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Evaluation of liquefaction potential on the reclamation area of Manila Bay

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ABSTRACT

Soil liquefaction is a phenomenon that occurs mostly in saturated and loose, medium to fine-grained sands wherein a mass of soil loses a large percentage of its shear resistance when subjected to monotonic, cyclic or shock loading and flows in a manner resembling a liquid. Much of the damage on substructures and foundations during earthquakes is attributed to this phenomenon. In this research, liquefaction potential in a near-shore reclamation site in Manila Bay has been calculated considering SPT (Standard Penetration Test) data at an earthquake magnitude of 7.0 with a peak ground acceleration of 0.4g using the liquefaction software, Liquefy Pro V.5. During analyses, many parameters including CSR (Cyclic Stress Ratio), CRR (Cyclic Resistance Ratio) & F.S. (Factor of Safety) are calculated at different borehole locations with respect to depths. The program presents liquefaction potential along the depth of the study (CRR versus CSR). Potentially liquefiable zones are shown graphically after calculations. The Factor of Safety (F.S.) for liquefaction potential is calculated as the ratio of the CRR to the CSR. Considering the proximity of a seismic source (Manila Bay is within a 10.0 km distance from a seismic source) capable of generating high – magnitude earthquakes and the effects of pore water pressure, the respective region is susceptible to liquefaction. It is observed that the liquefiable regions are at shallow depths (up to 15 m below ground surface) while dense sandy soils at greater depth (≥ 15 m) are non-liquefiable. This liquefaction hazard can be minimized by using soil improvement techniques to improve the physical properties of grounds. The best way to increase the ground density of sandy grounds is by vibration. The vibration due to ground improvement may affect any existing or adjacent structures within the study area. These structures should be carefully monitored for any movement or settlement. A methodology of liquefaction remediation for the Manila Bay area is presented.

Keywords: liquefaction, SPT, CSR, CRR, Factor of Safety, Manila Bay

1 INTRODUCTION

Soil liquefaction is a phenomenon that occurs mostly in saturated and loose, medium to fine-grained sands wherein a mass of soil loses a large percentage of its shear resistance when subjected to monotonic, cyclic or shock loading and flows in a manner resembling a liquid. Much of the damage on substructures and foundations during earthquakes is attributed to this phenomenon.

Geologically, almost all of Manila sits on top of centuries of prehistoric alluvial deposits built up by the waters of the Pasig River and on some land reclaimed from Manila Bay. Manila's land has been altered substantially by human intervention, with considerable land reclamation along the waterfronts (Geography of Manila, 2010). Manila is also situated on the Coastal Lowland region, which consists of loose sand and soft clay deposits that can reach 40 meters in depth (Miura et al., 2008).

Comprehensive studies about the seismic hazards in the Philippines often show that the Philippine Islands' location almost guarantees that the level of seismicity will be high, and earthquakes will produce a large moment magnitude ($M > 7$). Based on historical records, more than 50 earthquakes of $M = 7.5$ and larger have struck the Philippines (Wong et al., 2018). Based on the seismic map published by the Philippine Institute of Volcanology and Seismology (PHIVOLCS, n.d.) as shown in Figure 1, the nearest seismic source is the West Valley Fault which is approximately 10.0 kilometers east of Manila.

Considering the near-shore location of the boreholes and the proximity of a seismic source capable of generating high-magnitude earthquakes, it is evident that the study area may exhibit susceptibility to liquefaction.

Various methods are used to evaluate the liquefaction resistance of soils by identifying the potentially liquefiable regions and computing the factor of safety (F.S.) against liquefaction. The liquefaction assessment was done based on the SPT-based methods using the liquefaction software, Liquefy Pro V.5.

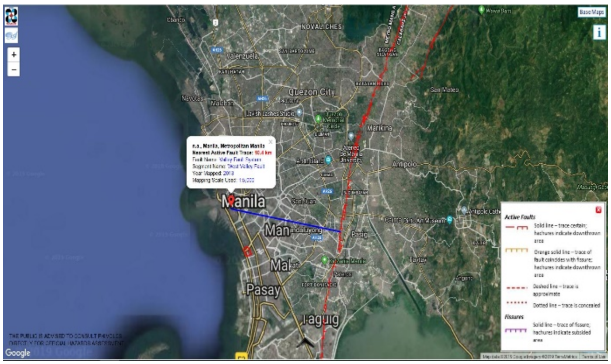


Fig 1. Approximate Distance of Manila from Nearest Seismic Source (PHIVOLCS, n.d.)

2 BACKGROUND OF THE STUDY

Manila Bay is located on the west edge of Luzon bounded by Cavite and Metro Manila on the east, Bulacan and Pampanga on the north, and Bataan on the west and northwest as illustrated in Figure 2. The geotechnical study aims to explore reclaimed sites planned for land extensions along Manila Bay.

Fig 2. Google Earth image of Manila Bay (Google Earth, n.d.)

The geotechnical study consisted of six (6) boreholes drilled at near-shore locations within the proposed reclamation study area as shown in Figure 3. Three (3) boreholes (BH-01 to BH-03) were drilled in the western portion of the Port Area, Manila up to a depth of 40.0 meters while the other three (3) boreholes (BH-04 to BH-06) were located near the eastern side of the study area and drilled to a depth of 50.0 meters. Standard penetration tests, undisturbed sampling and rock core drilling were performed on the boreholes.

The profile for BH-01, BH-02 and BH-03 is generally composed of alternating layers of sands and cohesive soils. The upper 5.0 to 6.5-meter layers are largely made up of very loose to medium dense sands with measured SPT N-values ranging from 2 to 21 blows. The tested silty sand samples contain about 0.2 to 40% fine-grained soils (passing No. 200 sieve) and are found to be non-plastic. For the clay samples, the plasticity indices (PI) are considerably highly-plastic with PI values ranging from 21 to 41 with an average SPT N-value of 2 blows.

The subsurface condition of BH-04 and BH-06 are generally made up of clays and silts with thicknesses ranging from 20.0 to 29.0 meters and with PI values ranging from 21 to 44. The upper 1.0 to 2.0-meter layers are composed of loose to medium dense cohesionless soils that contain about 7 to 11% fine-grained soils and are non-plastic with measured SPT N-values ranging from 5 to 13 blows.

For BH-05, the upper 18.5-m layer is generally made up of non-plastic, loose to medium dense sands and gravels with SPT N-values ranging from 2 to 26 blows that contain about 3 to 46% fine-grained soils. For the clay layers, the plasticity indices are considerably highly-plastic with values ranging from 40 to 43.

The boreholes (BH-04 to BH-06) are underlain by intensely fractured and extremely weathered rock layers starting at depths of 27.0 to 43.0 meters.

Fig 3. Location Plan of the Study Area (Google Earth, n.d.)

3 SEISMIC HAZARDS

The West Valley Fault, a segment of the active Valley Fault System, moves roughly every 400 years with the last major earthquake occurring in the year 1658. The West segment of the Marikina Fault was resolved to be almost fully locked, meaning it is currently accumulating and loading elastic strain, at the rate of 10 to 12 mm/year (Galgana G., 2007) with an interval movement of about 400 years. The fault could possibly generate a large-scale earthquake with an estimated magnitude, M = 7.2.

The largest earthquake (M = 7.5) to affect Manila was an event on 30 November 1645. The overall damage in Manila was severe. The number of deaths ranged from 600 to 3,000 (Jagor et al., 2004).

4 METHODOLOGY

The calculation procedure for evaluating liquefaction potential is divided into seven steps and are presented below:

Step 1: The Cyclic Shear Stress Ratio (CSR) is calculated using Seed's method. The equation is as follows:

$$\boldsymbol{CSR = 0.65\frac{\sigma_o}{\sigma'_o}a_{max}r_d} \quad (1)$$

Where:

CSR = cyclic stress ratio $\quad$ σ'_o = effective vertical induced by a given earthquake

0.65 = weighing factor (Seed)

σ_o = total vertical overburden stress

overburden stress

a_{max} = peak horizontal ground acceleration (PGA), units in g

r_d = stress reduction coefficient

Step 2: The uncorrected SPT blow count (N_m) is normalized and denoted as $(N_1)_{60}$ which is obtained by multiplying the uncorrected SPT blow count to additional correction factors. The corrections should be applied according to the following formula:

$$(N_1)_{60} = N_m C_n C_e C_b C_r C_s \qquad (2)$$

Where:

N_m = SPT raw data/measured standard penetration resistance from field

C_n = depth correction factor

C_e = hammer energy ratio (ER) correction factor

C_b = borehole diameter correction factor

C_r = rod length correction factor

C_s = correction factor for samplers with or without liners

Step 3: For soils containing fines, the blow count should be increased which would increase liquefaction resistance. The fines content correction formulas are based on the Idriss and Seed method.

$$(N_1)_{60f} = \alpha + \beta (N_1)_{60} \qquad (3)$$

Where:

For FC $\leq 5\%$, $\alpha = 0;\ \beta = 1.0$

For 5% < FC < 35%, $\alpha = e^{1.76\frac{190}{FC^2}};\ \beta = 0.99 + \dfrac{FC^{1.5}}{1000}$

For FC $\geq 35\%$, $\alpha = 5.0;\ \beta = 1.2$

Step 4: $CRR_{7.5}$ (M = 7.5) is determined using the formula below (Blake, 1997):

$$CRR_{7.5} = \frac{a + c\cdot x + e\cdot x^2 + g\cdot x^3}{1 + b\cdot x + d\cdot x^2 + f\cdot x^3 + h\cdot x^4} \qquad (4)$$

Where:

x = $(N_1)_{60f}$ c = -0.004721
a = 0.048 d = 0.009578
b = -0.1248 e = 0.0006136

Step 5: Additional vertical overburden stress correction of $CRR_{7.5}$ is suggested:

$$CRR_v = CRR_{7.5} \cdot K_\alpha \cdot K_\sigma \qquad (5)$$

Where:

CRR_V = corrected $CRR_{7.5}$

K_α, K_σ = correction factor for initial shear stress and overburden stress

Step 6: For a given earthquake with different magnitude, CRR_v needs to be corrected. Thus, a correction factor is applied to obtain the magnitude-corrected cyclic stress ratio.

$$CRR_M = CRR_V \cdot MSF \qquad (6)$$

Where:

CRR_M = magnitude-corrected CRR_v for a given magnitude

MSF = magnitude-scaling factor = $\frac{10^{2.24}}{M^{2.56}}$; M = earthquake magnitude

Step 7: The Factor of Safety for liquefaction potential (FS) is calculated as the ratio of the Cyclic Resistance Ratio (CRR) to the Cyclic Stress Ratio (CSR) presented in the formula:

$$FS = CRR_M / CSR_{fs} \qquad (7)$$

FS is the ultimate results of the liquefaction analysis. If FS > or equal to 1, there is no potential of liquefaction.

5 RESULTS AND DISCUSSION

5.1 Liquefaction Analysis

The study area is highly susceptible to liquefaction based on the published liquefaction hazard map of PHIVOLCS as shown in Figure 4. According to the National Structural Code of the Philippines (NSCP) 2015, the Philippine archipelago is divided into two seismic zones with Manila Bay falling under seismic zone 4. Therefore, the assigned seismic source factor (z) is 0.40 with predicted horizontal ground acceleration of 0.4g.

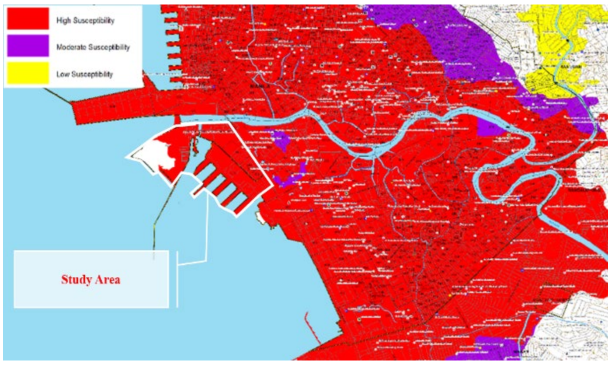


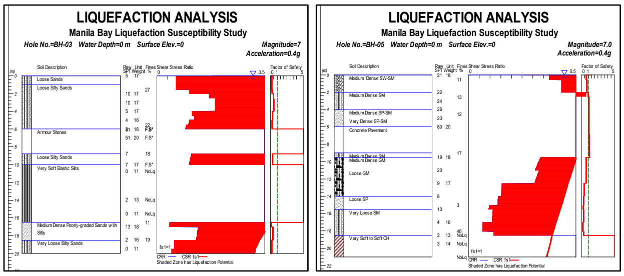
Fig 4. Liquefaction Hazard Map of Manila (PHIVOLCS, n.d.)

A 7.0-magnitude earthquake with a PGA of 0.4g was used in the LiquefyPro calculations to assess the area's liquefaction potential under seismic conditions. The boreholes were assumed to be submerged in seawater (W.L.= 0m) for more conservative analyses. Table 1 presents the results of liquefaction analyses.

Table 1. Summary of Liquefiable Depths per Borehole

Borehole No.	*Remark on Liquefaction [Depth]*
BH-01	Liquefiable [0.00 – 3.00 & 3.90 – 5.00 meters]
BH-02	Liquefiable [0.00 – 3.00 & 19.00 – 20.00 meters]
BH-03	Liquefiable [0.00 – 6.00, 9.00 – 10.00 & 16.50 – 20.00 meters]
BH-04	Liquefiable [0.00 – 2.00 meters]
BH-05	Liquefiable [0.00 – 2.50 & 9.50 – 18.50 meters]
BH-06	Negligible

BH-06 exhibits negligible liquefaction potential due to its cohesive nature. The liquefiable regions are mostly composed of cohesionless soils such as sands and gravels with relative condition of very loose to medium dense. The potential liquefiable regions are presented in Figure 5. The FS for liquefaction potential ranges from 0.13 to 0.66 for BH-03, and 0.18 to 0.98 for BH-05. Historically, sands and gravels were the only type of soil susceptible to liquefaction, but it has also been observed in sand-silt and gravel-silt mixtures in the study area. According to Kwambka (2011), strain-softening of fine-grained soils can produce effects like those of liquefaction.



(a) (b)

Fig 5. Liquefaction Analysis of (a) BH-03 and (b) BH-05

5.2 Liquefaction Mitigation Measures

For the reclamation site, ground improvement is required to improve weak and poorly conditioned granular fill. Proper mitigation measures should be undertaken to reduce seismic risks and withstand liquefaction-induced geotechnical hazards as well as to minimize total and differential settlement upon application of additional stresses (Bo et al., 2013). The liquefiable depths indicated in Table 1 are not reflective of the total settlement that the site may experience as settlement analysis is also needed to consider the possible settlement of the underlying cohesive soil layers that were not investigated.

The liquefaction hazard can be minimized by using soil improvement techniques such as vibration, to improve the physical properties of sandy grounds. Due to this, any adjacent structures within the study area should be carefully monitored for any movement or settlement. Deep foundations extending beyond the liquefiable layers may also be considered. The design of a ground improvement method must be implemented correctly in the field to reach its maximum performance extents. A post ground improvement evaluation should be done to ensure the effectiveness of the method and to assess the strength of the improved ground. Pilot tests are recommended in order to properly monitor the actual behavior of the soil when surcharge load is applied, and to determine the efficacy of the soil improvement measures (e.g. installation of vertical drains) to be applied. Control areas where the pilot tests will be done should be carefully selected such that the areas will properly represent the critical portions in the site.

6 CONCLUSIONS

The reclaimed area of Manila Bay is highly susceptible to liquefaction based on the published liquefaction hazard map of PHIVOLCS. This is supported by the liquefaction analyses done for the study area. A 7.0-magnitude earthquake with a peak ground acceleration of 0.4g was used in the LiquefyPro calculations. It is established that the underlying sands and gravels are liquefiable and many of the surrounding reclaimed areas of Manila Bay will be affected. The liquefaction hazard can be minimized by using soil improvement techniques to improve the physical properties of sandy grounds, or a deep foundation extending beyond the liquefiable layers may be considered. Detailed ground improvement design and technique should be carried out to further achieve the most appropriate liquefaction remediation for the study area.

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