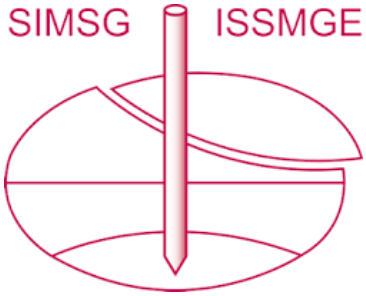
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Geological and Geotechnical Characterization for the Rehabilitation of the North-South Philippine Railway System

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ABSTRACT: A strategic transport system in the Philippines is essential to support the country's economic growth and growing population, consistent with the government's vision to promote inclusive growth and spur economic development in the underserved areas.

Currently, the railway system serving the National Capital Region has only four lines. Several other lines are presently under construction or in the planning and design stage. Meanwhile, the rehabilitation and development of the existing Philippine National Railway (PNR) mainline track is another major mass transport infrastructure.

The PNR North-South Commuter Rail Project will entail the construction of a 37.9 km rail system from the capital city of Manila to the nearby province of Bulacan, another 68.7 km rail from Bulacan to Clark Field in Pampanga, and a 68.5 km rail for the South alignment from Manila to the southern province of Laguna. The project shall include construction of viaducts, elevated embankments, bridge crossings, depots, a workshop and operations control center.

A reasonably comprehensive geological characterization, as well as geotechnical investigation and analysis play a critical role in the cost-effective design and implementation of the project, more particularly in the foundation design of the railway considering several geotechnical hazards. Some of these hazards include proximity of active faults, liquefaction, soft ground conditions, high groundwater level, expansive soils, and susceptibility to flooding (necessitating high embankments).

This paper presents the geological and geotechnical investigation carried out for the for the proposed rehabilitation of the PNR North-South Commuter Project, in the context of the revival of the Philippine railway system. The geotechnical investigation program, general characterization of the alignment based on the results of the investigation, and the assessment and recommendations for mitigation of various geotechnical hazards are discussed.

Keywords: Philippine railway system; geotechnical and geological hazards, geotechnical characterization

1. Introduction

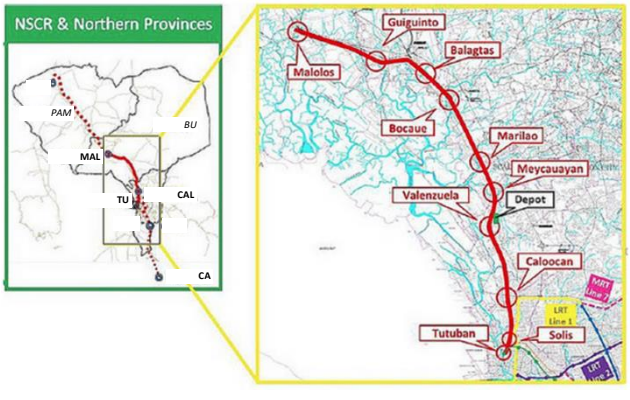
Part of the Philippine government's vision is to promote inclusive growth and spur economic development in the underserved areas. One way to fulfill this objective is to develop a strategic transport system in the Philippines.

Currently, there are only four (4) lines serving the National Capital Region (NCR): LRT Line 1 (from Baclaran to Roosevelt), LRT Line 2 (from Recto to Santolan), MRT Line 3 (from Taft to North Avenue), and the Philippine National Railway (PNR) South Commuter Line (from Tutuban to Alabang). This study focuses on the rehabilitation and development of the existing PNR mainline track.

The PNR North-South Commuter Rail Project will entail the construction of a 37.9-km rail system for the Solis station to Malolos station alignment, and another 68.7-km and 68.5-km rails for the North alignment (from Malolos to Clark stations) and South alignment (from Solis to Los Baños stations), respectively.

The project, whose objective is to link Metro Manila to the north and south areas of Luzon, shall include construction viaducts, elevated embankments, bridge crossings, depots, a workshop and operations control center, ten (10) initial stations (Solis to Malolos), eight (8) north line stations (Malolos to Clark), and twenty-three (23) south line stations (Solis to Los Baños).

Figure 1 shows the proposed alignment of the project.



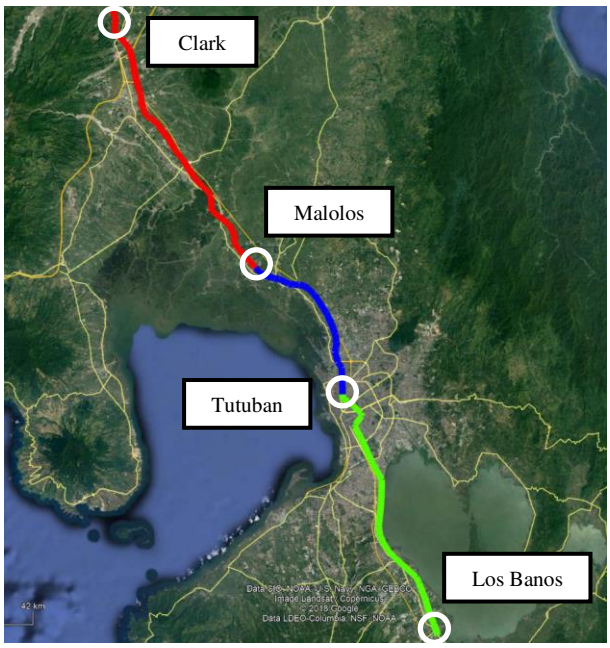


Figure 1. Alignment of the proposed railway.

2. Geology and Seismicity

The entire alignment can be subcategorized regionally and geologically into three (3) areas: National Capital Region, Central Luzon, and Southwest Luzon.

2.1. Geology

The alignment traversing NCR is characterized by quaternary alluvial deposits of variable thickness, consisting of clays, silts, and sands. These deposits are underlain by the Guadalupe Tuff Formation (GTF), the regional bedrock of Metro Manila. GTF, also commonly referred to as "adobe", has a thickness of 1,300 to 2,000 meters and is of Pleistocene age. It consists of well laid rock formation of tuffaceous sandstone, tuffaceous siltstone, and shale being the weakest the member. GTF basically falls in the category of very soft rock to hard or very dense soil.

The North alignment, which runs from Malolos to Clark, is part of the Central Luzon Basin. It consists of 8,000-m thick sedimentary sequence. Its western and eastern flanks are stratigraphically distinguished from each other. Sediments on the western side, which cover areas from Pampanga to Tarlac, are Neogene sediments dominated by Middle Miocene turbidites, that overlie directly the Eocene ophiolites of Zambales. The eastern side covers the Bulacan area and are characterized by a significant number of volcanic sources (such as volcanic sandstones and shales, tuffs, and by a shallow marine depositional environment).

The South alignment, which runs from Solis to Los Baños, is divided between National Capital Region and Southwest Luzon. As mentioned, the National Capital region is underlain by GTF. Meanwhile, Laguna area regionally falls at the Southwest Luzon Uplands. The stratigraphy of the area generally consists of alluvium, fluviatile, lacustrine, paludal, beach deposits, raised coral reefs, atolls, and beach rocks.

Figure 2 and Figure 3 show the geologic maps and alluvial cover thicknesses as described in the preceding paragraphs.

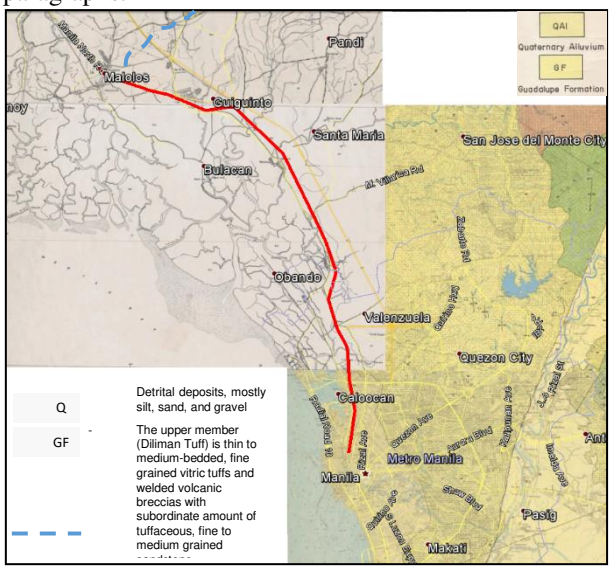


Figure 2. Combined detailed geologic maps of Bulacan area and Metro Manila.

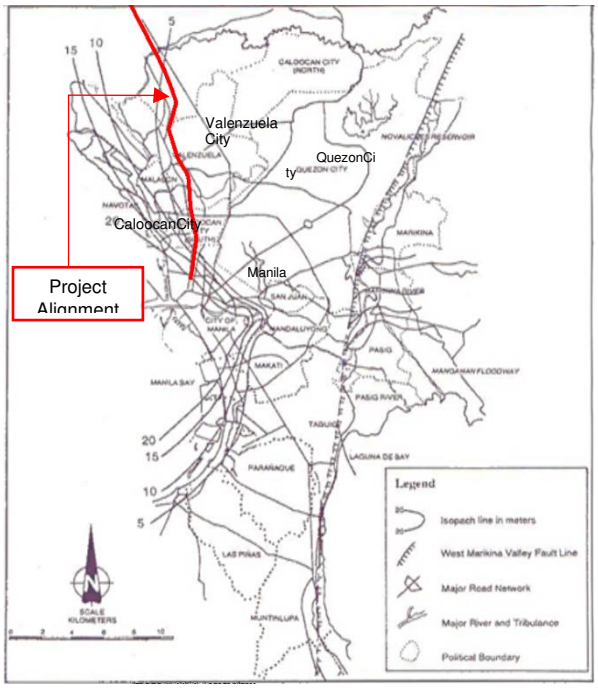


Figure 3. Map of alluvial cover thickness of Metro Manila (Source: PHIVOLCS)

2.2. Seismicity

The Philippines accounts for 3.2% of the world's seismicity. It is situated in the Circum-Pacific Belt or "Ring of Fire", where 80% of the world's earthquakes occur. Philippine seismicity is mainly related to plate subduction and in part to strike-slip motions along transcurrent faults.

Based on the seismic map by PHIVOLCS shown in Figure 4, the nearest seismic sources to the project alignment are East Zambales Fault (for the northern segment) and Valley Fault System (for the southern segments) that traverses a portion of the alignment as near as approximately 6.0km. The Valley Fault System is classified as Type A Seismic Source Type with distance

greater than 10km. A peak ground acceleration (PGA) of 0.5 was used as required by the project Owner.

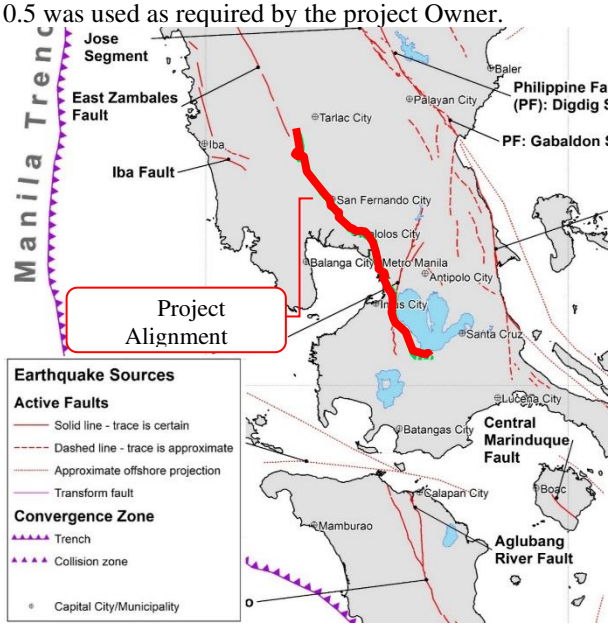


Figure 4. Distribution of active faults and trenches in the Philippines. (Source: PHIVOLCS)

2.3. Liquefaction

The Liquefaction Susceptibility Map published by Philippine Institute of Volcanology and Seismology or PHIVOLCS shown in Figure 5 indicate the alignment passes through some areas susceptible to liquefaction. These areas constitute parts of Central Luzon and the coastal areas of Metro Manila.

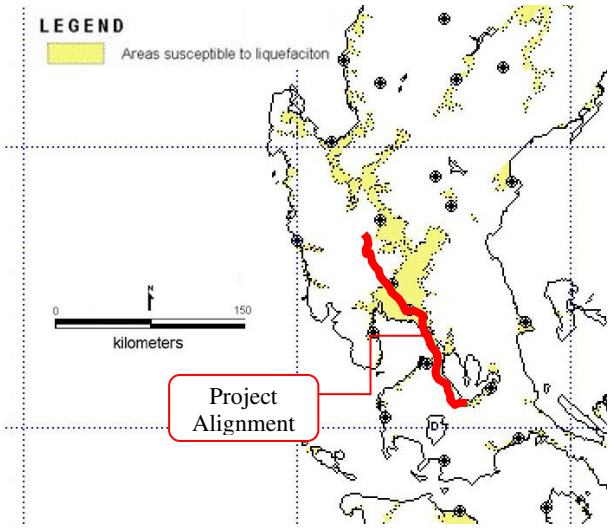


Figure 5. Liquefaction susceptibility map. (Source: PHIVOLCS)

2.4. Flood and Landslide

Based on the Mines and Geosciences Bureau (MGB) flood inundation map (Figure 6), most parts of Bulacan area and some parts of Pampanga area in the North Line have high susceptibility to flooding. Areas outside Bulacan have none to moderate susceptibility to flooding.

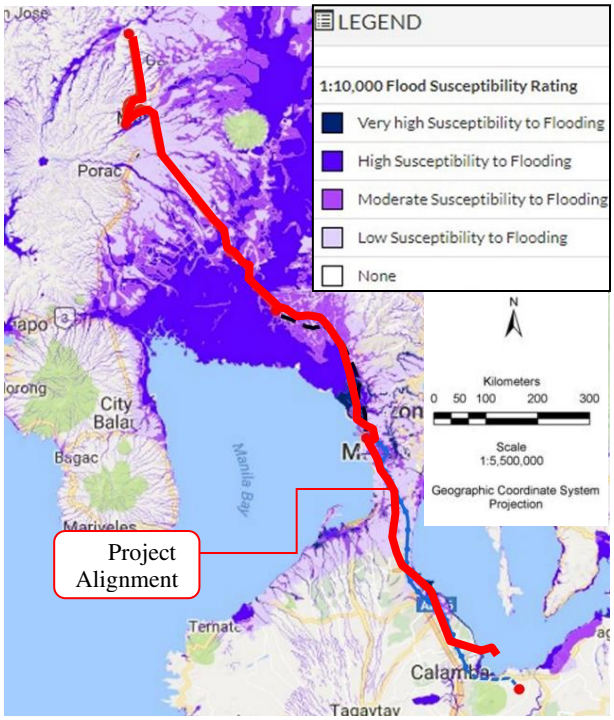


Figure 6. Flood susceptibility map. (Source: MGB)

Meanwhile, the landslide hazard map in Figure 7 shows that the entire alignment is not susceptible to landslides except for some areas in the north and south, which have low susceptibility to landslides.

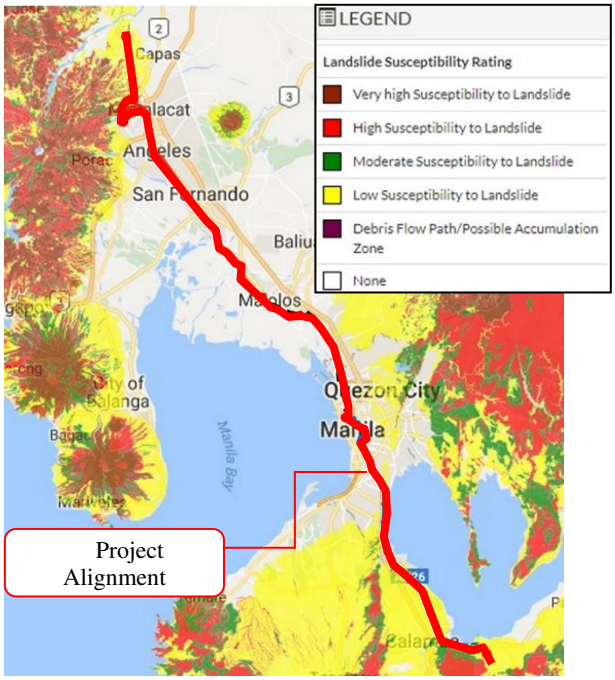


Figure 7. Landslide susceptibility map. (Source: MGB)

2.5. Tsunami

According to the United States Geological Survey or USGS, a tsunami is a sea wave of local or distant origin that results from large-scale seafloor displacements associated with large earthquakes, major submarine slides, or exploding volcanic islands.

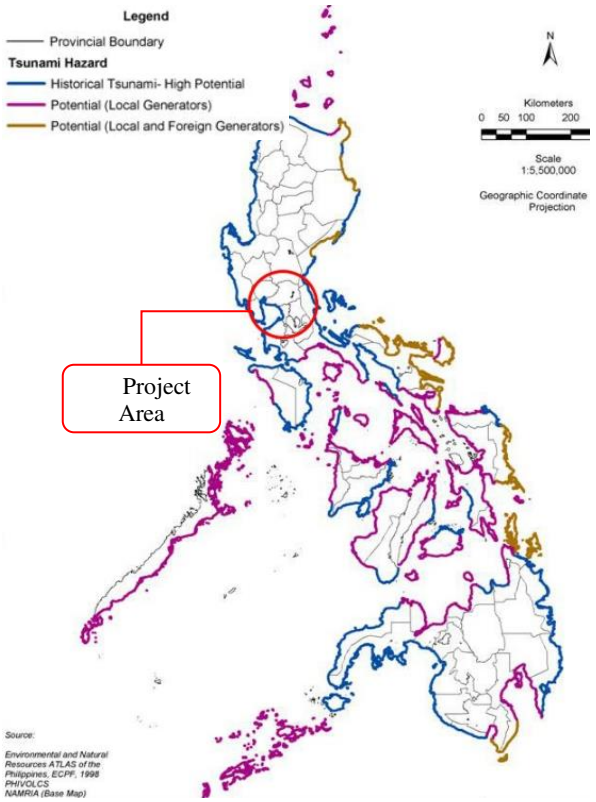


Figure 8. Tsunami vulnerability map of the Philippines (Source: Manila Observatory and DENR)

Due to the proximity of Manila Bay to the project alignment, especially the segment situated in Metro Manila, the susceptibility to tsunami is potentially high. This is supported by Figure 8, which is published by Manila Observatory and Department of Environmental and Natural Resources (DENR).

3. Subsurface Conditions and Geotechnical Assessment

Stated in the previous sections, the project alignment can be subdivided into three (3) regions, namely: National Capital Region, Central Luzon, and Southwest Luzon. Subsurface conditions and geotechnical assessment of these three (3) regions are discussed in the succeeding subsections.

3.1. Soil Investigation and Subsurface Conditions

As with any geotechnical assessment, the first step is to conduct soil investigation in order to gather data and information on the underlying soil layer/s. Soil samples are extracted from the ground and tested in the laboratory with the objective of classifying the soil materials and obtaining index and material properties. Results of such undertaking will be used to derive geotechnical parameters necessary for the conduct of various geotechnical assessment and analysis for the project.

For the PNR North-South Commuter Rail project, a total of four hundred ninety (490) boreholes were drilled along the entire alignment of the railway. Holes were drilled at an average depth of about 20.0 m from the ground, with an overall total aggregate depth of approximately 9.9 km. Water table is encountered at very shallow depths, mostly at ground level, since the alignment is located near the coastal area at the eastern side of Luzon.

With the railway alignment traversing different geologic areas across the Luzon Island, it is expected that soil stratification will vary for each identified geologic area. In general, the subsurface condition in areas along the alignment consists of thick soil cover, with areas nearer the coastline having relatively thicker soil layers, underlain by the predominant rock formation in Manila, the Guadalupe Tuff Formation, which consists of siltstones, sandstones, and shale.

In Bulacan area (upper portion of alignment), the site subsurface condition consists mostly of clays and silty sands underlain by sandstone or siltstone. Depth of rock formation varies depending on the local area.

In Valenzuela area (upper mid-portion of alignment), borehole data show that the upper soil layers are made up of medium dense to dense sands with some very stiff to hard clays, all underlain by Sandstone or Tuff formation.

In Manila and Caloocan areas (lower mid-portion of alignment), the site subsoil is predominantly made up of loose to medium dense sands, underlain by dense to very dense sands or stiff to hard clays. Rock formation were encountered in some boreholes at approximately 20m depth.

In Alabang area (lower portion of alignment), the subsurface condition consists of medium dense to dense sands, underlain by stiff to hard silts and clays and sandstone or siltstone.

Table 1. Summary of subsurface conditions

Area	Segment	Subsurface Conditions
Central Luzon (CL)	Meycauayan-Marilao	Upper 5.0m: Soft to very stiff clays and loose to medium dense sand. > 5.0m: Dense to very dense sands and hard clays
Metro Manila (MM)	Valenzuela	Upper 5.0m: Medium dense to dense sands and stiff silts/clays. > 5.0m: Sandstone and siltstone
Metro Manila (MM)	Manila-Caloocan	Upper 10.0m: Loose to medium dense sands >10.0m: Very dense sands, stiff to hard clays, sandstone and siltstone

South Luzon (SL)	Alabang-Los Banos	Upper 15.0m: Medium dense to dense sands > 15.0m: Sandstone and siltstone

The following figures below present the SPT N-value vs depth chart for the different areas considered. It should be noted that most of the borehole data came from Central Luzon (Meycauyan-Marilao segment) and Metro Manila area. Further testing would be conducted in order to fully characterize the subsurface condition in Southern Luzon.

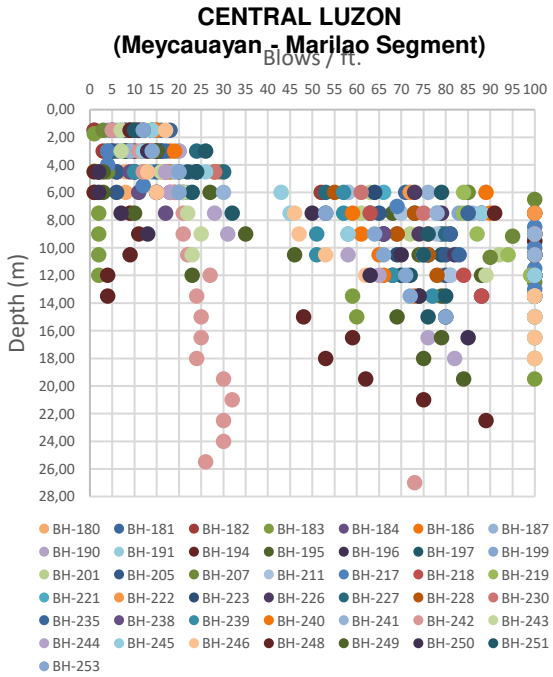


Figure 9. SPT N-value vs Depth chart for Central Luzon

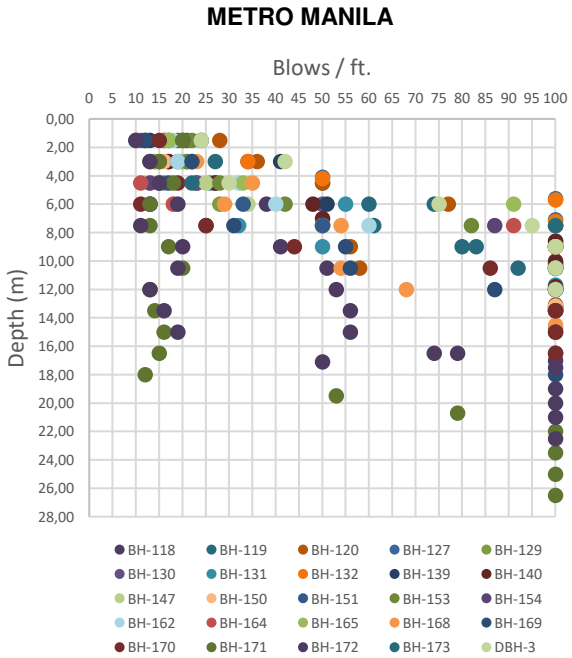


Figure 10. SPT N-value vs Depth chart for Metro Manila (1)

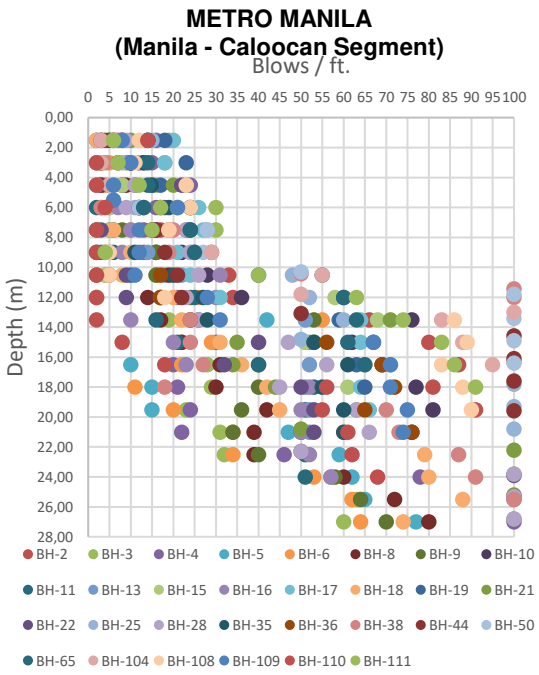


Figure 11. SPT N-value vs Depth chart for Metro Manila (2)

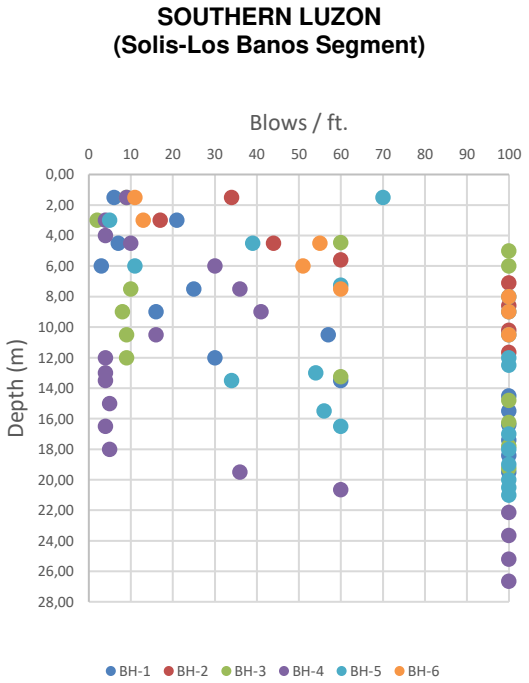


Figure 12. SPT N-value vs Depth chart for Southern Luzon

3.2. Shear Wave Velocity, Vs

The shear wave velocity is a measure of how the soil/rock material will respond when subjected to certain ground motion. Soils/rocks are classified using a site class system which is based on how fast seismic waves propagate through the strata and how stiff the subsoil is. In the National Structural Code of the Philippines 2015 (NSCP), soil/rock profile types are categorized by different site classes based on the average measured shear wave velocity of the top 30m (V_{S30}). V_{S30} is taken as the harmonic mean of the measured velocities with respect to depth:

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

where:
d_i – Depth of 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)

Table 3 presents the site classes based on shear wave velocities.

Table 2. Soil Profile Types (NSCP 2015)

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
S_A	Hard Rock	> 1500	
S_B	Rock	760 to 1500	
S_C	Very Dense Soil and Soft Rock	360 to 760	> 50
S_D	Stiff Soil Profile	180 to 360	15 to 50
S_E	Soft Soil Profile	< 180	< 15
S_F	Soil Requiring Site-specific Evaluation		

Shear wave velocities were measured in specific areas along the alignment of the proposed railway. Seismic Velocity Logging (SVL), an intrusive non-destructive test method, was used to determine the shear wave velocities of the underlying soil/rock layers and a Robertson Geo Suspension Logger (PS Logger) was utilized.

SVL tests were conducted for each identified geologic area in order to further assess and classify the subsurface conditions.

In Bulacan area (Central Luzon), due to the very soft conditions of the underlying soil, the holes were protected by a PVC-grout casing in order to prevent collapse during testing. Grout is injected to fill the voids or gap between the PVC and the soil. A grout mixture consisting of cement, bentonite, and grout was used in order to achieve the same density as the surrounding soil layers. Tests were conducted at every 1.0m for the entire 30.0m depth.

Results show that the upper 5m of soil layer have shear wave velocity values of V_S = 100 to 160 m/s, which are classified in the NSCP as Types S_E site classes with soft consistency and corresponding SPT N-values < 15.

Table 3. Summary of V_S for Bulacan area

Depth, m	Vs, m/s	Soil Type	Remarks
Upper 5.0m	100 to 160	S_E	Soft Soil



Figure 13. Seismic velocity logging in Bulacan Area (Central Luzon)

Figure 14 shows a typical V_s vs depth chart for the SVL test conducted at Bulacan area.

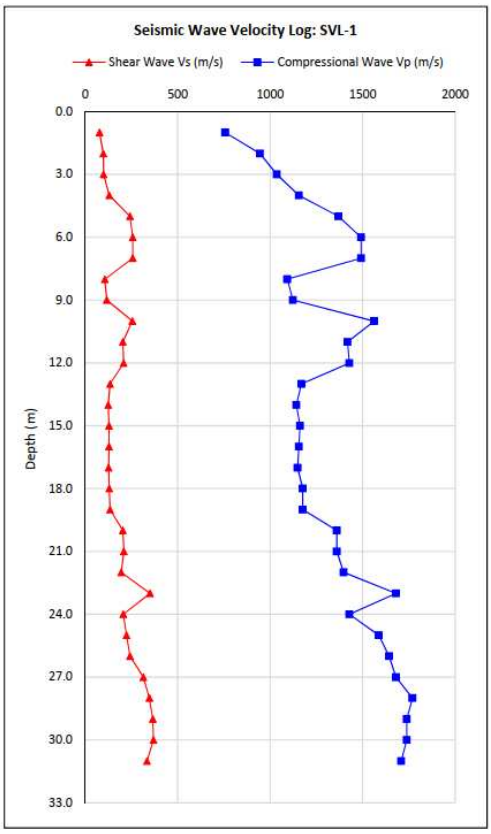


Figure 14. Typical V_s vs Depth chart for Bulacan Area (Central Luzon)

In Metro Manila area, no casing was necessary as the subsoil conditions are relative stiffer. Results of the testing show that the upper 5.0m has shear wave velocity of V_S = 180 m/s, classified as Type S_E soil (soft soil), and soil deeper have V_s = 446 to 1156 m/s corresponding to Type S_C soil (very dense soil and soft rock).



Figure 15. Seismic velocity logging in Metro Manila

Table 4. Summary of V_S for Metro Manila area

Depth, m	Vs, m/s	Soil Type	Remarks
Upper 5.0m	180 (ave)	S_E	Soft Soil
5.0m to 30.0m	446 to 1156	S_C	Very Dense Soil and Soft Rock

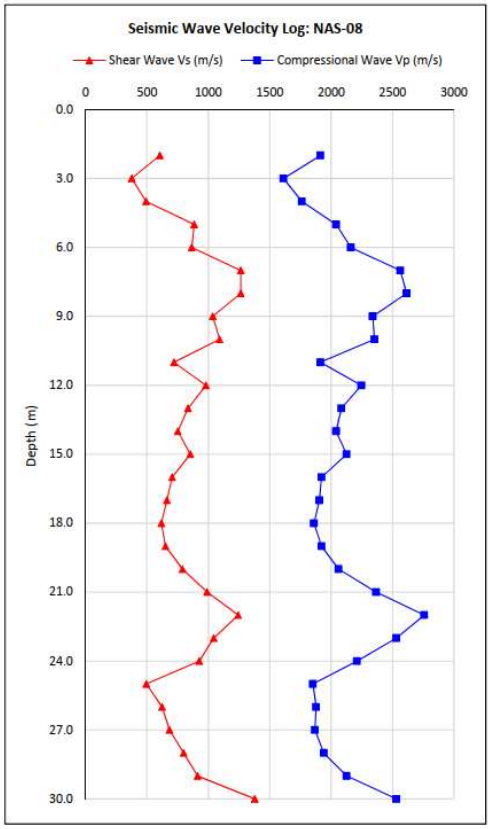


Figure 16. Typical V_s vs Depth chart for Metro Manila Area

Shear wave velocity testings at South Luzon area shall be conducted in the next phases of the project.

In general, the classification of the subsurface layers on both field testing (SPT) and geophysical testing (SVL) are consistent with one another. Furthermore, the results of the in-situ field testings are in agreement with the nationally published regional geologic map of Luzon.

3.3. Liquefaction

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 foundation during earthquake is attributed to this phenomenon.

Considering the data gathered from the geotechnical investigation (borehole data and measured shear wave velocity of the Central Luzon and Metro Manila area) conducted, and the relatively shallow groundwater level, liquefaction analysis was conducted in order to identify the areas along the project alignment that are deemed susceptible to liquefaction.

The liquefaction potential of the areas along the railway alignment is evaluated using two methods: 1) Procedures described in DPWH LRFD Seismic Bridge Design Specifications 2013 which is based in AASHTO LRFD Bridge Design Specifications, 6th Edition, and 2) Boulanger & Idriss 2014 method. The DPWH LRFD procedure is presented in Figure 17.

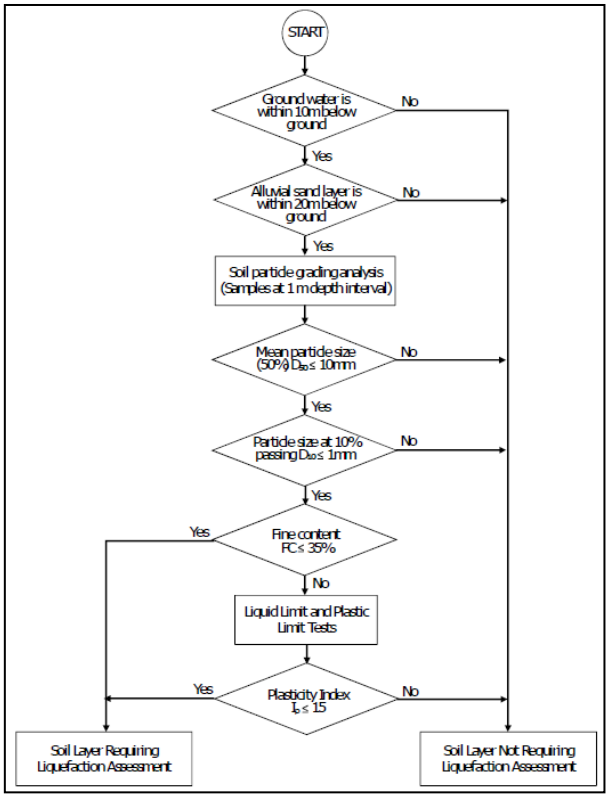


Figure 17. Determination of necessity for liquefaction assessment of soil layer (Source: DPWH LRFD Bridge Seismic Design Specifications)

The succeeding figures show the summary of the results of liquefaction analysis using both SPT N-values and Shear Wave Velocities.

Shown in the following figures are the results of the analysis utilizing the SPT N-value and shear wave velocity.

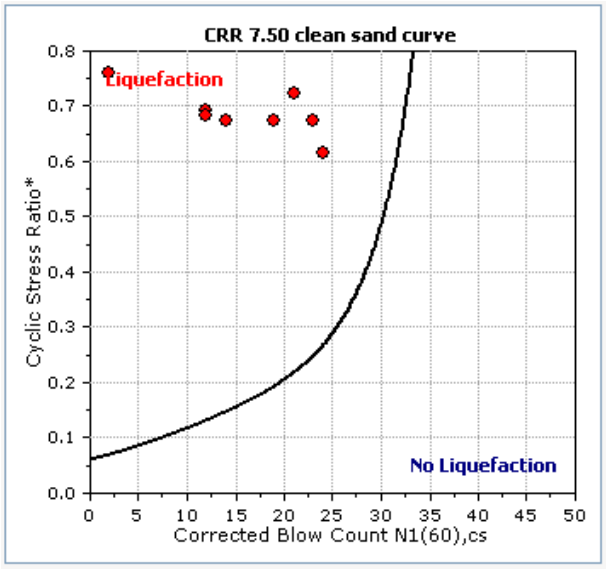


Figure 18. Liquefaction Susceptibility based on SPT N-value for Central Luzon

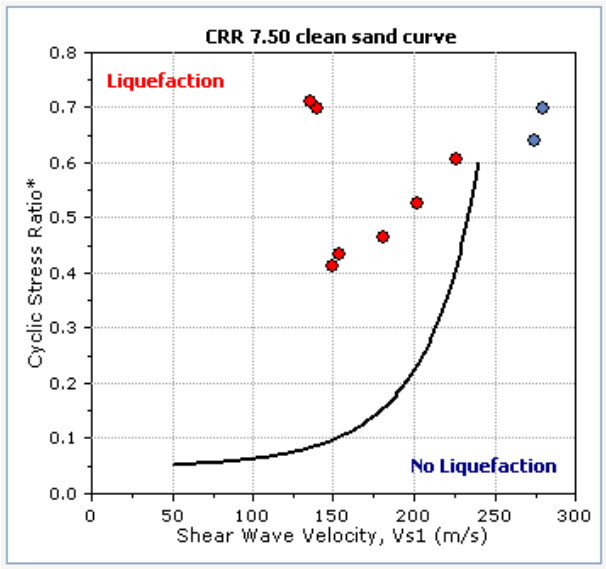


Figure 19. Liquefaction Susceptibility based on Vs for Central Luzon

It could be observed that some data points from Figure 19 can be considered as borderline-liquefiable (FS < 2 for liquefaction). However, it was treated as liquefiable layer as suggested by the SPT-N value (Figure 18).

In the Metro Manila – Valenzuela segment, the liquefiable layer depth was determined to be 15m. Likewise, some data points from Figure 21 were treated as liquefiable.

Upon analysis of the Manila-Caloocan segment in the Metro Manila area, it was found out that a layer depth of 10.5m was considered to be liquefiable (Figure 22). However, it should be noted that based on Vs, depths 10.5m to 18m is borderline liquefiable (see Figure 23) due to the computed FS against liquefaction being less than two (2).

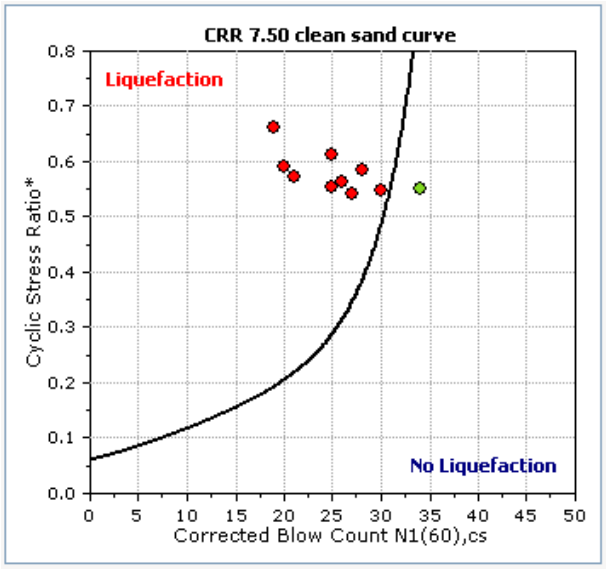


Figure 20. Liquefaction Susceptibility based on SPT N-value for Metro Manila (Valenzuela segment)

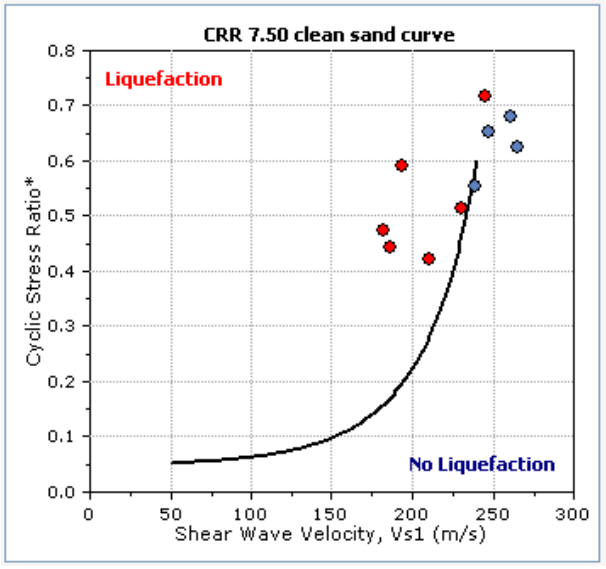


Figure 21. Liquefaction Susceptibility based on Vs for Metro Manila (Valenzuela segment)

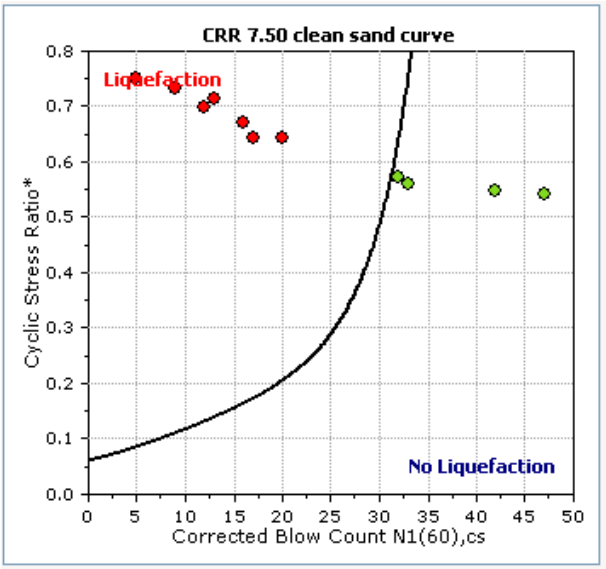


Figure 22. Liquefaction Susceptibility based on SPT N-value for Metro Manila (Manila-Caloocan segment)

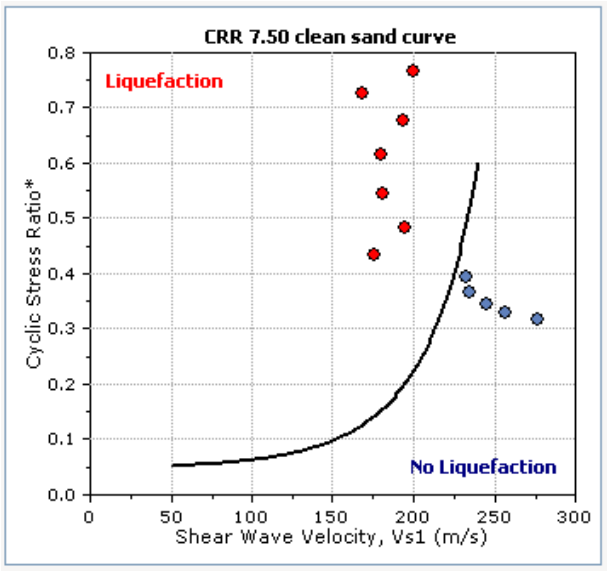


Figure 23. Liquefaction Susceptibility based on Vs for Metro Manila (Manila-Caloocan segment)

Since geotechnical investigation is yet to be conducted for South Luzon, liquefaction analysis cannot be conducted for this area.

The results of the analysis were compared with the Liquefaction Susceptibility Map. Figure 24 presents the locations of the boreholes analyzed overlain on the Liquefaction Susceptibility Map. The railway alignment is represented by the green line and the yellow shaded areas are the areas that are potentially liquefiable based on the hazard map. Therefore, the analysis conducted is consistent with the published hazard map.

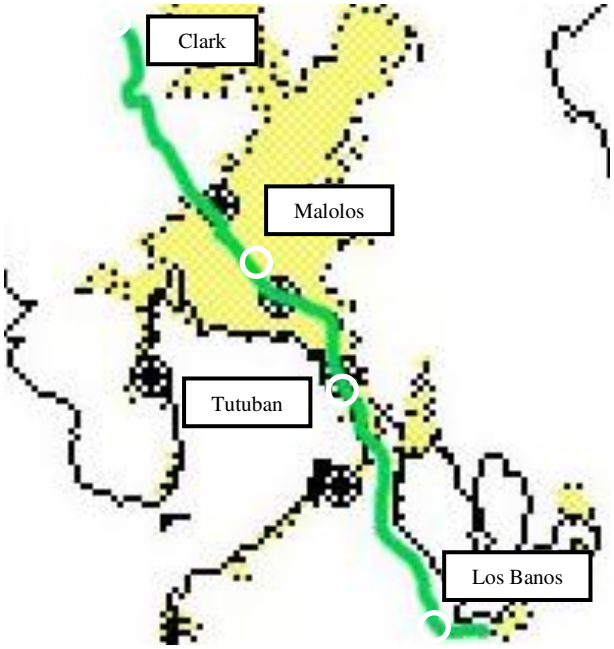


Figure 24. Map of areas with potentially liquefiable subsurface

3.4. Settlements

In some sections along the proposed alignment, the railway will be constructed on top of embankments in order to provide a stable platform and foundation, and elevate the level of the alignment to satisfy the civil and hydraulics requirements of the design. These embankments will then induce surcharge loads to the underlying soft clay/loose sand layers which may cause both immediate and long-term (consolidation) settlements. Such settlements should be considered and accounted for in the design of both the embankment and the railway structure, i.e. determination of required fill thickness, allowable settlement (uniform and differential), consolidation time, etc.

Settlement analyses were carried out using the Settle3D software by Rocscience, which is based on the one-dimensional consolidation theory by Terzhagi, in order to estimate the magnitude of ground settlement/deformation.

Settlement parameters were obtained and derived from the field and laboratory tests. Average depth of compressible layers for each area are: Manila-Caloocan segment (Metro Manila): 1.5m to 6.0m; Valenzuela-Meycauayan segment (Metro Manila): 2.0m to 3.0m; Marilao-Malolos segment (Central Luzon): 2.0m to 12.0m; Alabang (Southern Luzon): 5.0m to 12.0m. The geotechnical parameters used in the analyses are:

Table 5. Settlement parameters

Parameters	Values
Compression index, C_c	0.15 to 0.3
Modulus of elasticity, E	3 MPa (loose/soft soil) to 75 MPa (rock)
Initial void ratio, e_0	0.5 to 2.38

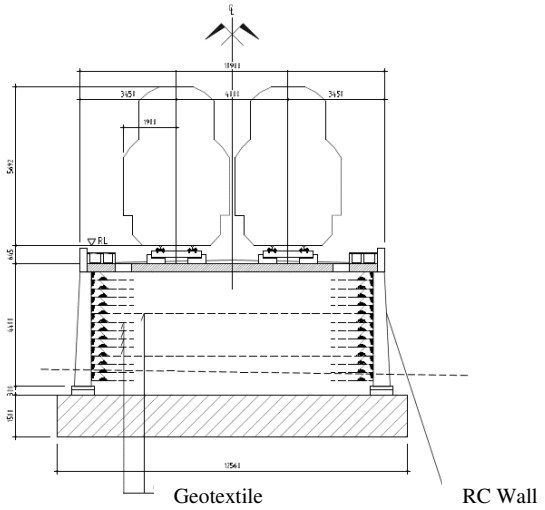


Figure 25. Typical embankment section

The embankment section is modeled as a surcharge load on top of the existing ground with the following parameters: Height=5.0m; Width=12.56m; Length=37.68m; Depth of embedment=2.0m; Unit weight=18 kN/m^3.

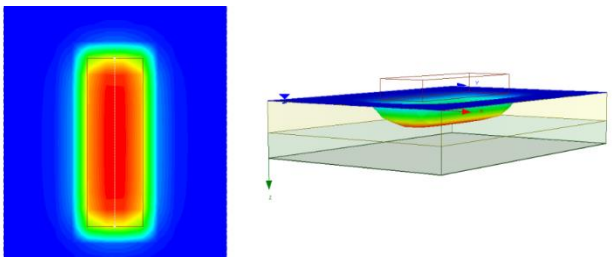


Figure 26. Settle3D model

Excessive settlements were estimated for most of the sections analyzed. Calculated immediate settlements range from 2mm to 68mm mostly for the granular sand layers while long-term (consolidation) settlements range from 240mm to 935mm for fine-grained clays/silts. These were anticipated due to the presence of thick soft clay layers and loose sand layers in these sections.

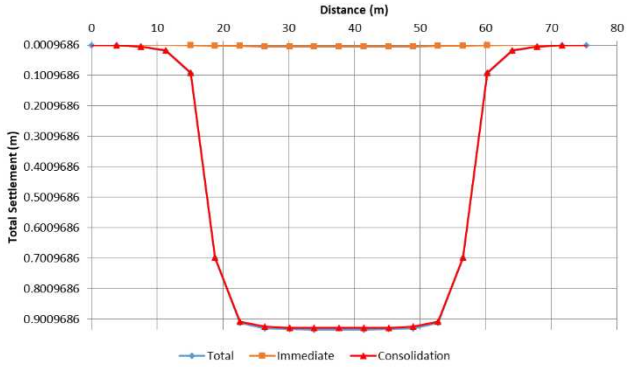


Figure 27. Typical depth vs. settlement graph

Considering such results, ground improvement measures as well as deep foundations are recommended to be explored to mitigate excessive consolidation settlement. Examples of ground improvement are preloading/surcharging with vertical drains, stone columns/aggregate piers, soil-cement column, deep compaction, vibro-compaction/vibro-flotation, etc. Ground improvement will mitigate settlement while also improving the bearing capacity of the underlying soil, while deep foundation will bypass the loose/soft soil layers and mobilize strength of the hard strata.

4. Summary and Conclusion

One objective of the Philippine government is to promote inclusive growth and spur economic development in the underserved areas. The development of a strategic transport system in the Philippines will positively fulfill this objective.

In line with the government's vision, the PNR North-South Commuter Rail Project, which connects Metro Manila to the north and south areas of Luzon, aims to revitalize the PNR mainline track. The project will not only offer convenience to passengers, but will also improve the economic activity in the areas.

As the Philippines continue to embark on major projects like this, aimed at closing the huge transport infrastructure gap, close collaboration of geologists, engineers and allied professionals is essential. The application of new technologies in geophysical and geotechnical characterization significantly contributes in ensuring a safe, cost-effective and sustainable design.

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