAWALL INFRASTRUCTURE ALONG TYPHOON-FREQUENTED MANILA BAY

E.C. Cruz[1], I.A.D. Inocencio [2] and J.C.E.L.Santos[2]

ABSTRACT: Manila Bay is an important host of several physical infrastructures of Metro Manila. During recent strong typhoons, the Roxas Boulevard seawall has been damaged and overtopped by huge waves from Manila Bay. The economic and other costs of the damage have been attributed to the inundation of the road and other infrastructures due to the overtopped seawall. In order to find suitable engineering interventions, it is important to understand and quantify the waves and water levels that may be induced near the seawall by offshore meteorological conditions. Initial results synthesized from the application of a nonlinear wave model are discussed in this paper based on available data of water levels and met-ocean forcing. The simulations indicate the critical importance of historical storm surge values and offshore wave approach conditions in determining the overtopping potential of waves on the seawall. Proposed mitigating solutions are also discussed.

Keywords: Waves, seawall, typhoon, storm surge, manila bay

INTRODUCTION

The Philippine archipelago is known to be in the path of typhoons usually generated in the Pacific Ocean. Its capital, Manila, is situated along Manila Bay (Fig. 1) facing an open sea (West Philippine Sea), which is usually an exit region of typhoons from Pacific Ocean, and is connected to a freshwater body, Laguna lake, by Pasig River. Laguna Lake serves as a large reservoir of floodwaters from upstream catchment of Metro Manila. Manila Bay hosts the North Harbor, which handles the domestic cargoes and passenger transport within the Philippine archipelago, and the South Harbor, which handles all overseas cargoes. A relatively newer terminal, the Manila International Containerized Terminal (MICT), is the dedicated terminal for all containerized materials from international origin. The bay's geographic location, size, shape, and location of the entrance had been seen by ancient planners as ideal features for a city port with natural harbor abutting land formations that fortress the port against natural hazards from the sea.

Manila is not only a political capital but is also an place for many economic, social and recreational activities of Metro Manilans. Along Manila Bay are numerous infrastructures that are crucial to the economic activities in Metro Manila cities, including the various ports of Manila, city drainage outfall system, inter-island marine terminals, tourism areas, sightseeing places, bank buildings, cultural activity buildings, exhibition centers, embassy buildings, hotels, casinos, commercial outlets and retail malls. Manila Bay itself is a tourism magnet with its famous sunset view at dusk. It is also a host to many active and recreational marine activities especially during non-storm season as the bay is protected from surface winds from the northeast. A number of recreational facilities, commercial establishments and sightseeing promenades have been built in the last decade in conjunction with the promotional campaign of the Philippine tourism department. Roxas Boulevard is primarily a radial road connecting the city of Manila to the suburban southern cities. Among the places of interest along the boulevard are the Cultural Center of the Philippines, the Laguna Boardwalk, Manila Hotel, Rizal Park, the Army-Navy Marina, the Harbor Center, Mall of Asia, the Central Bank depository, Star City amusement center, and Baclaran market among others.

Roxas Boulevard is thus important not only as a transportation corridor but also as an economic, social and cultural infrastructure host. In recent years, historical typhoons caused severe inundation of the road and adjacent urban properties due to the overtopping of its seawall by storms from Manila Bay. The frequency of such occurrence necessitated a review of the infrastructure's adequacy for coastal flooding mitigation.

This paper presents a study conducted to understand the problem, assess its scale, and quantify the hazards of high waves in Manila Bay. The study will serve as basis to synthesize the wave and storm surge loadings due to recent strong typhoons, determine the magnitude of the overtopping occurrence, and recommend suitable

[1] Institute of Civil Engineering, University of the Philippines, Diliman, Quezon City 1101, PHILIPPINES
[2] AMH Philippines, Inc., Bahay ng Alumni Building, U.P. Diliman Campus, Diliman, Quezon City 1101, PHILIPPINES

possible solutions to the problem. This paper summarizes the context of the problem, methodology of analysis, results of the preliminary analyses, and possible mitigation alternatives that are being considered.

Fig. 1: Manila Bay location

ROXAS BOULEVARD SEAWALL

Roxas Boulevard (Fig. 2) is an important backbone of Metro Manila's transport infrastructure. As a major component of Metro Manila's road network, it serves as a north-south radial road to the major circumferential roads C-4 and C-6. The boulevard is a local scenery area that visitors from all walks of life enjoy to stroll along the seawall patio or patronizing the stores and dining areas along the road. With 8 lanes and a total length of about 12 km and, it is also a high-capacity road connecting Manila to the suburban southern areas of Cavite.

Fig. 2: Aerial view of Roxas Boulevard

Along the road are reclaimed lands that host numerous commercial developments, while the northern reach extending to Pasig River is protected by a 1.4-km long seawall. This seawall is a gravity-type concrete structure that supports the road backfill, pavement, drainage works and promenade (Fig. 3). The seawall's inland height from grade is about 60 cm affording strollers a view of the famous sunset in Manila Bay. However, with a low elevation from mean sea level and a road setback of just about 20 m from the seawall, Roxas Boulevard is often inundated during strong storms.

Fig. 3 RB seawall before Typhoon Pedring occurrence

EXTREME STORMS

In a typical year, the Philippine archipelago is tracked by 20 typhoons on the average. In recent years however, not only has the proportion of these typhoons that make landfall on Philippine coasts visibly increased, the ones that do reach land have become more intense. In 2012, typhoons that tracked close to the country have become more numerous (Fig. 4). In Manila, the passage of strong typhoons has caused massive coastal flooding when the Roxas Boulevard seawall was overtopped during Typhoon Pedring (international name: Nesat) (23-30 September 2011) and Typhoon Gener (Saola) (July 26 – Aug. 4 2012). Typhoon Pedring made landfall in Quezon province and tracked north of the capital (Fig. 4, bottom, Fig. 5). The entire seawall was battered by huge storm waves that overtopped the structure, causing massive flooding inland (Fig. 6). Inundated facilities include a public hospital, the U.S. embassy, Sofitel hotel on a reclaimed land, and parked vehicles that were flooded to their roofs.

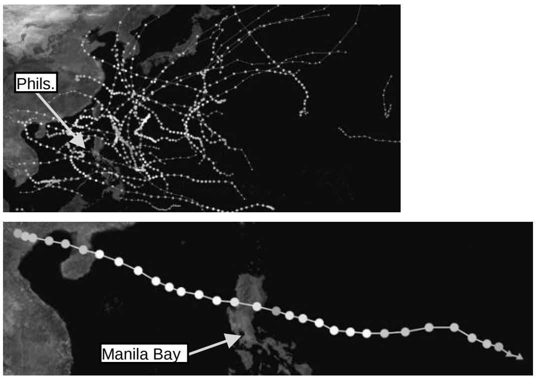

Fig. 4 Tracks of all typhoons in 2012 (top); track of Typhoon Pedring (bottom)

Typhoon Saola did not make landfall but tracked closest southeast of Manila Bay and reinforced the prevailing southwest monsoon, resulting in huge amounts of rainfall in Luzon. The reported casualties reached 51 and government offices and school classes were suspended for 3 days. Traffic was paralyzed due to knee-high flood on the roads that also triggered evacuation of tens of thousands of residents. La Mesa Dam, which supplies water to almost 12 million people, spilled excess water at least 2 times into a major river that passes through suburbs of Quezon City and other Metro Manila cities which are already submerged. Roxas Boulevard was closed to traffic due to the floodwaters, and the seawall experienced huge overtopping waves that carried volumes of debris into inland (Fig. 7).

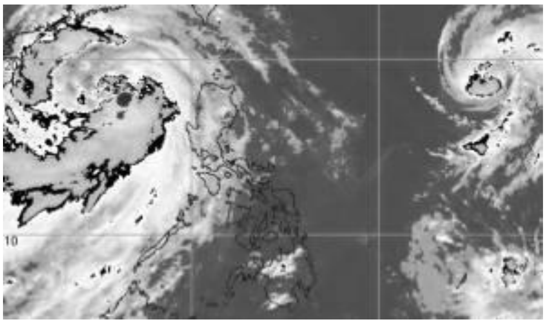

Fig. 5 Satellite image of Typhoon Pedring

Fig. 6 (top) Storm waves overtopping the seawall; (bottom) inundated Roxas Boulevard during T.Pedring

The national public works agency DPWH has collaborated with other related national agencies to come up with initial concepts of mitigating the flooding on Roxas Boulevard. The agency is seriously studying the problem to draw up engineering solutions, including cost estimates and projected completion times, to mitigate the hazard. It is clear to the agency that the overtopping of waves from Manila Bay is the dominant cause of inland flooding. After Typhoon Pedring, the seawall underwent major repairs, including replacing damaged reaches with strengthened gravity-type wall of higher crest (Fig. 8). However, the new structure manifested other visible damages, such as cracking of the seawall capping and some displacements, after TS Gener.

Fig. 7 (left) The seawall overtopped and Roxas Blvd flooded during TS Gener.

Fig. 8 Rehabilitation of RB seawall after T.Pedring

ANALYSIS OF NEARSHORE WAVES

In order to study the action of storm waves on the seawall, knowledge of the local wave field is important. To study the local waves in the nearshore area of the seawall, a model of wave transformation is applied. A model that is valid for unbounded domains on impermeable seabed is a nonlinear Boussinesq-type nonlinear model of wide frequency dispersivity range (Cruz et al., 1997), written as follows:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot \left[\mathbf{u}(h+\eta) \right] = 0 \qquad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} + g\nabla\eta + \frac{h^2}{6}\left(\nabla \cdot \frac{\partial \mathbf{u}}{\partial t}\right) - (\tfrac{1}{2}+\gamma)h\nabla\left(h\nabla\cdot\frac{\partial \mathbf{u}}{\partial t}\right) - \gamma g h \nabla\left[\nabla\cdot(h\nabla\eta)\right] + \mathbf{F}_b + \mathbf{F}_s + \mathbf{F}_w = 0 \qquad (2)$$

where $\eta(x,y,t)$ is the water surface displacement from still water level, $\mathbf{u} = (u,v)$ the depth-averaged fluid particle horizontal velocity vector, (x, y) the horizontal coordinates, t time, $\nabla = (\partial/\partial x, \partial/\partial y)$ the horizontal gradient operator, γ the frequency dispersivity extension factor, and g the gravity acceleration. The last three terms in Eq.(2) incorporate the energy-dissipating effects of wave interactions with the seabed and offshore structures, namely, $\mathbf{F_b}$ the wave-breaking energy-dissipation term, $\mathbf{F_s}$ the structure-induced damping term, and $\mathbf{F_w}$ the bottom friction term. Equations (1) and (2) respectively express the mass continuity law and the principle of momentum conservation of wave motion. The model is valid from relative depths h/L_0, where L_0 is the deepwater wavelength, ranging from the lower limit 0.50 of deep water to the shallow waters in front of the seawall.

Wave action is also influenced by the boundaries with which the waves interact. In the case of seawalls, a time-dependent boundary condition for wave reflection from partially reflective but dissipative seawall faces is enforced. The physical condition is based on the concept of volume flux resolution (Cruz and Aono, 1997). A wave breaking model is incorporated into the governing equations to determine the locations of wave breaking zones and wave energy dissipation rate. The mean sea level uplift due to wave set-up is implicitly incorporated by the application of the above wave model.

Open boundaries are assumed by default at all domain boundaries except on shore boundaries and coastal structures where local waves can run-up or run-down. The input to the model includes the still-water depths $h(x,y)$, initial values of the water surface elevations and velocities, wave conditions at the offshore boundary, and parameters of spatial and time discretization. The model solves for the unknown η and $\mathbf{u}$ at all grid points and time steps, from which the wave heights and other hydrodynamic parameters, such as breaking location and wave-induced currents, are determined. The numerical implementation of the wave model above and its verification are discussed in Cruz et al. (1997) and applications to harbor wave studies are discussed in Cruz (2007).

For preliminary analyses, the wave model has been applied to determine the local waves due to historical typhoons Rita and Nadine. These storms have tracks (Fig. 9) that are quite similar to recent stronger typhoons Pedring and Gener, although their met-ocean characteristics are different. Rita possessed surface winds on water of 41 m/s (148 kph) while Nadine is an entry-level typhoon with 31 m/s (112 kph). Table 1 summarizes the conditions of offshore wave conditions waves in deep water based on the SMB hindcasting method (USACE, 2004). The approach directions of the waves differ, exposing the seawall to potentially most critical scenario of seawall overtopping.

The methodology adopted in this preliminary study assumes virtually stationary conditions of the surface wind, so that a limited computational domain of the bathymetry and coastal morphology of Manila Bay can be used with the wave model. Figure 6 shows the limited bathymetric domain as a portion of the bay plan-form (bottom left), and the known present bathymetry in this domain based on consolidated offshore topographic map (NAMRIA, 1993) and local bathymetric survey from various locations including the nearshore areas of Roxas Boulevard and the reclaimed lands.

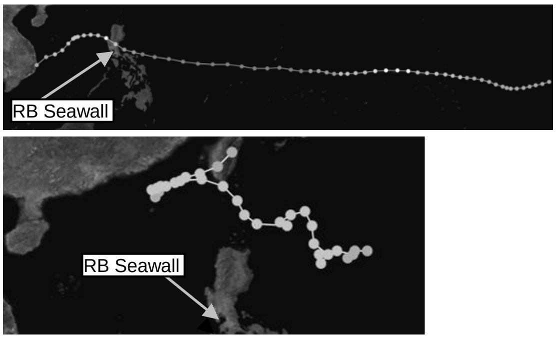

Fig. 9 Tracks of T. Rita and TS Nadine

Table 1 Offshore wave conditions of storms

Cyclone	Date	Direction	Max wind speed (m/s)	Offshore waves	
				height (m)	period (s)
T. Rita	10/26 /1978	W	41	5.6	9.1
TS Nadine	7/24/ 1968	WSW	31	5.0	9.1

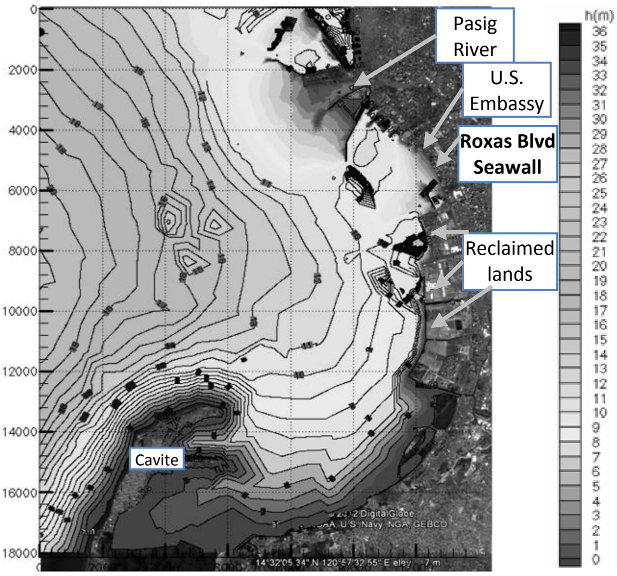

Fig. 10 Coastal morphology and bathymetric data

Astronomic tide data are also input into the wave model. In general, storm tides are the more critical levels for wave overtopping. Table 2 summarizes the measured extreme tide levels (up to year 2008) at the nearest tide station of PAGASA in North Harbor, Manila, which is very close to Roxas Boulevard seawall. The HHWL of +128 cm represents the highest recorded elevation (from mean sea level) of the water surface (NAMRIA 2011), and is assumed to include historical storm surge. This data is used in the following numerical simulations to hindcast the height of nearshore waves generated by historical typhoons.

Table 2 Tide Extreme Levels

MSL	High Water Level	Highest High Water Level
0.00	+0.79 m	+1.28 m

Numerical simulations of the nearshore waves were carried out to hindcast the waves conditions in front of the seawall during these typhoons. In one case, no account is made of the uplifted mean water surface due to storm surge, and in the second case, storm surge is accounted for by using an effective depth equal to the sum of the local mean depth in Fig. 10 and HHWL (+1.28 m), shown in Figs. 11 to 13. Figs. 11 and 12 are for Typhoon Rita where offshore waves approach the seawall from the west (see Table 1). Fig. 11 shows the simulated wave fields assuming there is no storm surge. The left figure is a transient water surface due to waves (red zones are crest lines, blue zones trough lines), while the right figure is the resulting wave heights at steady-state (stationary) wave conditions. Note that red zones indicate wave heights exceeding 6 m while blue zones denote wave-tranquil areas. It is seen that waves continue to shoal, i.e. grow in height, until a depth of about 12 m, then decrease in height due to wave breaking and other wave processes. In front of the seawall, local waves are 1.0 to 1.5 m high. Tranquil areas are found behind the South Harbor- and Army-Navy Breakwaters. There are pockets of wave energy concentrations in front of the reclaimed lands to the south, which appear to have highly reflective boundaries.

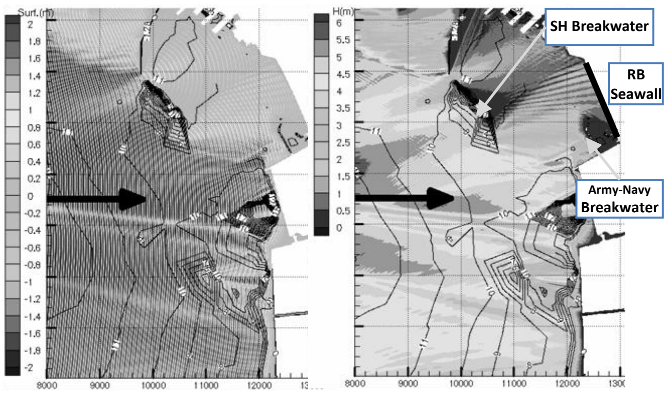

Fig. 11 T.Rita wave simulations without storm surge: transient water surface (left), and wave heights (right)

Fig. 12 has identical conditions with Fig. 11 except that the storm surge of 1.28 m is imposed. It seen that the maximum wave heights are attained in shallower areas, around 11.3 m of mean depth. The degree of wave penetration into the seawall is stronger, resulting in local wave heights of 2 to 2.5 m. The lee regions of the existing breakwaters are still calm wave regions, and wave energy concentrations still exist in front of the reclaimed lands. The water surface reveals that the wave scattering by their walls are less intense than in Fig, 11.

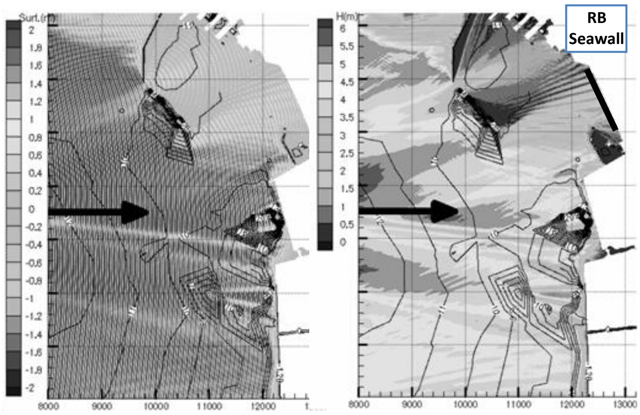

Fig. 12 T.Rita wave simulations with input storm surge: transient water surface (left), and wave heights (right)

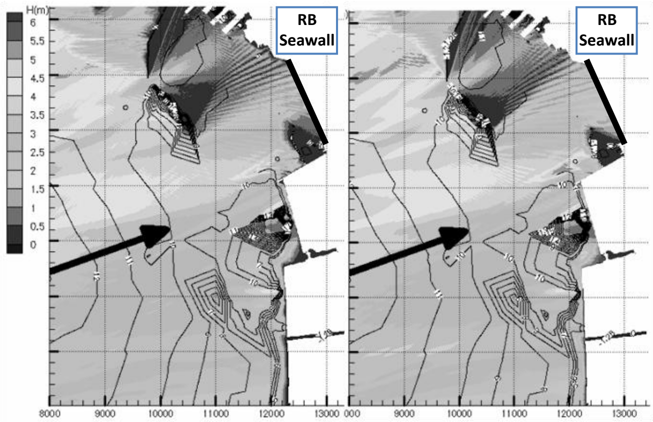

Fig.13 Typhoon Nadine simulated wave heights without storm surge (left) and with input storm surge (right)

Fig. 13 shows the wave heights for Typhoon Nadine, where offshore waves approach from the west southwest. The left figure is for no storm-surge case and right figure, with storm surge. Although the offshore wave height is lower compared to Figs. 11 and 12, the local waves are seen to be higher and more uniformly distributed in front of and along the RB seawall. The wave breaking zones are also seen to have shifted closer to the coast. In both cases of no and with storm surge, the exposure to of the seawall to west southwest offshore waves seems to be the more critical condition for the local waves that overtop the seawall. Consistent with the results shown in Figs. 11 and 12, the uplifted mean water surface due to storm surge leads to higher local waves that would have overtopped the seawall. The areas behind the breakwaters are still calm, but the wave energy concentration zones in front of the reclaimed land have become less prominent.

ENGINEERING SOLUTIONS OF OVERTOPPING

Several agencies have proposed mitigating solutions to the seawall overtopping problem. The Metro Manila Development Authority (MMDA), which is mandated with the operation of flood-control facilities in the metropolis, proposed a “double-wall” seawall, a conceptual sketch of which is shown in Fig. 14 (Boncocan, 2011). The fronting wall is to be designed as a hydraulic seawall to modulate the approaching storm waves.

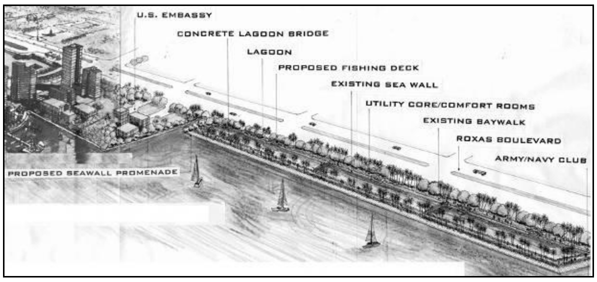

Fig. 14 Sketch of double-wall seawall concept of

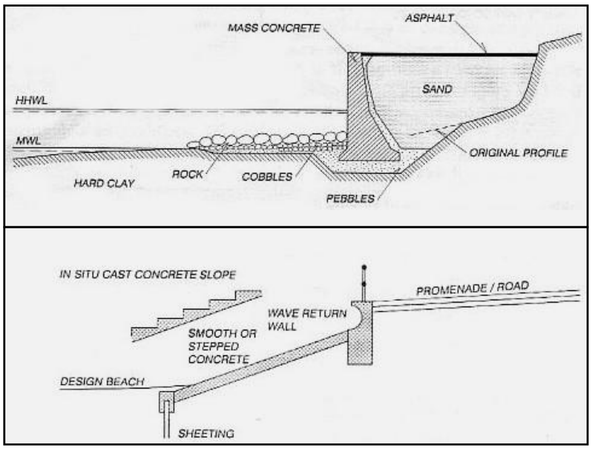

Fig. 15 Example of vertical-front seawall (top) and sloping-front seawalls (bottom) (USACE, 2004)

A professional engineers’ society proposed the use of a stronger gravity-type seawall (Fig. 15, top) with a fronting rock toe to reduce toe scour. The seawall is to be designed as a structure to both support the road and protect it from wave action and overtopping. Another design is a curved-face gravity type seawall to deflect waves back to sea, with a suitably designed parapet wall to deflect sprayed water jet that can cause inland flooding. To reduce the wave height in front of the wall, an inclined face with stepped slope is used (Fig. 15 bottom), as was used in the famous seawall for a beach coast in San Francisco, California (USACE, 1984).

CONLUSIONS

Based on preliminary results of wave simulations for the Roxas Boulevard seawall, the influence of approach direction of offshore waves appear to be critical to the height of local waves along the wall. Wave approach directions that tend to leave a wide exposure of the seawall to wave penetration through the gaps in the protective offshore structures such as breakwaters should be considered.

The input of a historical storm surge value in the model clearly shows that local waves near the seawall tend be significantly higher the case of mean sea level only. This is due to the shoreward migration of the wave breaking zones that cause less intense dissipation of wave energy.

The simulations suggest that a wider range of wave and storm surge conditions must be considered in order to determine the most effective engineering solution to reduce the overtopping potential of waves. It may also be necessary to predict the storm surge itself by employing a suitable storm surge model for translating storms that must be adapted to local meteorology and coastal morphology, i.e archipelagic.

REFERENCES

Boncocan, K. (2011) “MMDA proposes tourist friendly double-layered seawall design for Roxas Blvd”, in http://newsinfo.inquirer.net/70365/

Cruz, E.C. (2007) Wave climate studies in coastal harbors. Proc., 33rd Phil. Inst. Civil Engineers Annual National Convention, Cebu City. WRE 1-9.

Cruz, E.C. and Aono, T. (1997) Simulation of nonlinear wave field induced by partially reflective harbours. Proceedings, Joint 13th Australasian Coastal and Ocean Engineering Conference and 6th Australasian Port and Harbour Conference, Vol 2, 947-952.

Cruz, E.C., M. Isobe, and A. Watanabe (1997) Boussinesq equations for wave transformation over porous beds, Coastal Eng., Vol.30, Nos.1-2, 125-156.

National Mapping and Resource and Information Authority (NAMRIA, 1993) Offshore Topographic Map, Map No. 3130 II

National Mapping and Resource and Information Authority, Coast and Geodetic Survey Division (2011) 2011 Tide and Current Tables, Philippines

United States Army Corps of Engineers (1984) Shore Protection Manual, USACE Waterways Experiment Station, Volume 2.

United States Army Corps of Engineers (2005) Coastal Engineering Manual.