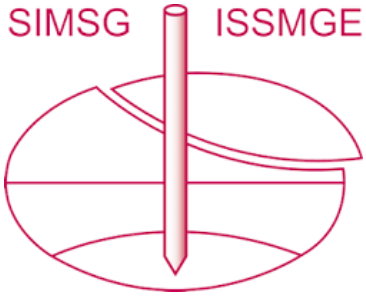
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Geohazard and geotechnical assessment for reclamation projects in the Philippines

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ABSTRACT: Several reclamation projects are proposed in Manila Bay for property development, new ports and airport. The nature and magnitude of the proposed projects require a comprehensive investigation program for reliable site characterization. The conducted geohazard assessment shows that the coastline of Manila Bay Area (MBA) is susceptible to various geologic hazards such as ground motion and liquefaction. This is confirmed in the geotechnical investigation program conducted where thick layers of very soft to soft clays and very loose to loose sands were encountered. The geotechnical investigation involved mainly of Standard Penetration Test (SPT) but limited data from Cone Penetrometer Test (CPT) and Seismic Velocity Logging (SVL) were also available and utilized for the site characterization. This study focused on two regions in the Manila Bay Area. The northern region, located in Bulacan, is characterized with thick layers of compressible soils ranging from 6.0 meters to 27.0 meters. The southern region, located near the City of Manila and Pasay City, is characterized with relatively thinner layers of compressible soils ranging from 1.5 meters to 23.0 meters. The measured shear wave velocities from SVL reveal that the regions can be classified under soil profile types S_E (soft soil profile) and S_D (stiff soil profile).

Keywords: Reclamation; Manila Bay; Site Characterization

1. Introduction

1.1. Study area

Metro Manila, Philippines has been classified as a megacity having a population of 12.8 million according to the 2015 census. As the country's national capital region, it is the political, economic, and cultural center which houses several business centers and government institutions. The metropolitan is considered to be one of the densest cities in Southeast Asia with a density of 42,000 inhabitants per square kilometer as of the October 2018 report of the Philippine Statistics Authority.

The Manila Bay plays a significant role in the economy of Metro Manila being a center for various shipping, industrial, commercial, fishing, and tourism activities. The bay is bounded by Malabon City, Navotas City, City of Manila, Pasay City, Parañaque City and Las Piñas City of Metro Manila and by four provinces: Bataan, Pampanga, Bulacan, and Cavite as shown in Figure 1. According to the published Manila Bay Area Environmental Atlas in September 2015 [1], the coastline of Manila Bay Area (MBA) has a total length of 190 kilometers.

1.2. Reclamation projects in Manila Bay

Land reclamation has been steadily advancing along Manila Bay to cater to the growing metropolitan. The Philippine Reclamation Authority (PRA) [2], established in 1977, has accomplished one reclamation project in Metro Manila: the Bay City Reclamation Project, formerly called Boulevard 2000. By 1986, 660 hectares had been reclaimed, including the site of the Cultural Center of the Philippines.



Figure 1. The Manila Bay, bounded by Bataan, Pampanga, Bulacan, Cavite, and Metro Manila [1]

Currently, there are twelve reclamation projects that are in the application stage while six projects are in the detailed engineering stage [3]. AMH Philippines, Inc. (AMH) has been engaged for site characterization in some of these projects.

Considering the magnitude of the proposed reclamation projects, characterization of the subsurface conditions of the land reclamation sites is one of the major factors in the evaluation of the feasibility of the projects. As such, a comprehensive geotechnical investigation program is usually implemented prior to reclamation.



Figure 2. Reclamation projects in Manila Bay as of February 2019 [3]

2. Geologic and Geohazard Assessment of Manila Bay

2.1. Regional Geology

Metro Manila may be described as being underlain by the Quaternary Diliman Tuff and Recent Deposits (fluviate, lacustrine, paludal, and beach deposits, raised coral reefs, atolls, and beachrock).

The Diliman Tuff, upper member of the Guadalupe Formation, underlies the Guadalupe-Diliman Plateau. The Marikina Basin and the coastal area, on the other hand, is underlain by Recent alluvial deposits.

The Diliman Tuff consists of thick welded tuffs and thinner tuffaceous sandstones, shales, and siltstones. Paleosol layers can be seen within the sequence. The welded tuff and tuffaceous sandstones may be classified as rock material.

The recent deposits overlying the Diliman Tuff consist of alluvial, delta, and coastal deposits consisting of unconsolidated sands, silts, and clays with anticipated low SPT N-values and possible low ground water levels. In general, these sedimentary deposits thicken toward the direction of Manila Bay in the west. Towards Quezon City in the east, the Diliman Tuff is normally encountered at a shallow level, usually within a few meters depth.

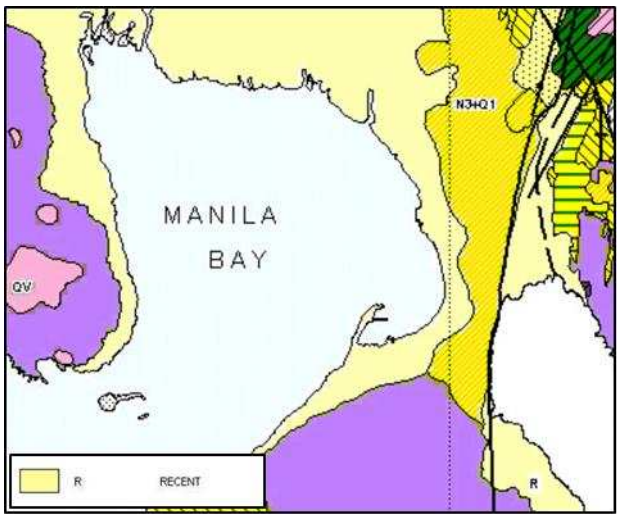


Figure 3. Geologic map of Metro Manila [4]

Table 1. Summary of site stratigraphy

Formation	Age	Lithology
Recent Deposits	Recent	Present-day alluvial, delta and coastal deposits consisting of unconsolidated sands, silts and clays, gravel
Diliman Tuff	Quaternary	Tuffaceous sandstones, shales, siltstones, tuffs, welded tuffs, paleosol

2.2. Tectonic Setting

The Philippine Mobile Belt (PMB) refers to the portion of the Philippine archipelago bounded to the west by the Manila-Negros-Cotabato Trenches (MT-NT-CT) and the east by the Philippine Trench (PT). It is traversed along its entire length by the active 1,200-kilometer long Philippine Fault.

As shown in Figure 4, Manila Bay falls within the PMB. The site is therefore located in a region that is tectonically, seismically, and volcanically active.

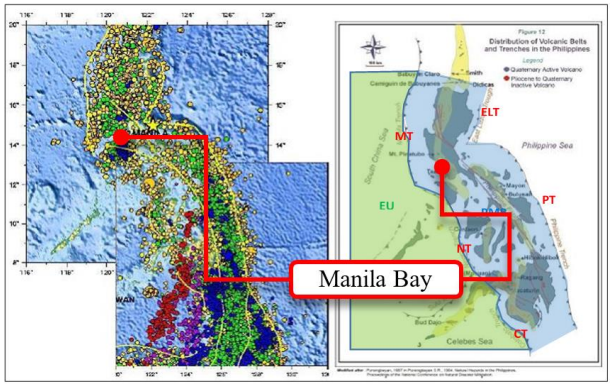


Figure 4. Earthquake epicenter distribution map (left) and tectonic map of the Philippines (right)

2.3. Structures

The major earthquake generators within a 100-kilometer radius of Manila Bay are the Valley Fault System and the Infanta segment of the Philippine Fault.

The NNE-SSW trending Valley Fault System, formerly known as the Marikina Fault, is a system of

active faults that cuts through Metro Manila [5]. It consists of the West Valley Fault and East Valley Fault.

The West Valley Fault extends from the southern Sierra Madre to Tagaytay over a distance of 110 kilometers. A well-defined, east-facing escarpment separates the Guadalupe-Diliman Plateau from the Marikina Basin.

The shorter East Valley Fault extends over a distance of about 30 kilometers. A prominent, west-facing escarpment observed in the San Mateo-Marikina-Antipolo area separates the Antipolo Plateau from the Marikina Valley. The southern termination of the East Valley Fault is poorly defined.

There is no seismic activity that can be definitely related to the Valley Fault System. Nevertheless, several lines of evidence indicate that the Valley Fault System is active:

- young morphological features along the fault
- the presence of a superposed drainage (Pasig River) on the Guadalupe-Diliman plateau which is underlain by the Quaternary Diliman Tuff
- the presence of fault planes in the Quaternary Diliman Tuff
- the presence of deformation in man-made structures (e.g. roads, houses) in the Muntinlupa-Taguig-Pasig area
- deformation in alluvial material in trenches excavated during a paleoseismic study conducted by Daligdig et al. [5] of the Philippine Institute of Volcanology and Seismology (PHIVOLCS)
- carbon-14 dating [5]

The Infanta segment, on the other hand, is also considered as seismically quiet. However, it is associated with a seismic gap which is believed to indicate that stress is accumulating and is not being released. The segment therefore is a candidate site for a major earthquake.

The Infanta segment forms part of the Philippine Fault, a left lateral strike slip fault that is considered to be the most active earthquake generator in the country and has been the source of several devastating earthquakes. The segment north of the Infanta segment, the Digdig Fault, was the source of the July 16, 1990 Northern Luzon earthquake which resulted in a magnitude 7.8 earthquake and a left lateral displacement of 5 to 6 meters over a ground rupture of 90 kilometers. On the other hand, segment south of it, in Bondoc Peninsula, gave rise to the March 17, 1973 Ragay Gulf earthquake of magnitude 7.3 which likewise gave rise to a ground rupture whose length could not be determined since it extended offshore in both directions. However, a left lateral displacement of 3.2 meters was measured.

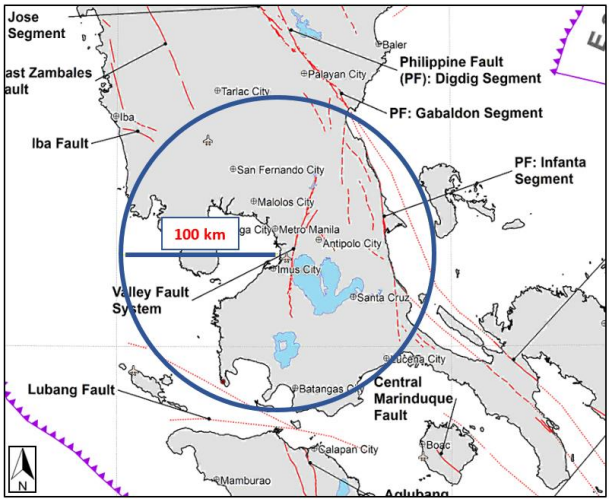


Figure 5. Earthquake generators within 100-kilometer radius from Manila Bay [6]

2.4. Geohazards

The geology and tectonic setting of Manila Bay indicate that the site is susceptible to various geohazards. Of particular importance are the seismic hazards, such as ground motion and liquefaction, anticipated from the movement of the structures within the vicinity of the site.

2.4.1. Ground motion

A search of the USGS NEIC earthquake data base for earthquakes equal to or larger than magnitude 4.0 that occurred from January 1, 1970 to August 31, 2019 within a 100-kilometer radius from Manila Bay yielded a total of 529 events as shown in Figure 6.

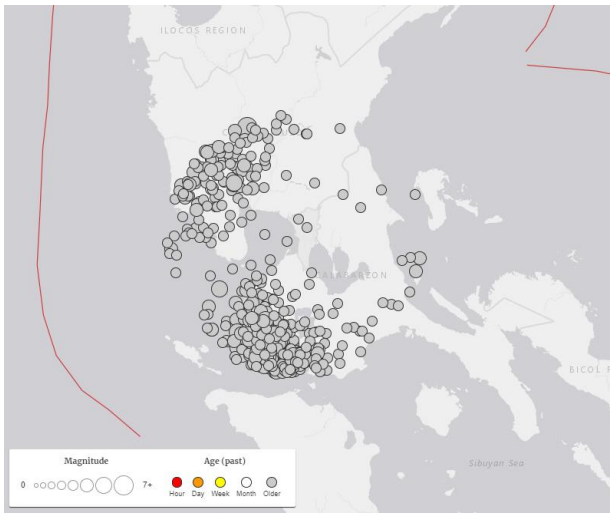


Figure 6. Earthquake distribution within the 100-kilometer radius from Manila Bay

The earthquake magnitude distribution shows that the strongest event has magnitude of 7.0 which occured in 1985 in Tarlac with coordinates 15.344 North latitude, 120.61 East longitude. Four (4) events between magnitudes 6.0 and 6.9 were also recorded in the specified period while the rest of the 524 events are between magnitudes 4.0 and 5.9 as shown in Table 2.

Table 2. Earthquake magnitude distribution within 100-kilometer radius from Manila Bay from January 1970 to August 2019

Magnitude interval	Number of events	Percentage
≥ 7.0	1	0.19
6.0 to 6.9	4	0.76
5.0 to 5.9	93	17.58
4.0 to 4.9	431	81.47
Total	529	100.00

Structures and foundations experience seismic loading in case of major earthquakes along any of the nearby earthquake generators. Ground motion, particularly the peak ground acceleration (PGA), that the site may experience can be estimated using the attenuation model by Fukushima and Tanaka [7] knowing the earthquake magnitude and the distance to the earthquake generator. Correction factors are applied depending on the type of foundation material present: rock, 0.6; hard soil, 0.87; medium soil, 1.07; and soft soil, 1.39.

$$\log PGA = 0.41M - \log(r + 0.032 \times 10^{0.41M}) - 0.0034r + 1.30 \quad (1)$$

where PGA – mean of the peak acceleration from two horizontal components at each site (cm/s^2)
r – shortest distance between the site and fault rupture (km)
M – surface-wave magnitude

A study jointly conducted by the Metro Manila Development Authority (MMDA), Japan International Cooperation Agency (JICA), and PHIVOLCS [8] reports that the West Valley Fault is capable of generating a magnitude 7.2 earthquake. The Philippine Fault, on the other hand, is a major fault capable of generating a magnitude 8.0 earthquake. A magnitude 8.0 earthquake is such a rare event that occurs, on the average, only once a year or once in two years worldwide.

Results show that, without taking foundation conditions into account, the highest uncorrected peak ground acceleration that the site can experience is 0.47g in case a magnitude 7.2 earthquake occurs along the West Valley Fault with epicenter 8.0 kilometers away. On the other hand, ground acceleration estimated for the Infanta Fault is significantly lower as shown in Table 3.

Table 3. Estimated uncorrected peak ground acceleration from the different earthquake generators

Earthquake generator	Magnitude, M	Distance, r (km)	PGA (cm/s^2)
West Valley Fault	7.2	8.0	0.47g
Philippine (Infanta) Fault	8.0	70.5	0.17g

2.4.2. Liquefaction

Liquefaction pertains to a variety of phenomena usually associated with loose, saturated, cohesionless soils subjected to cyclic shear stresses under undrained conditions—as in the case during earthquakes—that results in an increase in pore water pressure and reduction of the effective stress to zero. This results in the fluid behavior and near-zero shear resistance of the soil. The map shown in Figure 7 indicates the varying degrees of liquefaction susceptibility for different areas in Metro Manila.

Evidently, areas cut by the Pasig River delta near Manila Bay are highly susceptible to liquefaction. This is expected since the soil types found in these areas are mostly composed of loose deposits of sedimentary origin. This is also consistent with the geologic map of Metro Manila shown in Figure 3, wherein the areas near Manila Bay are said to be underlain by recent deposits consisting of alluvial, delta, and coastal deposits characterized with low SPT N-values.

On the other end of the Pasig River at its entrance to Laguna de Bay, certain portions of the cities of Taguig, Pateros, and Pasig also have high liquefaction potential. Some areas in Marikina City along Marikina River, are also chacterized as an area of high liquefaction susceptibility.

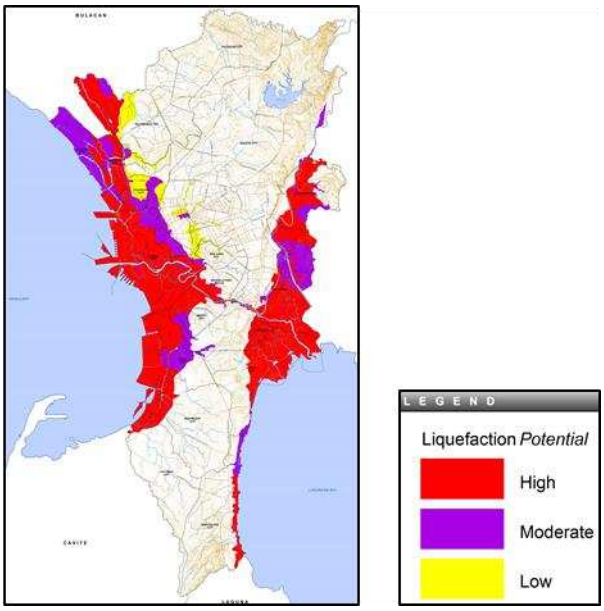


Figure 7. Liquefaction susceptibility map of Metro Manila by PHIVOLCS [9].

2.4.3. Tsunami

Offshore seismic events can sometimes lead to vertical displacements of the seabed, or less often submarine landslides, causing disturbances under the sea. This disturbance then generates ripples in the sea or ocean, resulting to series of massive waves, called tsunamis, spreading across great distances.

Figure 8 presents the PHIVOLCS tsunami hazard map, which is based on inundation heights. The said map used earthquake and tectonic data, topographic, and bathymetry maps to model tsunami waveheight and inundation generated by a magnitude 8.3 earthquake at shallow focal depth associated with the movement of the Manila Trench.

It can be observed from the tsunami hazard map that all of the coastal areas of Metro Manila could be at risk of tsunami destruction, with the cities of Navotas and Malabon having the highest projected inundation heights.

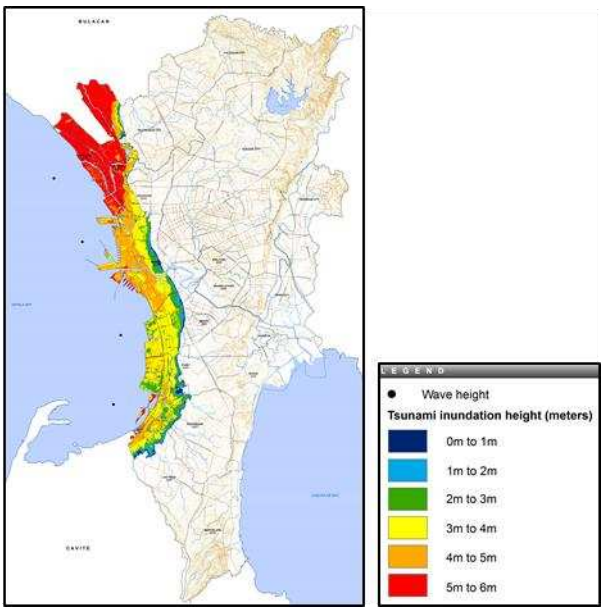


Figure 8. Tsunami hazard map of Metro Manila by PHIVOLCS [9]

2.4.4. Storm surge

Storm surges, such as those that struck Tacloban City, Philippines during typhoon Haiyan in 2013, are strong waves generated by a typhoon. Normally, waves recede after hitting shore. However, during storm surges, waves do not recede. Instead, water piles up and is pushed inland.

The Philippines is frequently visited by tropical cyclones due to its geographical location. With this, the susceptibility of the coastline of the MBA to storm surges in case a typhoon strikes Metro Manila should be assessed. From the Preliminary Storm Surge Hazard Map of Metro Manila by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) [10], some of the port areas and huge areas of Navotas and Bulacan are highly susceptible with inundations from 1.0 meter to 4.0 meter-surges. This is based from tropical storm with maximum winds from 64 kph to 117 kph and typhoon with maximum winds greater than 117 kph.

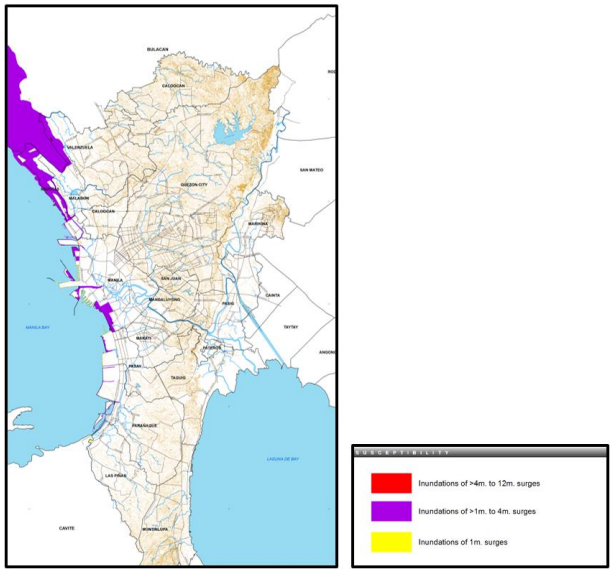


Figure 9. Storm surge hazard map of Metro Manila by PAGASA [10]

3. Results of Geotechnical Investigation

AMH has been involved in some reclamation projects in Manila Bay, particularly in the areas shown in Figure 10. These areas were the focus of the site characterization for this study. The northern area is located in the Municipality of Bulakan in Bulacan province while the southern area is located in the City of Manila and in Pasay City in Metro Manila.

A total of 124 boreholes were drilled in the northern area while 41 boreholes were drilled in the southern area. The geotechnical investigation program involved mainly of Standard Penetration Test (SPT) to estimate the properties of the subsurface. Limited data from Cone Penetrometer Test (CPT) and Seismic Velocity Logging (SVL) were also available and were utilized in this study for the site characterization.

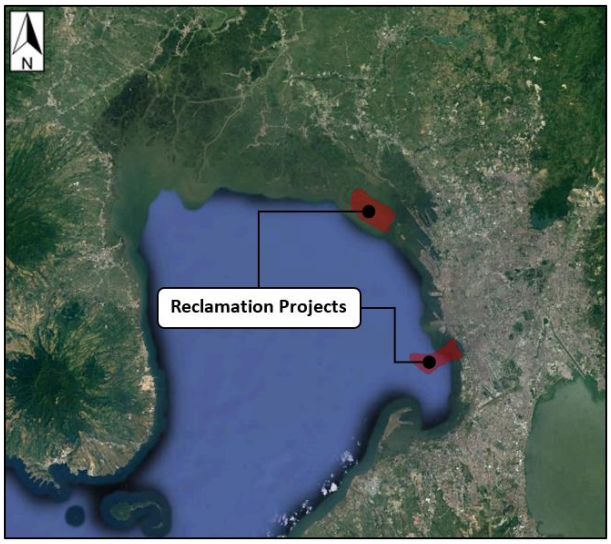


Figure 10. The study focused on the shaded areas due to the limitation of available data

3.1. Standard penetration test

SPT has been a standard test for most of geotechnical investigation programs in the Philippines. Soil parameters, such as cohesion and friction angle, can be estimated from the obtained SPT N-values using correlations.

Borehole data in the northern region show that the site is generally underlain by thick layers of very soft to soft clays and very loose to loose sands ranging from 6.0 meters to 27.0 meters. Beneath these layers, stiff to hard clays and medium dense to very dense sands were encountered until termination of boreholes.

The southern region, on the other hand, is underlain by relatively thinner layers of very soft to soft clays and very loose to loose sands with thickness generally ranging from 1.5 meters to 23.0 meters. Beneath these layers, stiff to hard clays and medium to very dense sands were encountered until termination of boreholes.

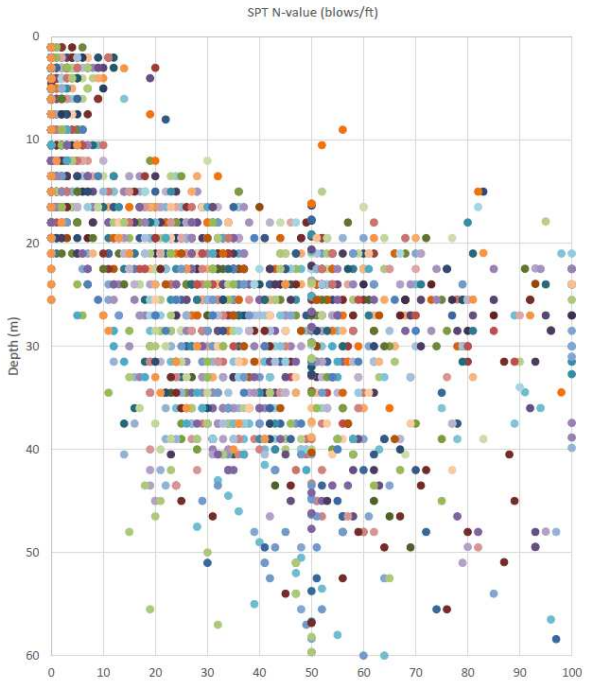


Figure 11. Plot of SPT N-values versus depth for boreholes in the northern area

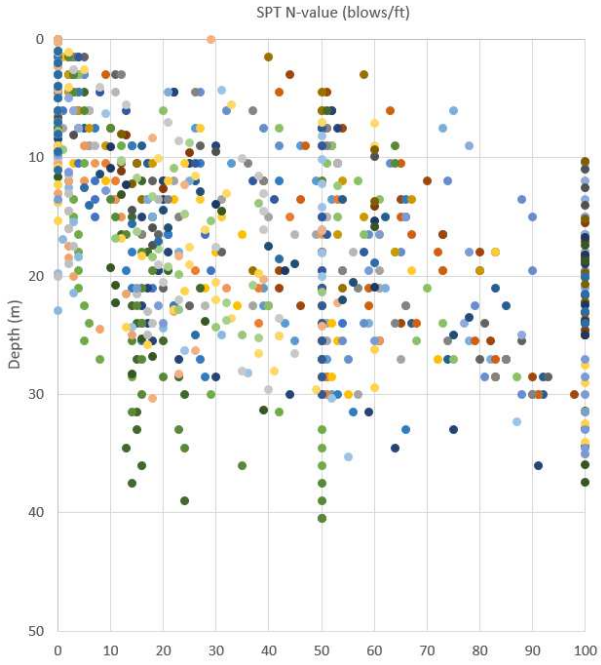


Figure 12. Plot of SPT N-values versus depth for boreholes in the southern area

3.2. Cone penetrometer test

CPT is an in-situ test typically conducted on soft soils to estimate geotechnical parameters by pushing a 1.41 in (35.8 mm)-diameter 60˚ cone through the ground. Unlike SPT, CPT provides continuous data on tip resistance, side friction, and pore pressure with depth. CPT probe may also be equipped with geophones to measure in-situ seismic wave velocities. However, no samples are retrieved when conducting CPT. Interpretation programs are employed to classify the layers based on the behavior of the soil deduced from the obtained measurements. These programs utilize methods suggested by various authors such as the classification chart developed by Robertson in 1990 [11].

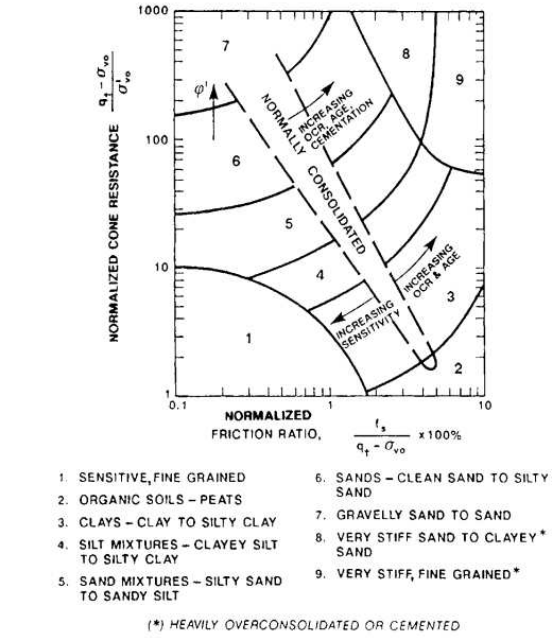


Figure 13. CPT classification chart by Robertson presented in the journal article by Rogers [12]

Results of the CPT conducted in the southern area reveal that the subsurface is underlain by thick layers of very soft to soft soils with low cone resistance and sleeve friction. From the classification chart by Robertson [11], the measured parameters suggest that the upper layers generally consist of clays and sensitive fine grained soils.

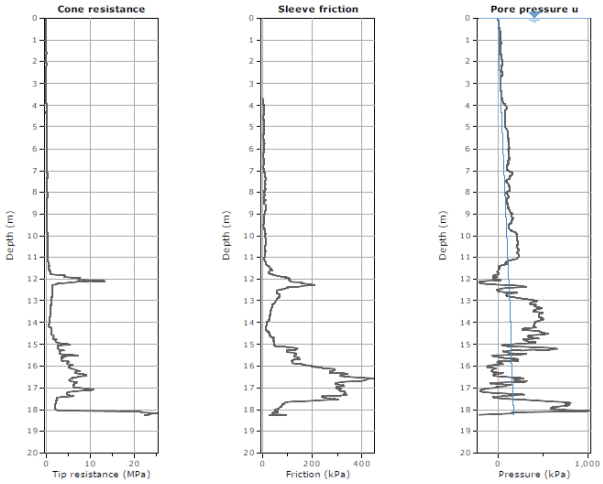


Figure 14. Plot of cone resistance, sleeve friction, and pore pressure against depth for CPT conducted in the southern area

3.3. Seismic velocity logging

Seismic velocity logging (SVL) is an intrusive non-destructive method used to measure seismic wave velocities and determine the physical properties of the underlying soil or rock surrounding a borehole. PS suspension logging, considered to be a relatively new process of measuring in-situ compressional wave (P-wave) and shear wave (S-wave) velocities (V_p and V_s, respectively), was conducted for the geophysical investigation of the proposed reclamation projects. PS

suspension logging is deemed more suitable in offshore surveys compared to conventional seismic surveying methods.

Shear wave velocities measured from SVL tests can be used to estimate the V_{s30} of a site to determine the soil profile type. The National Structural Code of the Philippines (NSCP) 2015 [13] categorizes the different soil profile types based on the average measured shear wave velocity of the top 30 m (V_{s30}), as shown in Table 4. The V_{s30} also serves as a primary input in seismic hazard analysis. Furthermore, these seismic wave velocities can be used to calculate the other elastic material properties of rock and soil, which can be used in Finite Element Modeling and Soil-Structure Interaction.

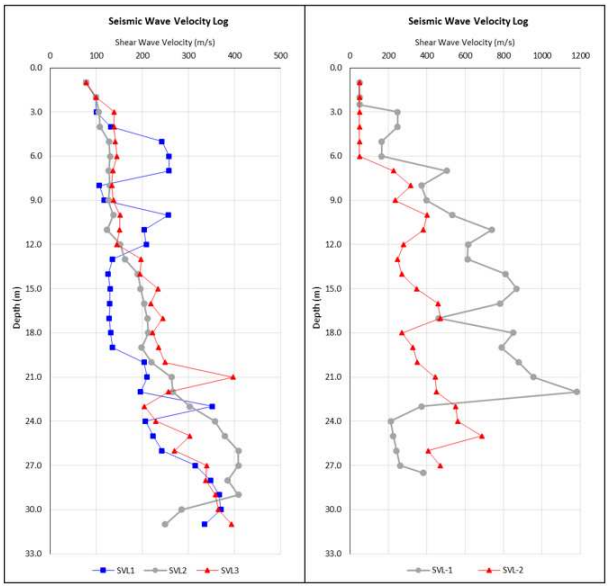


Figure 15. Plot of shear wave velocities against depth for northern area (left) and southern area (right)

Results of the SVL conducted in the northern area show thick layers of soil with low shear wave velocities (V_s < 180 m/s) which extends up to 19.0 meters. These velocities are associated with soft soil type. The computed V_{s30} for the area ranges from 176 m/s to 196 m/s which are borderline values of soft soil and stiff soil profile types as shown in Table 4.

On the other hand, the results of the SVL conducted in the southern area show thinner layers of soil with low shear wave velocities. The same trend is observed in the results of the SPT. The computed V_{s30} are 281.27 m/s for the borehole closer to the shoreline and 163.37 m/s for the borehole farther away from the shoreline. The two values may be associated with stiff soil profile and soft soil profile, respectively.

Table 4. Soil profile types from NSCP [13]

Soil Profile Type	Soil Profile Name / Generic Description	Average Soil Properties for Top 30 m of Soil Profile		
		Shear Wave Velocity, V_{s30} (m/s)	SPT, N-value	Undrained Shear Strength, S_u (kPa)
S_A	Hard Rock	> 1500		
S_B	Rock	760 to 1500		
S_C	Very Dense Soil and Soft Rock	360 to 760	> 50	> 100
S_D	Stiff Soil Profile	180 to 360	15 to 50	50 to 100
S_E	Soft Soil Profile	< 180	< 15	< 50
S_F	Soil Requiring Site-specific Evaluation			

4. Subsurface conditions

The results of the geotechnical and geophysical tests conducted in the Manila Bay are generally consistent with each other. Thick layers of soft soils were encountered both in the northern and southern area during the SPT and CPT which were confirmed with low shear wave velocity readings from the SVL.

It was also apparent, during the geotechnical investigation, that some areas have relatively thicker layers of soft soils compared to others. The northern area may be divided into three zones as shown in Figure 16. The depth of the soft layers for Zone 1 ranges from 21.0 meters to 27.0 meters with an average depth of 26.0 meters. The zone also has the lowest harmonic mean of measured shear wave velocities, which is equivalent to the V_{s30}, equal to 176.69 m/s which corresponds to soil profile type S_E (soft soil profile).

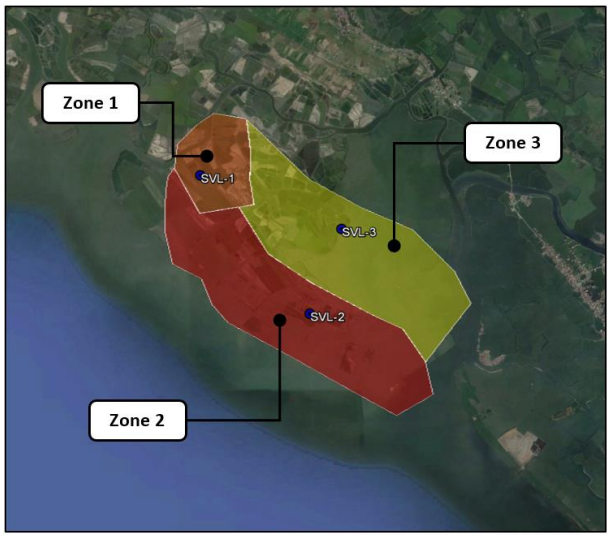


Figure 16. The northern area may be divided into three zones based on the thickness of soft soil layers

On the other hand, the depth of compressible layers for Zone 2 ranges from 16.5 meters to 21.0 meters with an average depth of about 19.0 meters while for Zone 3, the depth of the soft layers ranges from 12.0 meters to 16.5

meters with an average depth of about 15.0 meters. Both zones may be classified under soil profile type S_D (stiff soil profile) with harmonic mean of measured shear wave velocities equal to 183.26 m/s and 195.88 m/s, respectively. However, these values are considered as borderline values and due to the sparsity of the data compared to the total area, the zones may conservatively be classified under soil profile type S_E.

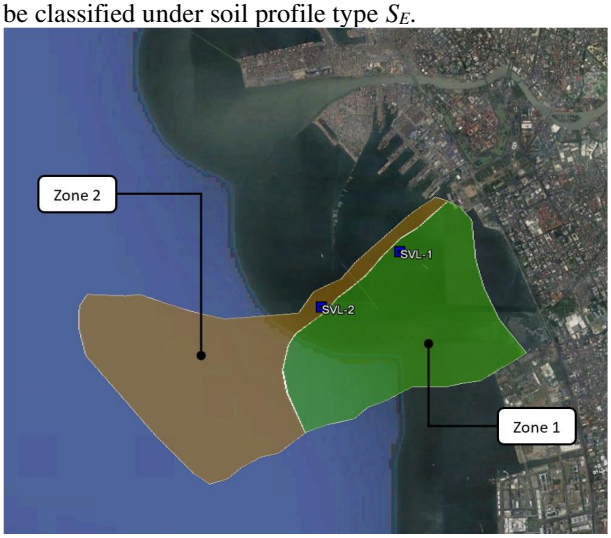


Figure 17. The southern area may be divided into two zones based on the thickness of soft soil layers

The southern area can be divided into two zones as shown in Figure 17. The depth of compressible layers in Zone 1 ranges from 1.5 meters to 9.0 meters with an average depth of 5.76 meters. The zone has the highest harmonic mean of measured shear wave velocities equal to 281.27 m/s which corresponds to soil profile type S_D. This is expected since it has the thinnest layer of soft soils.

The depth of compressible layers in Zone 2 of the southern area ranges from 9.0 meters to 23.0 meters with an average depth of 14.45 meters. The harmonic mean of measured shear wave velocities for the zone is equal to 163.37 m/s which corresponds to soil profile type S_E.

5. Liquefaction analysis using SPT and CPT data

From the assessment of geologic hazards, it was concluded that the sites for the reclamation projects may be susceptible to liquefaction.

A reliable method of assessing liquefaction potential based on SPT data was developed by Seed and Idriss in a series of their publications. Based on their study [14], the following criteria describe soils with liquefaction potential:

- SPT N-value < 10
- D_{50} is between 0.02 mm to 2.0 mm
- Saturated soil material or below the water table
- Non-plastic fines (cohesionless)
- Proximity to a source capable of generating ground shaking

Considering these criteria and the results of the soil investigation, majority of the study area were assesssed for susceptibility to liquefaction.

Liquefaction analysis considering SPT data was undertaken using LiqSVs software. This software implements the most commonly used calculation methods such as those recommended by the National Center for Earthquake Engineering Research (NCEER) and by Boulanger and Idriss.

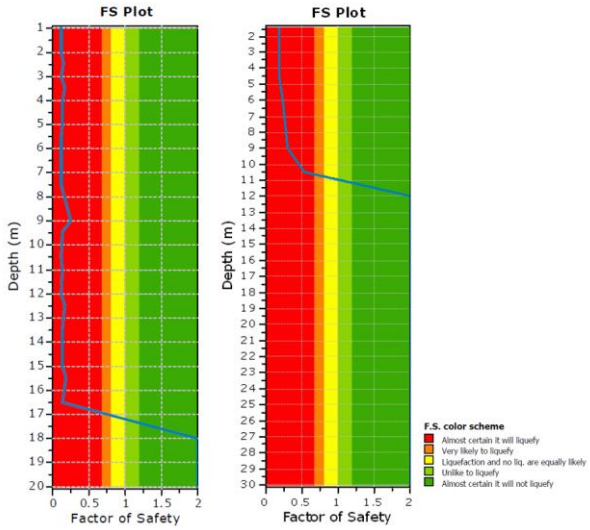


Figure 18. Plot of Factor of Safety (FS) for sample borehole from the northern area (left) and the southern area (right) using LiqSVs

Liquefaction analysis was also done on the available CPT data using CLiq software. The results show that the lower depths, from 15.0 meters to 18.0 meters are most prone to liquefaction.

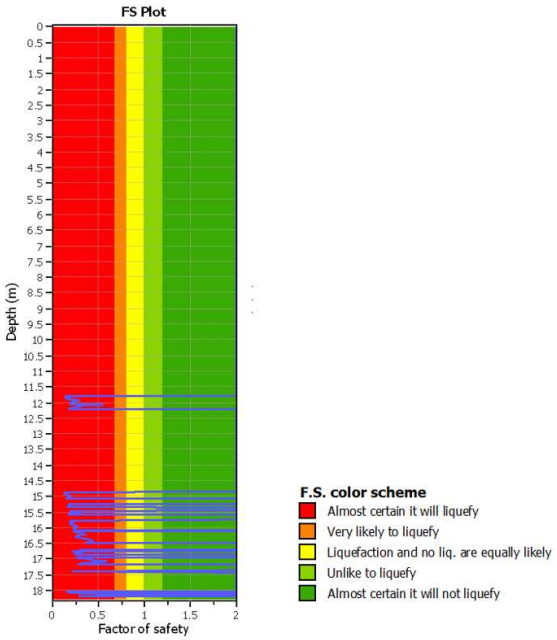


Figure 19. Plot of Factor of Safety (FS) for the available CPT data in the southern area using CLiq

6. Conclusion

The geotechnical and geophysical investigation conducted for the reclamation projects in Manila Bay provided a general characterization of the area which served as the foundation for further studies and detailed design. The study was able to show that joint employment of various tests, such as SPT, CPT, and

SVL, provides a better understanding of the subsurface for more reliable site characterization.

In the lack of available data such as the V_{s30}, particularly for offshore sites, seismic velocity logging using PS suspension logging was deemed to be very helpful in determining in-situ parameters such as the shear wave velocities. The harmonic mean of shear wave velocities was also used in classifying the soil profile types based on the criteria provided by the NSCP.

Furthermore, the utilization of available softwares provided a more effective and efficient way of computing, which aided in the analysis and design of structures and supports.

References

[1] Department of Environment and Natural Resources – Manila Bay Coordinating Office "Manila Bay Area Environmental Atlas", Manila Bay Coordinating Office, Quezon City, Philippines, Available at:http://mbco.denr.gov.ph/wp-content/uploads/2016/08/Manila-Bay-ATLAS-2nd-Edition.pdf [Accessed: 3 October 2019]

[2] Philippine Reclamation Authority "Reclamation", Available at: http://www.pea.gov.ph/programs-and-projects/reclamation [Accessed: 3 October 2019]

[3] Rappler "At least 6 Manila Bay reclamation projects to start soon", Available at: https://www.rappler.com/business/223793-list-manila-bay-reclamation-projects-starting-soon [Accessed: 3 October 2019]

[4] Mines and Geosciences Bureau "Geologic Map of Luzon Islands, Philippines"

[5] Daligdig, J., Punongbayan, R., Besana, G., Tungol, N. "PHIVOLCS Professional Paper 01: The Marikina Valley Fault System: Active Faulting in Eastern Metro Manila", PHIVOLCS Press, Quezon City, Philippines, 1997.

[6] Philippine Institute of Volcanology and Seismology "Distribution of Active Faults and Trenches in the Philippines"

[7] Molas, G., Yamazaki, F. "Attenuation of Earthquake Ground Motion in Japan Including Deep Focus Events", Bulletin of the Seismological Society of America, Volume 85, No. 5, pp. 1343-1358, 1995. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.715.930&rep=rep1&type=pdf [Accessed: 4 October 2019]

[8] Japan International Cooperation Agency "Earthquake Impact Reduction Study for Metropolitan Manila, Republic of the Philippines", Available at: http://ndrrmc.gov.ph/attachments/article/1472/Earthquake_Impact_Reduction_Study_Volume_1.PDF [Accessed: 4 October 2019]

[9] Philippine Institute of Volcanology and Seismology. "PHIVOLCS Hazard Maps".

[10] Philippine Atmospheric, Geophysical and Astronomical Services Administration "Preliminary Storm Surge Hazard Map of Metro Manila", Available at: http://www.namria.gov.ph/download.php [Accessed: 7 October 2019]

[11] Robertson, P. "Soil classification using the cone penetration test", Available at: https://www.researchgate.net/publication/245377236_Soil_classification_using_the_cone_penetration_test/link/571a633e08ae408367bc8ae9/download [Accessed: 15 October 2019]

[12] Rogers, J. "Subsurface Exploration Using the Standard Penetration Test and the Cone Penetrometer Test", Environmental and Engineering Geoscience, Volume XII, No, 2, pp. 161-179, 2006. Available at: https://www.researchgate.net/publication/242296193_Subsurface_Exploration_Using_the_Standard_Penetration_Test_and_the_Cone_Penetrometer_Test [Accessed: 13 October 2019]

[13] The Association of Structural Engineers of the Philippines, Inc., "National Structural Code of the Philippines Volume I", Association of Structural Engineers of the Philippines, Inc., Quezon City, Philippines, 2016.

[14] Seed, H., Idriss, I. "A Simplified Procedure for Evaluating Soil Liquefaction Potential", Available at: https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB198009.xhtml [Accessed: 15 October 2019]