

Geophysical characterization for the proposed Metro Manila subway

R. A. C. Luna

AMH Philippines, Inc., Quezon City, Philippines, racluna@amhphil.com

R. D. Quebral¹, J. M. B. Gargullo², K. J. R. Leobrera³, P. A. Y. Selda⁴, E. D. Marasigan⁵, M. D. C. Andal⁶,
F. J. T. Bernales⁷

AMH Philippines, Inc., Quezon City, Philippines, ramon_quebral@yahoo.com¹, michael.gargullo@amhphil.com², karen.leobrera@amhphil.com³, patrick.selda@amhphil.com⁴, emmanuel.marasigan@amhphil.com⁵, deandra.andal@amhphil.com⁶, francis.bernales@amhphil.com⁷

S. Shibata, T. Shiga, K. Yamamoto, R. C. S. Albea

Japan International Cooperation Agency – Design Team, Pasig City, Philippines

ABSTRACT: Part of the comprehensive geological and geotechnical investigation for the proposed Metro Manila subway is the conduct of geophysical testing to estimate the dynamic properties of soil and rock underlying the alignment. This consists of seismic downhole tests, and seismic velocity logging using P-S suspension logger on several boreholes along the alignment. This paper focuses on the results of seismic velocity logging conducted in sixty (60) boreholes located along the proposed subway alignment. The obtained shear wave velocity measurements show that the subsurface surrounding the opening for the proposed subway alignment is generally underlain by soft rock to rock formations with the overall average $V_{s,hm}$ of 779.72 m/s, which falls in the borderline of S_C and S_B soil profile types. The results are consistent with the published V_{30} site model map by the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and the Unconfined Compression Tests (UCT) conducted in the core samples obtained from the geotechnical investigation. The results are expected given that the alignment is underlain by Guadalupe Tuff Formation.

Keywords: geophysical characterization; Guadalupe Tuff Formation; Metro Manila Subway Project

1. Introduction

1.1. Study area

Metro Manila, the Philippines' National Capital Region (NCR), is the political, economic, and cultural center of the Philippines. With a total area of approximately 620 km², NCR houses several business districts, schools, hospitals, and government offices. A census conducted in 2015 showed that the population in Metro Manila is approximately 12 million which is rapidly increasing every year. Metro Manila is thus considered as one of the most densely-populated areas in Southeast Asia.

Although several transportation networks such as rail transit systems, national roads, and expressways are available, they still prove to be insufficient in reducing the traffic congestion as well as the travel time in the metropolitan area. To alleviate the urgent need for an efficient mass transport system, the first underground rapid transit line in the Philippines, known as the Metro Manila Subway, was recently approved by the government for design and construction.

The proposed alignment of the subway is subdivided into three zones, namely, the north, central, and south zones. The north and south alignments of the subway are reserved for future development, connecting the capital region to its neighboring provinces.

This study focuses on twelve out of fifteen proposed stations in the central zone. It runs in a northern to north-western direction, spanning approximately 25 kilometers—traversing the cities of Quezon, Pasig, Makati, and Taguig.

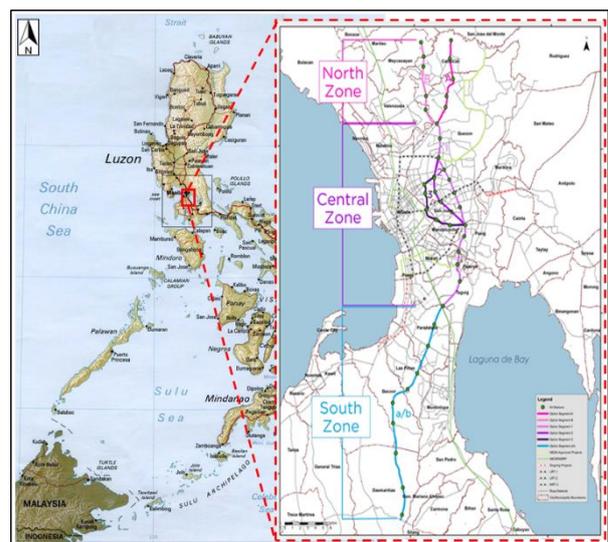


Figure 1. Metro Manila Subway Project (Source: JICA Design Team)

1.2. Significance of the study

Metro Manila is influenced by several earthquake generators, among which is the Valley Fault System. Paleoseismic and geologic data have shown that the Valley Fault System is active. Trenching across the northern portion of the fault, coupled with Carbon-14 dating, show that three or four faulting events occurred during the last 1400 years. An estimate of approximately 200 to 400 years has been suggested as a possible recurrence interval for large magnitude earthquakes (i.e. magnitudes of at least 7.0) [1].

The Philippine Institute of Volcanology and Seismology (PHIVOLCS) estimates a possible magnitude of at least 7 for this fault; and considering that no seismic event is known after the 17th century, a large-magnitude earthquake is forecasted to hit Metro Manila in the near future, which will result in tens of thousands of serious injuries and fatalities and trillions of pesos in economic loss.

It is an opportune time to conduct appropriate geophysical testing methods to estimate the dynamic properties of the soil and rock underlying the alignment in order to provide a safe and cost-effective design for the proposed major transport infrastructure.

2. Regional geology

2.1. General topography

Metro Manila is built on an extensive flood plain with very little variation in elevation, and can be considered as flat to rolling. The majority of its land is flat, which makes it prone to floods. Relative to the mean sea level, the ground elevation of the area ranges from 10-30 meters, with slopes of 0 to 15%. Among the lowland areas include the cities of Manila, Navotas, Malabon, and parts of Caloocan. On the eastern part, the lowland areas are the cities of Pasig, Marikina, Taguig, and the municipality of Pateros. Its low plateau ranges from the southern part of the Sierra Madre Mountain Range to the slope of Taal Plain.

2.2. Stratigraphy

The subsurface underlying Metro Manila (Figure 2) can be generally classified into three major parts: (1) Guadalupe Formation (GF, central part); (2) Pasig River delta plain (western part); and (3) Marikina Valley plain (eastern part).

The Guadalupe Tuff Formation (GTF)—locally referred to as “adobe”—is the dominant feature of Metro Manila. It is approximately 1,500 to 2,000 meters thick, which can be dated back to the Pliocene-Pleistocene period. It is overlain by up to 2 meters of weathered soil, and covers most of the eastern portion of this region. This formation can still be subdivided into two (2) parts: the Alat Conglomerate (lower member) and Diliman Tuff (upper member).

The Alat Conglomerate forms an extensive outcrop bet underlying Eastern Bulacan and Southeastern Nueva Ecija. It is about 200 meters thick, and mostly composed of a group of massive poorly sorted round pebbles and small boulders, conglomerate and sandstone with medium to thin-bedded mudstone or shale.

On the other hand, the Diliman Tuff stretches from Quezon City and extends to the Province of Cavite in the south. It is roughly 1,300 to 2,000 meters thick, and is made up of volcanic ejecta with some amount of pyroclastic breccias, tuffaceous sandstones, tuffaceous siltstone, and shale [2].

The Pasig River delta plain, which has an average elevation of 5 meters, has a roughly concave shape, and has a poor drainage and gentle slope that is directed towards Manila Bay. This plain is composed of beach and estuarine deposits in the northern part, and lagoonal and beach sediments from the clastic sediments dumped by the Pasig River [3].

The last major part is the Marikina Valley plain, which is composed of deep alluvial deposits. It is located between the Sierra Madre Mountain Range and the Guadalupe plateau. The sharp contact between the alluvial plain and the Guadalupe plateau forms a segment of the western part of Marikina Valley Fault System [4].

The mantle of residual soil in Metro Manila is composed of Quaternary Alluvium (QAI) deposits. From the opening of Pasig River to the Makati-Mandaluyong Bridge, the ground is composed of loose sand, soft silt, and clay. It is in the greater depths of the land where the hard soil and rock layers, although not of uniform depth, are encountered. In the mid-layers of soil, alluvium, with clay and sand present, can be found. These layers are classified as marine deposits, deltaic deposits, and sediments of the flood plain. From the Makati-Mandaluyong Bridge to Pasig City, the area is described as a narrow valley. The major component of the ground surface in this area is loose gravel in the Makati area, and clayey soil in the Pasig area. Lastly, the floodplain area in Pasig has a lot of geologic variations, which is why is it divided into different regions. On the average, alluvial layers (loose and soft soils) are dominant in the area, with an elevation ranging from -4 meters (because of the underground drowned valley) up to 6 meters. The depth of the hard rock layer is still not clearly defined because of the thick layer of very hard clay and dense sand [5].

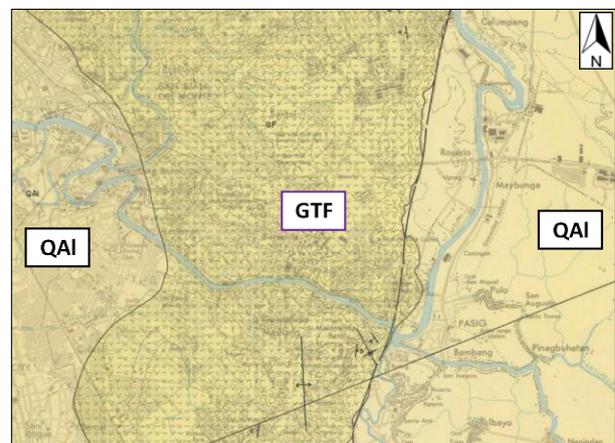


Figure 2. Extract from the geologic map of Manila & Quezon City Quadrangle by MGB [6].

3. Geohazards

3.1. 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 3 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. 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. Certain areas in Marikina City along Marikina River, are also characterized as an area of high liquefaction susceptibility. This assessment is expected since soil types in the said areas are mostly composed of loose deposits of sedimentary origin.

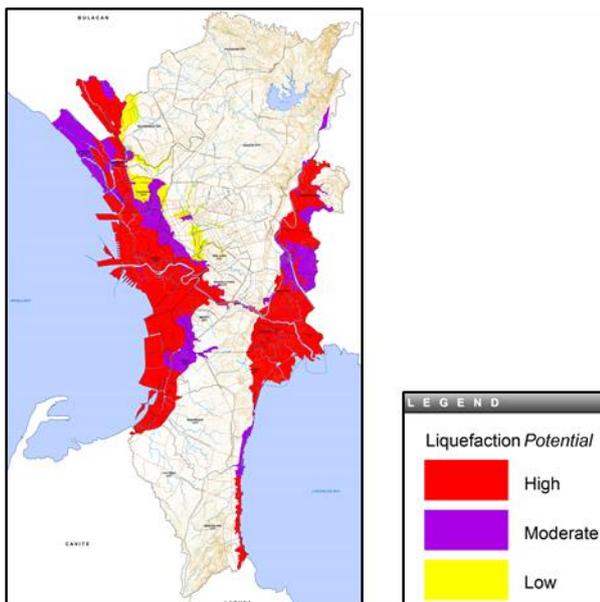


Figure 3. Liquefaction susceptibility map of Metro Manila by PHIVOLCS [7].

3.2. Ground rupture

In the event of an earthquake, the rupture along the surface of an active fault may cause severe damage to structures or other developments around the vicinity of the trace. The ground rupture hazard map of Metro Manila (Figure 4) shows minor risk of ground rupture for most areas in Metro Manila except for those near the West Valley Fault. Nonetheless, PHIVOLCS recommends a minimum buffer zone of at least 5 meters as reckoned from both sides of a fault trace or deformation zone.

Moreover, one study estimated the potential casualties, both dead and injured, to be around 147,100. Several offices, residential, mid-rise and high-rise structures are also expected to be heavily damaged.

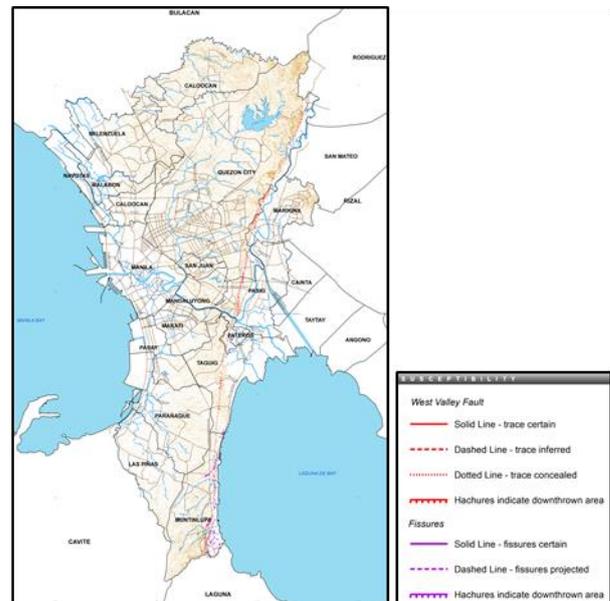


Figure 4. Ground rupture hazard map of Metro Manila by PHIVOLCS [7].

3.3. 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.

The first warning of an incoming tsunami is the withdrawal of water from beaches. This receding tsunami contains very high potential energy which is released upon collision with the first wave (from the disturbance) approaching towards the shore. Water levels can reach several meters high as the tsunami finally meets the coast.

The potential height of the tsunami is largely influenced by the shoreline topography and configuration. Shorelines with flat gradients have little resistance and waves are free to propagate further inland. In contrast, steep shorelines force the waves up resulting to larger run-up heights.

Figure 5 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.

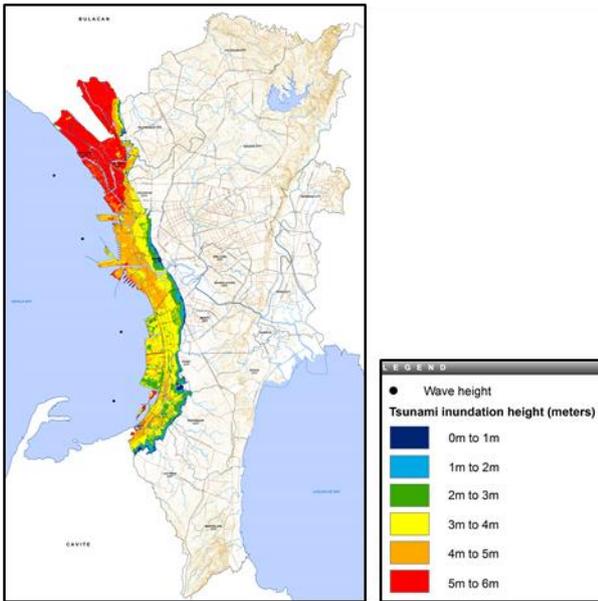


Figure 5. Tsunami hazard map of Metro Manila by PHIVOLCS [7].

3.4. Seismic hazard

Ground motion (or shaking) intensity is typically utilized as a means to measure the overall seismic hazard at a given study area. Since the other geohazards previously mentioned are typically linked to the consequences of ground movement or displacement, these could be mitigated by modeling potential ground motions through seismic hazard analysis.

Seismic Hazard Analysis (SHA) is the process of quantifying the overall seismic hazard of an area primarily in terms of potential shaking. The probabilistic approach (PSHA) in performing SHA quantifies seismic hazard at different ground motion levels depending on the recurrence interval or return period for a desired performance objective. PSHA also considers multiple seismic sources simultaneously and accounts for uncertainties related to distance, time, recurrence, and size (magnitude).

In performing SHA, empirically-formulated attenuation models are utilized to determine the expected surface acceleration by estimating how seismic waves propagate and travel from source to site. Attenuation models, commonly referred to as Ground Motion Prediction Equations (GMPE), were formulated using globally-acquired earthquake information (e.g. epicenter location, depth, and magnitude). Predictor variables in a GMPE that incorporate effects of seismogenic parameters, rupture mechanism, local site conditions, and uncertainties are then used as an input to calculate a certain intensity measure level, say a peak ground acceleration (PGA).

Filipino engineers today typically extract seismic design accelerations from the NSCP, which utilizes a generalized national-scale response spectrum developed in 1994. Design accelerations for seismic analysis can be taken from the response spectra generated from PSHA. In light of this, PHIVOLCS conducted a national-scale PSHA in 2017 and published the Philippine Earthquake Model (PEM)—an atlas of maps containing isolines of equal spectral acceleration.

4. Subsurface conditions

A total of 136 boreholes were drilled with depths ranging from 28 to 68 meters and an average depth of 44.16 meters along the central zone of the alignment. The alignment is generally underlain by GTF mantled with varying thickness of sedimentary deposits ranging from 0.50 to 14.65 meters; with the exception of 17 boreholes and 3 boreholes wherein Tuff Formation and fill material, respectively, were already encountered at the onset of drilling.

Offshore boreholes, on the other hand, have varying subsoil conditions. One borehole has 7.50 meters of sedimentary deposits, while another has 55.80 meters. Most core samples taken from these offshore boreholes were also fractured.

In this study, the Unconfined Compression Test (UCT), a common laboratory testing method used to provide a measure of the undrained strength and stress-strain characteristics of rocks, was conducted on 2,134 out of 3,746 recovered core samples, spread throughout the alignment. The Uniaxial Compressive Strength (UCS) values range from 0.07 MPa to 18.46 MPa with an average value of 3.53 MPa.

The UCS of rock is used as an input in various design equations. It is also employed in selecting the appropriate excavation and/or tunneling technique. The in-situ properties of rock core samples are largely affected by joints, faults, inhomogeneity, weakness planes, and other factors. In order to make a more accurate representation of these in-situ properties, it is important to conduct tests on intact rock core specimens.

The UCS central bandwidth, where most samples lie upon, is within 0.07 to 4.07 MPa. Outliers were also observed, such as those with very low UCS (<1 MPa), indicating the presence of semi-fractured or soil-like rock samples for those depths; and those with above-average UCS (>11 MPa), which may suggest scattered hard rock deposits. Specimens within the lower strength range might be influenced by physical characteristics, such as size, saturation, weathering, and mineral content.

It can be concluded that rock mass surrounding the proposed tunnel can be classified as soft rock. As such, it is expected that a number of intact rock core samples might exhibit some form of elastic-plastic behavior. Elastic-plastic behavior is characterized by gentle-to-horizontal slope outside of the linear elastic region, like as shown in the right image of Figure 6.

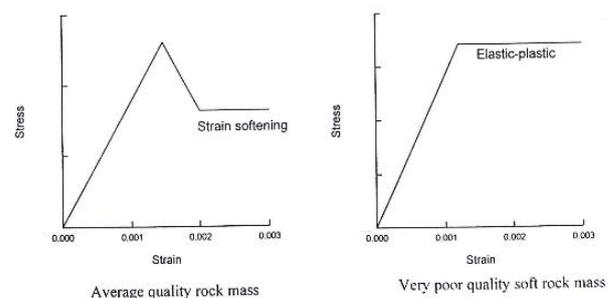


Figure 6. Sample Stress-Strain Curves of Rocks [8]

The trend of the UCS versus the static modulus of elasticity (E_s) generally follows the expected behavior of rocks, that is, as the UCS increases, so does the static modulus of elasticity, as shown in Figure 7.

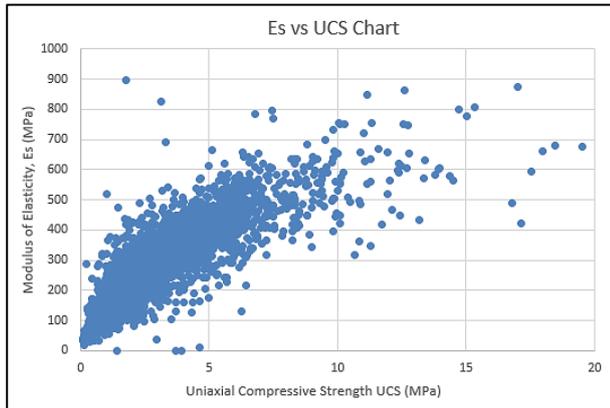


Figure 7. Static Modulus of Elasticity vs UCS Chart

5. PS Suspension 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 subway using the Robertson Geo PS Suspension Logger (PS Logger).

The PS Logger was developed by researchers at OYO Corporation in Japan in the mid-1970's and later gained acceptance in the country in the mid-1980's. In the early 1990's, the PS Logger was also accepted in the United States especially among earthquake engineering researchers.

SVL, using the PS Logger, is performed in water-filled uncased boreholes or well-grouted PVC/HDPE-cased boreholes. PS Logger gives high resolution seismic wave measurements with estimated precision of $\pm 5\%$ and $\pm 10\%$ for S-wave and P-wave, respectively [9].

P-waves and S-waves are seismic body waves that travel at different speeds depending on the media they are propagating through. P-waves are able to propagate through solids and fluids, while S-waves can only propagate through solids.

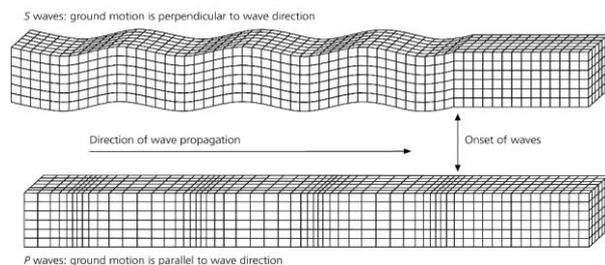


Figure 8. Body wave propagation [10]

P-waves travel faster compared to S-waves, but the latter is known to have a more significant physical implication in seismic design considerations.

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. The range of P-wave and S-wave velocities for common materials are shown below in Table 1.

Table 1. Range of seismic wave velocities for common materials [11]

Material	V_p (m/s)	V_s (m/s)
Air	343	n/a
Water	1450 – 1500	n/a
Ice	3400 – 3800	1700 – 1900
Oil	1200 – 1250	n/a
Vegetal Soil	300 – 700	100 – 300
Dry Sands	400 – 1200	100 – 500
Wet Sands	1500 – 2000	400 – 600
Saturated Shales and Clays	1100 – 2500	200 – 800
Porous and Saturated Sandstones	2000 – 3500 (1400 – 4500) [12]	800 – 1800
Marls	2000 – 3000	750 – 1500
Chalk	2300 – 2600	1100 – 1300
Coal	2200 – 2700	1000 – 1400
Salt	4500 – 5500	2500 – 3100
Anhydrites	4000 – 5500	2200 – 3100
Limestones	3500 – 6000	2000 – 3300
Dolomites	3500 – 6600	1900 – 3600
Granite	4500 – 6000	2500 – 3300
Basalt	5000 – 6000	2800 – 3400
Gneiss	4400 – 5200	2700 – 3200

5.1. Equipment

The PS Logger assembly comprises of a probe that is connected to both a winch and the Micrologger. The PS Logger probe is a 6.03-m long low-frequency acoustic wireline tool designed to measure seismic wave velocities using indirect excitation rather than mode conversion as in conventional sonic. It is capable of acquiring high resolution P-wave and S-wave data in borehole depths up to 600 meters.

The probe assembly comprises of an acoustic wave source and two geophones spaced 1 meter apart. The Micrologger is a compact and lightweight portable surface interface system for handling logging data acquisition.

5.2. Methodology

The following diagram presents the methodology for performing PS suspension logging.

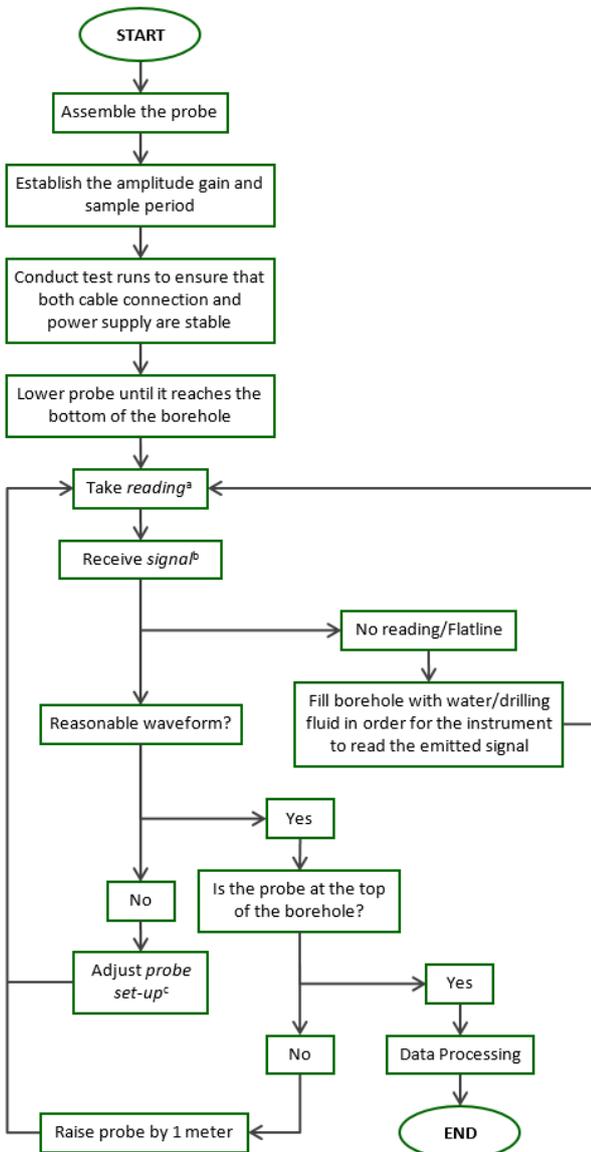


Figure 9. Flowchart for PS suspension logging

Notes:

- The source releases a set/stack of acoustic waves which are collected by the geophone receivers. One set or stack of readings comprises of one shot of P-wave and two shots of horizontally-polarized S-waves. The pair of polarized S-waves are expected to be mirror images of each other.
- Because the receivers are 1 meter apart, the wave form of the signal measured by the far receiver is expected to have lagged for some time with respect to the wave form measured by the near receiver.
- The probe set-up is the configuration of the probe dealing with the energy output of the source. This comprises of the amplitude gain, the number of stacks, and the sample period.

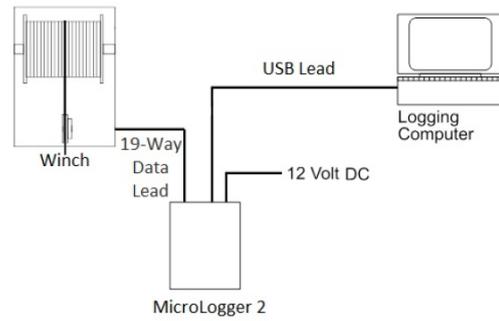


Figure 10. Setup connection diagram [9]

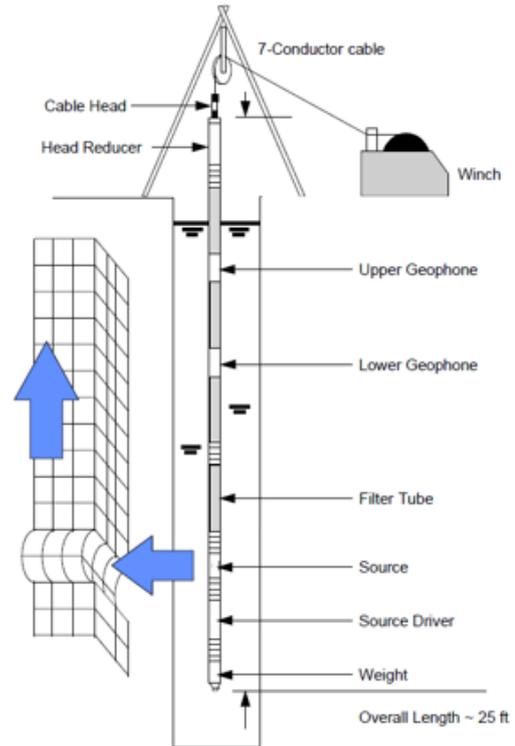


Figure 11. Schematic of the set-up [13]

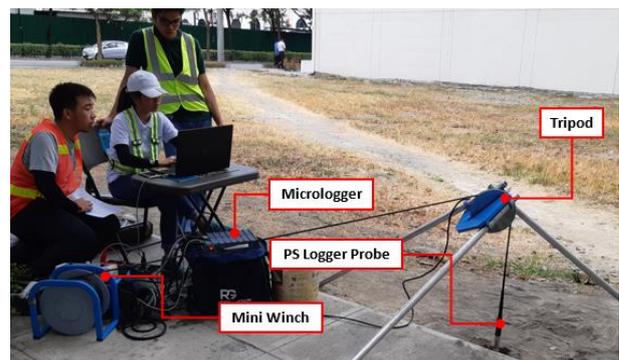


Figure 12. Actual field set-up

Data processing includes picking a point in the wave form measured by the near receiver, and locating exactly the same particular point in the lagged wave form measured by the far receiver. The point should be the same particle in both waves in order to determine the transit time needed for the particle to propagate a distance of 1 meter along the borehole wall. The difference in travel time between these points is used to calculate the seismic wave velocity for that segment between both receivers.

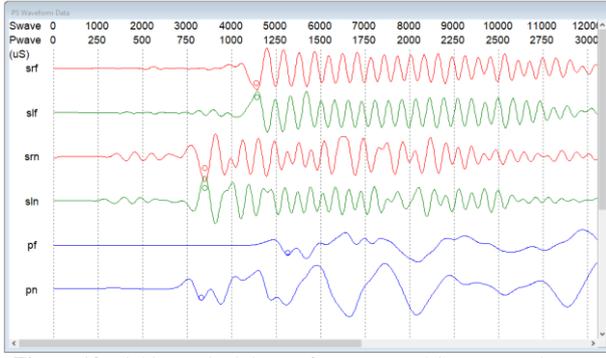


Figure 13. Picking arrival times of P-waves and S-waves at the near and far receivers

The National Structural Code of the Philippines (NSCP) 2015 [14] 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 2. The V_{s30} of a particular borehole can be obtained by taking the harmonic mean of the measured velocities with respect to depth (NSCP 2015 Equation 208-1). If the final depth corresponds to the upper 30 meters,

$$V_{s,hm} = \frac{\sum_{i=1}^n d_i}{\sum_{i=1}^n [d_i/V_{s,i}]} = V_{s30} \quad (1)$$

where d_i – length of soil segment in consideration (m)
 $V_{s,hm}$ – harmonic mean of measured shear wave velocities (m/s)
 V_{s30} – average shear wave velocity of the top 30 m (m/s)

From measured seismic wave velocities, several elastic properties can be calculated through empirical equations formulated through non-destructive test methods.

$$E_d = \frac{\rho V_s^2 (3V_p^2 - 4V_s^2)}{(V_p^2 - V_s^2)} \quad (2)$$

$$G = \rho V_s^2 \quad (3)$$

$$\nu = \frac{1}{2} \frac{(V_p^2 - 2V_s^2)}{(V_p^2 - V_s^2)} \quad (4)$$

where E_d – Dynamic Modulus of Elasticity or Young’s Modulus (Pa)
 ρ – Density (kg/m^3)
 G – Shear Modulus of Elasticity or Modulus of Rigidity (Pa)
 ν – Poisson’s Ratio

6. Field work details

Seismic velocity logging was performed in sixty (60) boreholes located along the subway alignment to measure the seismic wave velocities of the underlying strata—particularly the rock layers. Two of the tested boreholes are situated within the vicinity of Pasig River, a river that runs from Laguna Bay to Manila Bay which intersects the proposed subway alignment. The two boreholes are characterized with 7.5 and 21.0-meter thick soil layers mostly composed of medium dense to dense sands overlying the rock formations.

Field testing was carried out from November 6, 2018 to August 8, 2019 with test depths varying from 12.5 to 61.0 meters.

7. Results

The measured seismic wave velocities from SVL reveal that there is no governing trend that defines the dynamic behavior of the subsurface with respect to depth, as shown in Figure 14. There are random pockets of rock with relatively higher velocity/stiffness than the rest, just as there are random pockets of rock with poor condition trapped within the stratification.

The respective harmonic mean of the shear wave velocity ($V_{s,hm}$) for each borehole was calculated and it was evident that majority of the values, except for Pasig River boreholes, lie between 659 m/s to 902 m/s. These suggest that the subsurface can be categorized under S_C (very dense soil/soft rock) or under the weaker class of soil profile type S_B (rock). The overall average $V_{s,hm}$ is around 779.72 m/s, which falls in the borderline of soft rock and rock classification.

For these designated boreholes, elastic properties were calculated from the measured in-situ seismic wave velocities. The distribution reveals that majority of the data fall within the central bandwidths shown in Table 3.

The central bandwidth of the measured seismic wave velocities suggests that the subsurface is mostly composed of either shale, clay, or porous sandstone.

Table 2. Soil profile types [14]

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			

This finding is consistent with published values shown in Table 1. This composition was also expected given that the alignment is underlain by GTF.

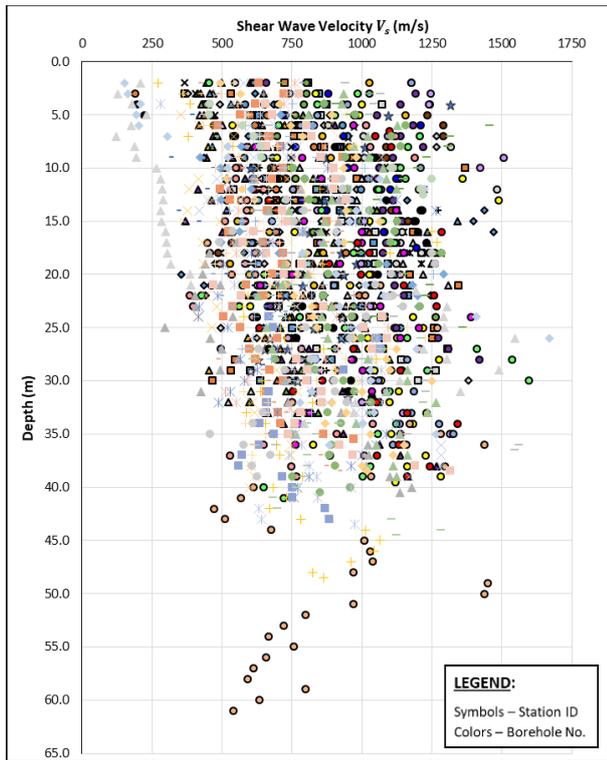


Figure 14. Plot of shear wave velocities against depth for sixty test boreholes

Table 3. Central bandwidths of soil/rock properties obtained from the results of SVL

Parameter	Central Bandwidth
Compressional wave velocity V_p (m/s)	1,736.0 – 2,270.3
Shear modulus G (MPa)	516.5 – 2,001.3
Young's modulus E_d (MPa)	1,522.0 – 5,337.5
Poisson's ratio ν	0.33 – 0.45

On the other hand, the measured shear wave velocities for the rock layers of Pasig River boreholes fall within 867 m/s to 1,305 m/s, with exception in some layers, particularly at depths 23.0 meters to 31.0 meters, where the mean velocity is relatively higher, presumably due to the layers of impermeable rocks above the confined aquifer at 31.5 meters observed during the geotechnical investigation. However, the computed harmonic means of the shear wave velocities were lower due to the thick layers of soil encountered in the upper layers. With high risk of borehole collapse, steel casings were installed preventing measurements to be taken in the soil layers. Instead, empirical correlation by Akin, Kramer, and Topal [15] was used to compute the shear wave velocities from the SPT N-values. The computed $V_{s,hm}$ for Pasig River boreholes suggest that the subsurface falls under the soil profile type S_C (very dense soil/soft rock) and soil profile type S_D (stiff soil).

7.1. Philippine Earthquake Model (PEM)

The results from the geophysical tests are consistent with the generalized Metro Manila V_{s30} site model map published by PHIVOLCS [16], which shows that the northern segment of the alignment falls under S_B , while the southern segment of the alignment falls under S_C . The range of the computed $V_{s,hm}$ values in Figure 16 show that the northern area is characterized with a few borderline values from soft rock to rock classification which may represent boreholes located in areas where the soil profile type transitions from S_C to S_B , as shown in Figure 15.

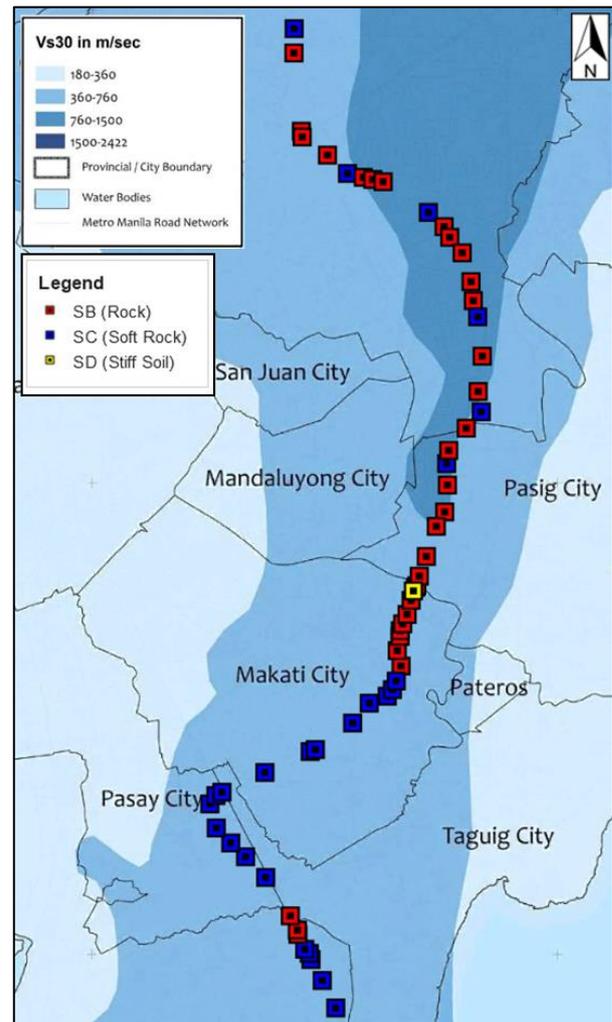


Figure 15. Metro Manila V_{s30} site model [16]

Also marked in Figure 16 are $V_{s,hm}$ values that may be considered as outliers due to the sparsity of field measurements because of problems encountered during testing. Such problems include:

1. unrecognizable waveforms from boreholes with significant presence of cracks or voids which hinder the transmission of shear waves
2. loose water in the borehole
3. highly unstable borehole collapsing

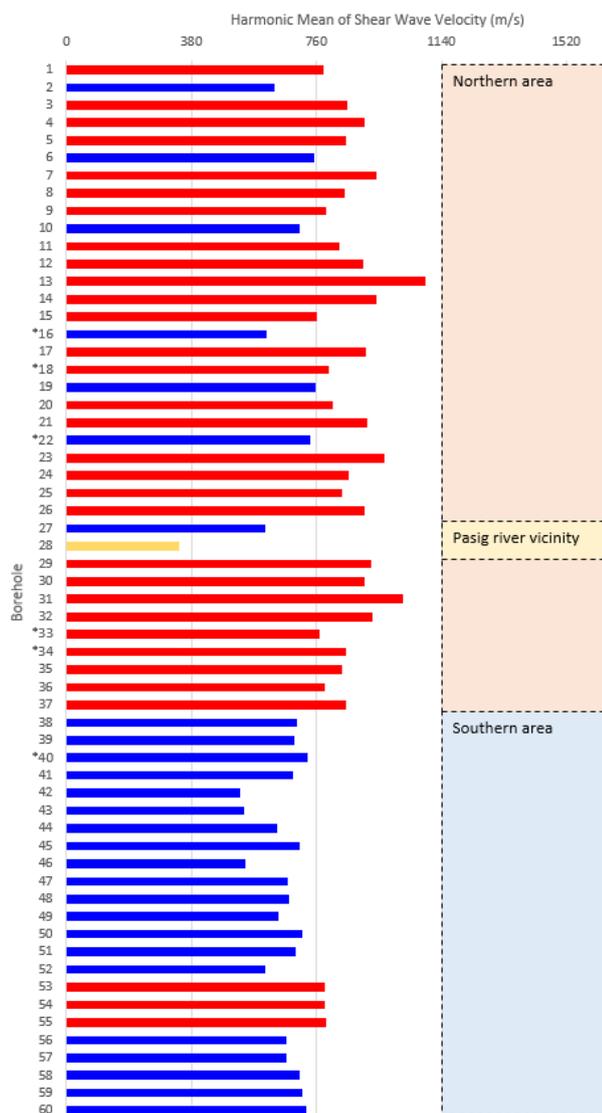


Figure 16. Range of computed $V_{s, hm}$ throughout the alignment

8. Conclusions

The geophysical survey conducted reveals that the GTF within Metro Manila can generally be divided into two areas. The northern area is characterized with relatively stiffer subsurface underlain by rocks while the southern area is underlain by soft rocks. The overall $V_{s, hm}$ is consistent with the conclusion deduced from the UCT which categorized the subsurface as soft rocks.

Seismic velocity logging, particularly PS suspension logging, provides an accurate way of measuring in-situ seismic wave velocities directly especially at depths deeper than 100 meters, which is its main advantage over surface wave-based methods because the subway alignment stretches over a lot of land with varying existing grade lines. For these types of projects that are located within the center of an already developed city, the PS Logger is also more convenient compared to other geophysical methods given the amount of vibrational noise at the surface due to moving traffic and ongoing construction works.

Also, the consistency of the results with the other tests conducted and the expected characteristics of the subsurface gave a higher level of confidence to the general condition of the project site. Furthermore, the shear wave velocities measured from the PS Logger can be used to validate the primary data (e.g. SPT N-value, UCS) obtained from past project, and can, perhaps, be even used to develop new correlationw between these parameters for the GTF.

Majority of subsurface explorations employed in the Philippines depend on standard tests such as the SPT and UCT. This study can be treated as a good starting point to further develop the geophysical testing practice in subsurface explorations in the country.

Acknowledgement

The authors would like express their utmost gratitude to MGB, PHIVOLCS, and USGS for the tremendous effort they have put into research which provided essential information to this study, and to Soil Philippines Index Testing, Inc. (SPI) for conducting the geotechnical investigation for this study. The authors would also like to thank AMH Philippines, Inc. and the organizers of the 6th International Conference on Geotechnical and Geophysical Site Characterization for providing the opportunity to present this study.

References

- [1] Nelson, A., et al. "Multiple Large Earthquakes in the Past 1500 Years on a Fault in Metropolitan Manila, the Philippines", Bulletin of the Seismological Society of America, 90 (1), pp. 73-85, 2000, doi: 10.1785/0119990002
- [2] Besana, M. G. "Evaluation of Earthquake Hazards in Metropolitan Manila", Earthquake Engineering and Disaster Management for Establishing Building Administration Systems in the Philippines (Phase II) Final Report: Part I, DPWH UNDP/UNCRD, World Bank, NEDA, Manila, 1992.
- [3] Besana, M. G. and Daligdig, J. A. "Hydrological and Meteorological Hazards in Metro Manila, Disaster Prevention and Mitigation Metropolitan Area", UNCHS Project INT 90 701, 1993.
- [4] Abeki, N., et al. "Site Response Evaluation of Metro Manila using Microtremor Observation", 11th World Conference on Earthquake Engineering, 1-8, 1996. ISBN: 0-08-042822-3
- [5] Japan International Cooperation Agency. "Chapter 2: Profile of the Study Area", pp. 1-33.
- [6] Mines and Geosciences Bureau. "Geologic Map of Manila and Quezon City Quadrangle".
- [7] Philippine Institute of Volcanology and Seismology. "PHIVOLCS Hazard Maps".
- [8] Hoek, Evert. "Practical Rock Engineering", 2007.
- [9] Robertson Geologging Ltd. "Digital P-S Suspension Logger Operations Manual"
- [10] Stein, S., Wysession, M. "An Introduction to Seismology, Earthquakes, and Earth Structure", Available at: <http://levee.wustl.edu/seismology/book/> [Accessed: 26 September 2019]
- [11] Mavko, G. "Conceptual Overview of Rock and Fluid Factors that Impact Seismic Velocity and Impedance", Stanford Rock Physics Laboratory, Available at: <https://pangea.stanford.edu/courses/gp262/Notes/8.SeismicVelocity.pdf> [Accessed: 26 September 2019]
- [12] Reynolds, J. "An Introduction to Applied and Environmental Geophysics", Available at: https://www.researchgate.net/publication/228078106_An_Introduction_to_Applied_and_Environmental_Geophysics [Accessed: 26 September 2019]
- [13] GEOvision, Inc. "PS Suspension Logging", Available at: <http://www.geovision.com/suspension.php> [Accessed: 26 September 2019]

- [14] 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.
- [15] Akin, M., Kramer, S., Topal, T. “Empirical correlations of shear wave velocity (V_s) and penetration resistance (SPT-N) for different soils in an earthquake-prone area (Erbaa-Turkey)” Available at: https://www.researchgate.net/publication/251558592_Empirical_correlations_of_shear_wave_velocity_V_s_and_penetration_resistance_SPT-N_for_different_soils_in_an_earthquake-prone_area_Erbaa-Turkey [Accessed: 26 September 2019]
- [16] Philippine Institute of Volcanology and Seismology “The Philippine Earthquake Model” Available at: <https://op.up.edu.ph/index.php/2018/01/18/the-philippine-earthquake-model-december-2017/> [Accessed: 02 September 2019]