# Geotechnical Identification of Urban Manila using Geographic Information System

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**Abstract:** The goals of sustainable development in future cities involve inclusive, safe, and resilient human settlements and infrastructure. This study aims to contribute to these sustainable developments by providing insights on the types of soils present in a highly urbanized city in a disaster-prone country. Using the 471 available geotechnical reports, this study investigates the subsoil of Manila, the capital city of the Philippines. Applying data cleansing, and criteria, six geotechnical properties were mapped using geographic information system (GIS). The key findings of the study include: the city has relatively flat terrain with elevations of around 3-6 meters above sea level; considering the seismicity of the Manila, areas with thicknesses of loose coarse-grained soils of greater than 12m pose greater risk to liquefaction; thicker depths of soft fine-grained soil deposits that are found in some areas near the Pasig River are susceptible to excessive settlement, softening, and seismic amplification; and the depth to hard strata increases from the western side of the city towards Manila Bay with some parts greater than 36m and some isolated hard strata can be encountered. Recommendations on disaster mitigation and future improvements for this study are discussed.

**Key Words:** sustainable development goals (SDGs); liquefaction; soft soils; seismic amplification; geotechnical database

## 1. INTRODUCTION

Disaster risk reduction has been an integral part in attaining sustainable development of future cities and societies. Goal 11 of the United Nations Sustainable Development Goals (SDGs) is to make cities and human settlements inclusive, safe, resilient, and sustainable while Goal 9 is to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (United Nations, 2023). In terms of disasters related to soil failure, numerous accounts have been recorded. According to Daniel (et al., 2017) somewhere between 60 and 75% of economic losses as well as deaths due to earthquakes have been due to shaking effects, and between 25 and 40% of these impacts have been due to secondary effects in the form of tsunamis, landslides, liquefaction, slope failures, and other less common types.

Liquefaction is one of the most prominent disastrous phenomena in the list. During seismic shaking, shear waves propagate, causing the loose saturated sand-like materials to contract, resulting in to increase in pore water pressure (Day, 2002). There are four common damages associated with liquefaction: settlement, bearing capacity failure, flow slides, and lateral spreading. Settlement and bearing capacity failure are common to buildings or structures with shallow foundations sitting on liquefiable soils. Liquefaction analyses are commonly done using the simplified procedures on liquefaction triggering assessments developed by Seed and Idriss (1971) and improved by various researchers (Robertson and Wride, 1998; Youd et al., 2001; Boulanger and Idriss, 2014). However, observation from recent seismic events revealed that the simplified procedures must level up. There is a need for a broadening of the horizon to understand and mitigate the effects of these geotechnical hazards.

Recent cases of liquefaction events uncovered that liquefaction-like manifestations can also occur even in geologic layers which are predominantly fine-grained soils. Boulanger and Idriss (2004) used the term cyclic failure to these kinds of soil failure caused by softening of clays during earthquakes. Most of the time, engineers are overconservative in mitigating the liquefaction effects but overlook the other hazards. On the other hand, thickness of the problematic soils (e.g., liquefiable, or soft soil) are very crucial parameters in geotechnical hazard assessment. Previous studies revealed that the thickness of liquefiable layer has significant effects on the susceptibility of soil to liquefaction (Demir 2023), on the response of piles during cyclic loading (Zhang et al., 2023) and the settlements of shallow foundations during seismic loading (Bazaios et al., 2023; Kim et al., 2023). Therefore, an overview or estimate of the presence and expected volume of problematic soil in the site will be helpful to engineers and decision-makers to mitigate risks.

On the other hand, the importance of the thickness of soft sediments should not be taken for granted. Seismic waves propagate faster in bedrock than in soft sediments. Waves travelling in soft sediments have greater amplitude compared to those in the bedrock, resulting in greater shaking in areas underlain by soft sediments compared to those underlain by bedrock (Cakir and Walsh, 2012). This is why local site effects are important in seismic hazard analysis. Moreover, previous investigations revealed that the increase in plasticity and clay minerals of fine-grained soils reduces the shear strength of soils (Tiwari and Ajmera, 2011).

On that note, the main objective of this study is to create digital maps for the City of Manila showing geotechnical parameters that can be used for hazard assessment. The following parameters are considered: (1) thickness of loose coarse-grained soils, (2) mean grain size of loose coarse-grained soils, (3) average fines content of loose coarse-grained soils, (4) thickness of soft fine-grained soils, (5) average plasticity index of soft fine-grained soils, and (6) depth to bedrock.

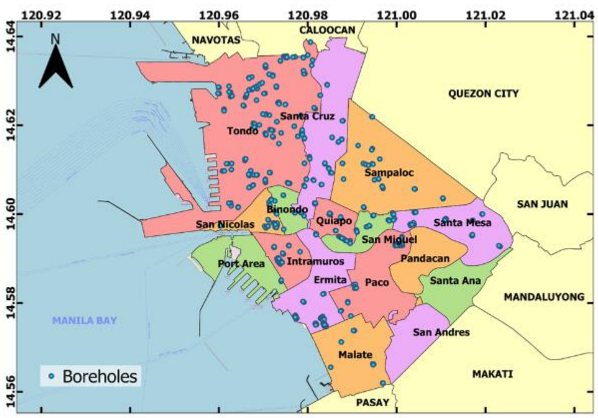
The findings and recommendations from this study will be beneficial to the City of Manila local government unit (LGU). They can use the results and recommendations to mitigate the geotechnical hazard risks that the city may encounter. It can also be beneficial to engineers and designers as reference for their hazard assessment and construction plans. Researchers and geotechnical engineers can also use the methodology discussed in this paper especially to areas that are like the City of Manila, i.e., highly urbanized and located in a disaster-prone region.

# 2. METHODOLOGY

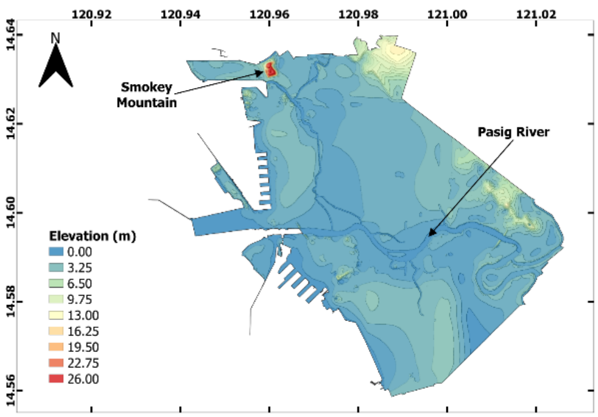
## *2.1 The Study Area*

With a total area of 42.34 km$^2$, the City of Manila is considered one of the densest cities in the world with 41,515 inhabitants per km$^2$ in 2015. According to the World Risk Report 2022, out of 193 countries around the world, the Philippines has the highest disaster risk index (Atwii, et al., 2022). One of the major contributors to disaster risk is the population density in highly urbanized areas. On the other hand, the surficial geology of the city is generally young, and it belongs to unconsolidated quaternary alluvium deposits (Bureau of Mines and Geosciences, 1983). This suggests that the soil in the city is composed of poorly sorted organic material, clay, sand, and rounded pebbles and cobbles. The geomorphology of Metro Manila reveals that the City of Manila is sitting in coastal lowlands with some portions along Manila Bay as reclaimed land (JICA, MMDA, & PHIVOLCS, 2004).

The elevation map of the City of Manila, as shown in Fig. 1b, shows that the city is generally flat with elevations of around 3-6 meters above sea level. Studies show that the capital city of the Philippines is highly risk to flooding. The study of Rubio (et al., 2020) revealed that the City of Manila has the highest disaster risk among the localities in the National Capital Region. The number of housing and elevation are among the highest weights criteria that contributes to flood risks. Moreover, studies on geotechnical hazards in the Philippines revealed that the City of Manila has a high liquefaction potential (Dungca and Chua, 2016). In the study of Daag (et al., 2022) the average shear wave velocity in the National Capital Region was correlated with the SPT-N value. The model developed in their study suggests that an SPT N-value of less than 10 can have a shear wave velocity of less than 180 m/s and can be considered as very soft to soft soils. Furthermore, the study of Dungca and Montejo (2022) highlights the importance of site-response analysis and the effects of seismic amplification in seismic hazard assessment. Relative to its nearby cities, the City of Manila is found to have the highest seismic amplification which means that even a low magnitude earthquake from a distant fault line can cause intense ground shaking in the city.




(a)




(b)

Fig. 1. (a) Geographical location of the City of Manila and the distribution of boreholes used in this study; (b) Contour map of the City of Manila with 1-m intervals.

## *2.2 Methods of the Study*

The study's methodology involves six key steps: data collection, data cleansing, computations, mapping, statistical analysis, and interpretation as shown in Fig. 2. First, data was collected from various sources, like geotechnical reports, to understand the soil conditions in Manila. Data cleansing was a critical step in ensuring data accuracy by identifying errors and confirming adherence to the appropriate standards. In document screening, each report was ensured and checked to be locatable using their coordinates. On the other hand, data processing was performed to make sure that information in the borehole reports: (1) is free from human error (e.g., typographical errors), (2) satisfies with the principles of mechanics, and (3) adheres to the standard procedures set by the American Standard for Testing Materials (ASTM). Correction of was done to some data based on the three criteria mentioned, but alteration or manipulation of information such as fill of missing data was not part of this study.

After data cleansing, the computations of geotechnical parameters commenced. Table 1 shows the geotechnical parameters measured in this study as well as the criteria used to estimate the values. Next, computations were done to calculate six geotechnical properties, such as soil thickness and grain size, making assumptions like the water table being at the surface. The computed data was then used to create maps using a technique called Inverse Distance Weighting (IDW), which helps visualize the information. Figure 1a presents the 471 borehole locations used in this study distributed to 16 districts of the City of Manila.

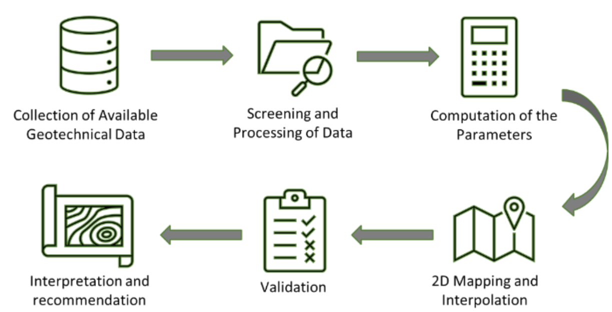



Fig. 2. General flow of methods in the present study

In computing for the geotechnical parameters, assumptions are necessary. One of the assumptions made in computing the $(N_1)_{60}$ is that the water table is at the ground surface. This is in consideration of the general topography of the City of Manila which is relatively flat. Moreover, numerous studies revealed that the city is also flood-prone, especially during wet seasons. Geotechnical maps for the computed and obtained parameters were developed using QGIS 3.16.10.

Table 1. Geotechnical parameters and criteria used in this study.

| Parameters | Units | Criteria / Geotechnical Properties |
|---|---|---|
| 1. Thickness of loose coarse-grained soils (LCGS) | Meters | The sum of all layer thicknesses with particles > 50% retained on sieve No. 200 and having $(N_1)_{60}$ less than or equal to 15. |
| 2. Mean grain size of loose coarse-grained soils | Milli-meters | The average mean grain size (D50) of the soils in parameter 1. |
| 3. Average fines content of loose coarse-grained soils | Percent | The average fines content (% passing sieve No. 200) of the soils in parameter 1. |
| 4. Thickness of soft fine-grained soils (SFGC) | Meters | The sum of all layer thicknesses with particles > 50% passed sieve No. 200 and having $(N_1)_{60}$ less than or equal to 10. |
| 5. Average plasticity index of soft fine-grained soils | Percent | The average plasticity index of the soils in parameter 4. |
| 6. Depth to hard strata | Meters | Top depth of the encountered refusal during SPT.* |

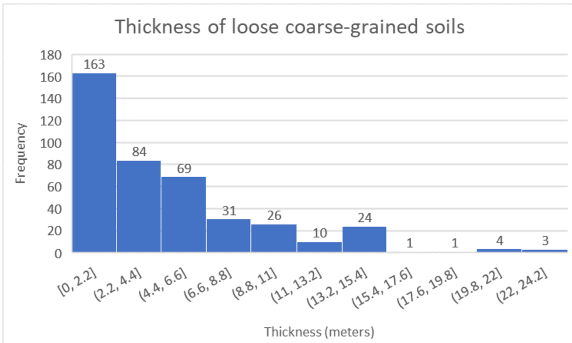
**Note: Hard layers (SPT N value greater than 50) sandwiched with soils having standard penetration resistance of less than 50 are not considered as bedrock layers.*

## 3. RESULTS AND DISCUSSION

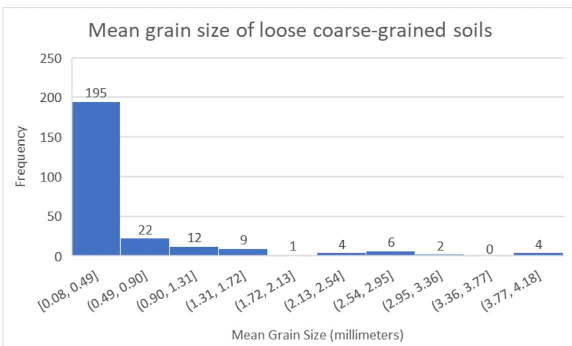
The contour map of elevation for the City of Manila is shown in Fig. 1b. From this topographic map, the City of Manila is relatively flat with much of the area at an elevation of 0 to 6.5m above the mean sea level. Moreover, large portions of the city flat terrain especially in the districts of Tondo, Santa Cruz, Ermita, and Malate. In this area, flooding is more prominent, causing the soil to saturate. On the other hand, some areas with higher elevation and steep terrain could be observed especially in the northern part of Santa Cruz, Sampaloc, and in the Smokey Mountain. In this area, soil erosion can be expected. Lastly, the River Pasig System also runs through a wide area across the city. The presence of this river system and the Manila Bay validates the existence of soft fine-grained soils and loose alluvial sands in the subsoil of some parts in the city.

As shown in Fig 1a, some districts have uniformly distributed boreholes (e.g., Tondo, Santa Cruz, and Sampaloc) while others have limited representative boreholes (e.g., Santa Ana, Pandacan, Paco, and Port Area). Generally, the distribution of borehole reports is uniformly scattered, and the density is around 11 boreholes per square kilometer.

Figure 3 displays the frequency of the geotechnical parameters used in this study. The histograms show the distribution of these geotechnical risk-related quantities and amount of these parameters that are most prominent in the subsoil of Manila. The chart in Fig. 3a and 3d shows the thickness of loose coarse-grained soils and soft fine-grained soils are mostly encountered with up to 2.2m thick. Furthermore, the thicknesses of loose coarse-grained and fine-grained soils are decreasing in frequency with respect to thicknesses. It also implies that the lithology of the subsoil in Manila can be alternating sand and clay layers which is common to coastal and river delta regions. For the mean grain size of loose coarse-grained deposits in the borehole reports, it can be observed that the average sizes range 0.08-0.49mm (about 0.02 in) or predominantly fine sands or silty sands. This information is backed-up by the histogram of the average fines content as shown in Fig. 3c. On the other hand, Fig. 3e implies that most of fine-grained soil layers are low-plasticity silts or clay with an average plasticity index ranging from 8-25. Lastly, the City of Manila has a wide range of depth to hard strata or bedrock as shown in Fig. 3f. However, caution must be taken in determining the actual depth of bedrock as in some cases, isolated hard stratum can be encountered.




(a)

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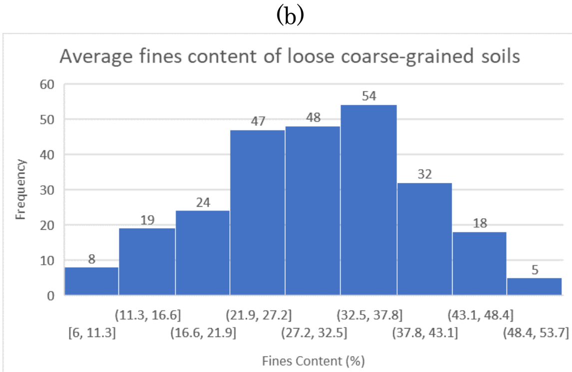


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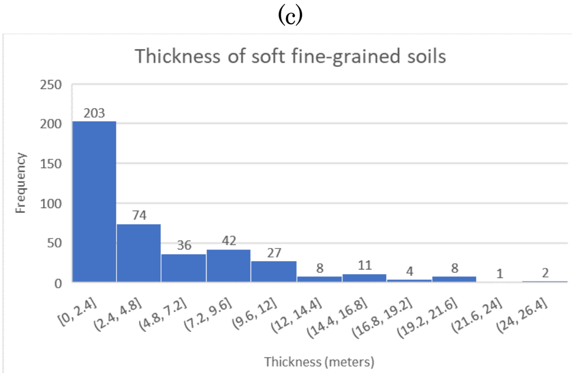


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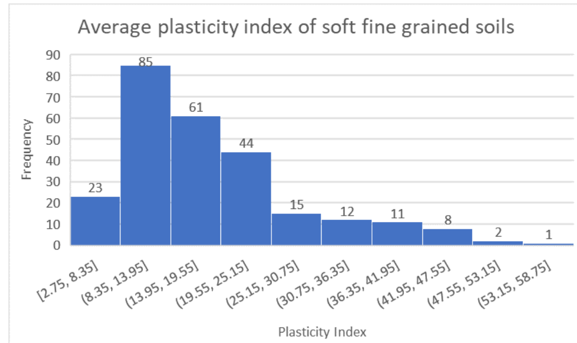


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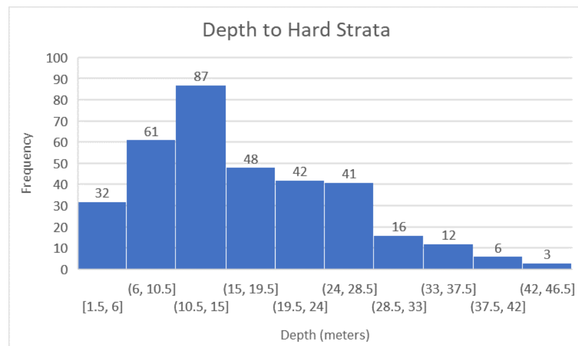



(f)

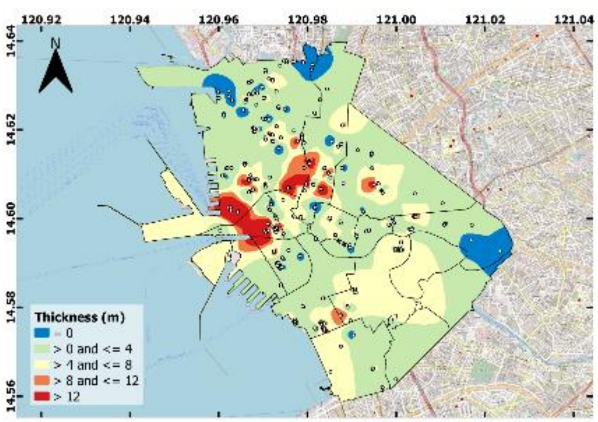
Fig. 3. Histogram of the Manila City borehole database for various geotechnical parameters.

Generally, the subsoil of the city has loose coarse-grained deposits from 4m to greater than 12m, as shown in Fig 4a. Areas with thicknesses of LCGS greater than 12m includes southern parts of Tondo and Santa Cruz, some parts of Binondo and Sampaloc, San Nicolas and parts of Port Area. These areas are found to have high risk in earthquake-induced soil liquefaction (Dungca, 1997).

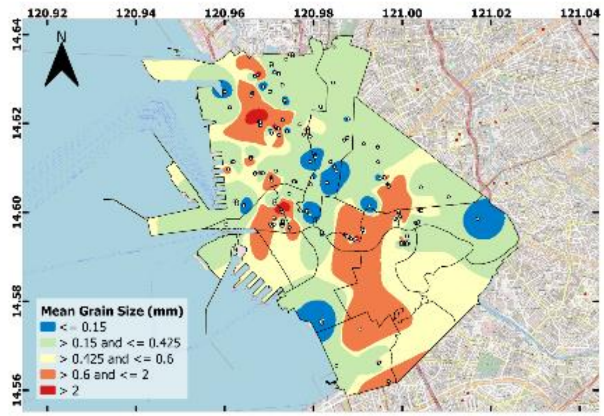
The mean grain size of loose coarse grains is predominantly 0.15 - 0.425 mm (about 0.02 in) in size indicating fine or poorly graded sands, as shown in Fig. 4b. Larger grains of sand deposits near the Pasig River and some arterial channels. Moreover, Fig. 4c revealed that the fines content of the loose coarse grains is generally sand with silt or silty sand is predominant in the subsoil layers.

Figure 4d displays the distribution of soft fine grained soil layers within the metropolis. Considerable thicknesses of soft soil deposits of greater than 15-20m are found near the Pasig River and the Manila Bay especially in some parts of Binondo and San Nicolas, South of Santa Cruz, Quiapo, Port Area, Intramuros, and Ermita. Alluvial deposits of silts and clays are found to be susceptible to liquefaction, sensitivity, excessive settlement, and cyclic softening. It implies that lower shear strength and bearing capacity can be expected in these areas. Seismic amplification can also happen on these soft soil deposits which could lead to greater ground shaking. Apparently, the average plasticity index in the City's subsoil is around 15, as shown in Fig. 4e. Nonetheless, similar areas show higher plasticity index as with the areas with thick fine grained soils deposits. It implies that lower shear strength and bearing capacity can be expected in these areas.

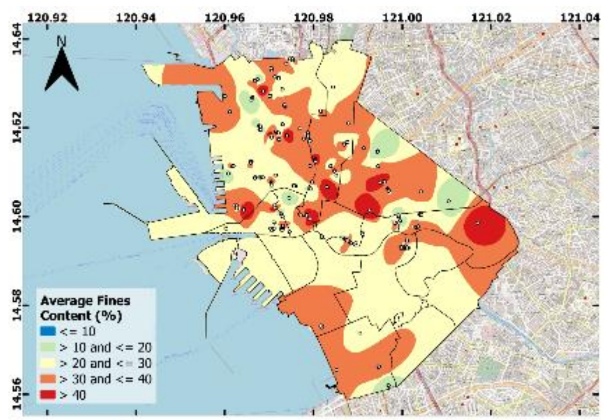
Finally, for the depth of hard strata, the City of Manila shows a median depth to hard strata of 15m. Moreover, it can be observed from Fig. 4f that hard layer is encountered at shallow depths from the west most side of the city (i.e., Sta. Mesa) and getting deeper as it approaches Manila Bay with some parts greater than 36m. In some cases, especially in shallow boreholes, hard layers are encountered at shallow depths. In those cases, one must not assume that the bedrock is already encountered as some isolated hard strata are sandwiched by softer or looser layers.



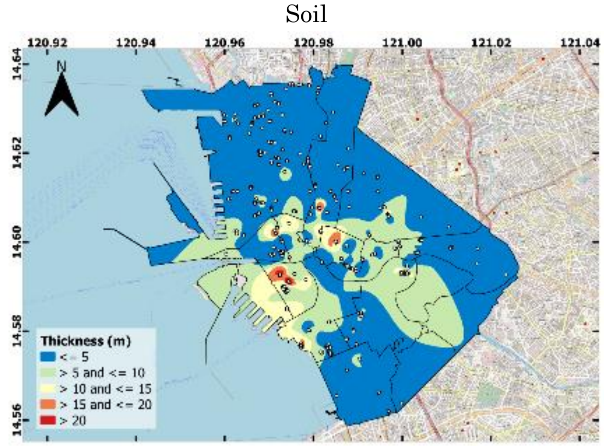

(a) Thickness of Loose Coarse-Grained Soil



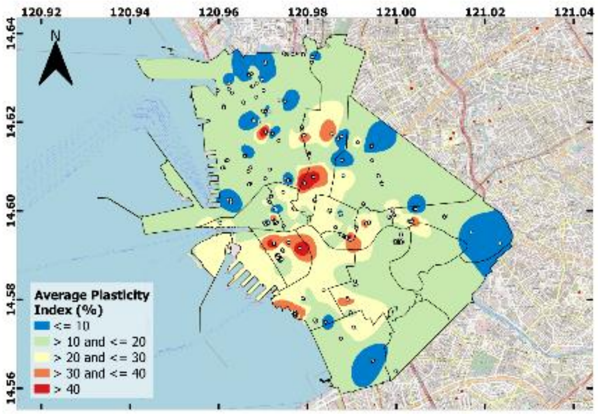

(b) Mean Grain Size of Loose Coarse-Grained Soil



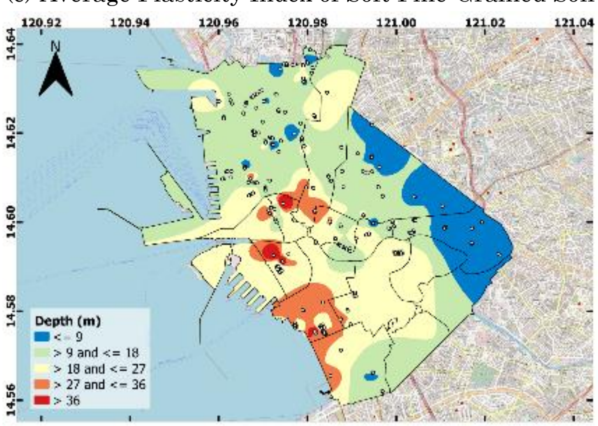

(c) Average Fines Content of Loose Coarse-Grained Soil




(d) Thickness of Soft Fine-Grained Soil




(e) Average Plasticity Index of Soft Fine-Grained Soil




(f) Depth to Hard Strata

Fig. 4. Generated maps of geotechnical parameters for the City of Manila

## 4. CONCLUSIONS

The key findings of the study include: the city has relatively flat terrain with elevations of around 3-6 meters above sea level expecting lower groundwater table that saturates the soil; considering the seismicity of the Manila, areas with thicknesses of loose coarse-grained soils of greater than 12m (i.e., southern parts of Tondo and Santa Cruz, some parts of Binondo and Sampaloc, San Nicolas and parts of Port Area) pose greater risk to liquefaction; thicker depths of soft fine-grained soil deposits that are found in some areas near the Pasig River (i.e., some parts of Binondo and San Nicolas, South of Santa Cruz, Quiapo, Port Area, Intramuros, and Ermita) are susceptible to excessive settlement, softening, and seismic amplification; and the depth to hard strata increases from the western side of the city towards Manila Bay with some parts greater than 36m and some isolated hard strata can be encountered.

Development of probabilistic and performance-based assessment of each geotechnical hazards are recommended for future studies to determine the most suitable structural design, disaster mitigation, and ground improvement techniques for future buildings and cities.

## 5. ACKNOWLEDGMENTS

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