Design considerations for high reinforced soil structures in a mountainous and seismically active region in Luzon, Philippines

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ABSTRACT: Development in mountainous areas of the Philippines has been continuous over the last decade. Working on these areas often involve the alteration of the topography to make space for roads, utilities, and pads for buildings, thus, requiring the construction of soil retaining structures. Conventional retaining structures such as reinforced concrete retaining walls and rubble masonry walls are commonly used in these areas. However, these types of structures are very rigid, can accommodate minimal differential settlement, may hamper the drainage of the adjacent soil mass, and are not economical for very high fills. Reinforced soil retaining structures were found to be better alternatives when working with high fills where settlement and drainage are a concern. This paper presents the design considerations for high Reinforced Soil Structures (RSS) considering the topography, drainage requirements, volcanic and tectonic earthquakes. Design methodology and construction considerations shall be discussed. Slope modelling and stability analysis utilizing limit equilibrium methods shall likewise be presented.

Keywords: Reinforced Soil Structures, soil retaining structures, stability analysis

1 INTRODUCTION

Recent developments in the Philippines have been extended to mountainous areas. Working on these areas often require alteration of the topography to make space for roads, utilities, and pads for buildings. These modifications to the topography often require the construction of earth retaining structures. Typical earth retaining structures are usually rigid which are composed of reinforced concrete or rubble masonry walls. The use of flexible type of earth retaining system has been established to be more effective when working with relatively high slopes. This type of protection is composed of granular backfill, reinforcements (geogrids), and facing. Depending on the adequacy of the subgrade, ground improvement may be needed.

This paper presents the design considerations for high reinforced soil structures (RSS) constructed on a seismically active mountainous region.

2 SITE CONDITIONS

A project site in Laurel, Batangas required the construction of an access road as part of its site development. The project site is located northwest of Taal Volcano and Lake, southwest of Laguna Bay, and South of Manila Bay.

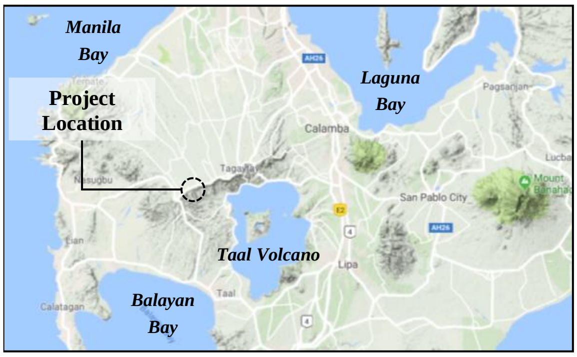


Figure 1. Location and vicinity map of the project site

2.1 *Topography*

The project site is located along the Tagaytay ridge with an average elevation of 600 meters above mean sea level. Tagaytay and Laurel, Batangas have generally rolling terrain, sloping downward towards Taal Lake. As such, structures for the developments on these areas often require alteration of the topography.

2.2 *Seismicity*

The Philippines is situated within the Circum-Pacific Belt or the “Ring of Fire”, where 80% of the world’s earthquakes occur. The country’s seismicity is mainly related to plate subduction and in part to strike-slip motions along trans-current. The nearest active seismic sources in Tagaytay are the West Valley Fault System and the offshore Lubang Fault which is located between the islands of Batangas and Mindoro. Considering these, earth retaining structures must be designed to withstand ground acceleration due to earthquakes that will be generated by the mentioned active seismic sources.

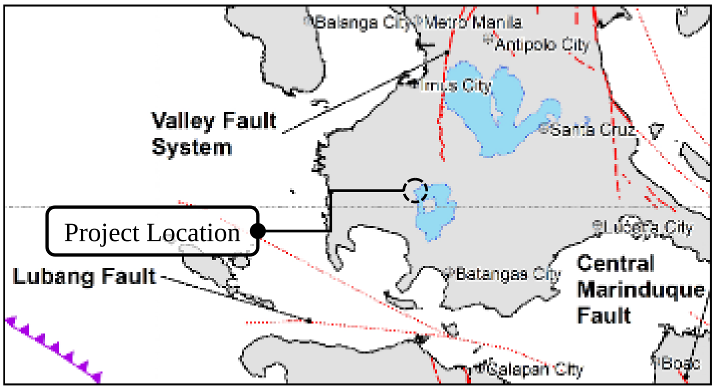


Figure 2. Extract from Active Faults and Trenches of the Philippines (PHIVOLCS)

2.3 *Precipitation*

On the average, twenty tropical cyclones pass through the Philippines, five of which can be classified as destructive. Moreover, the country often experiences heavy rainfall during Habagat or Southwest monsoon season which falls on the months of June to October. Based on the records of Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), the average rainfall on the month of September from 1981-2010, ranges from 300mm to 500mm in most areas of Luzon.

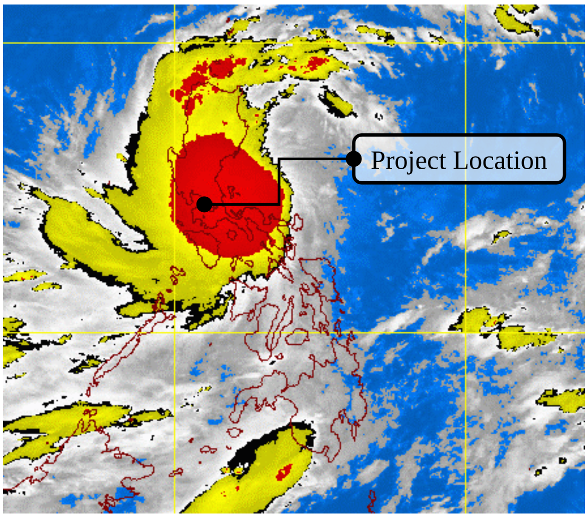


Figure 3. Satellite image During Typhoon Ketsana in 2009 (PAGASA)

2.4 *Geologic and geotechnical conditions*

The area is generally underlain by quaternary volcanic piedmont deposits which are chiefly pyroclastics and volcanic debris from the eruption of the Taal Volcano. These pyroclastics generally consists of interbedded shale and sandstone with thin layers of tuff and reworked sandy tuffs, calcareous and partly tuffaceous shale. The results of soil investigation reveal that the project site is generally composed of relatively thick residual soil which are classified as silt and silty sand. The geotechnical parameters that were used in the slope stability analyses are presented in the succeeding table.

Table 1. Soil Parameters

Depth (meters)	Type of soil	γ (kN/m^3)	c (kPa)	φ (degrees)
0.0 – 5.0	SM	18	5	30
5.0 – 10.0	SM	18	10	32
10.0 – 20.0	SM	19	15	35
> 20.0	SM	20	20	37

3 SITE DEVELOPMENT AND REINFORCED SOIL STRUCTURE (RSS)

The development of the project site calls for the construction of an access road with segments of hairpin configuration. Considering the topography of the project site and the proposed layout of the access road, earth retaining structures would be needed to support the backfill for the road construction. With this, a flexible system such as reinforced soil system was deemed to be one of the most effective solutions. Taking into consideration the seismicity of the project area, a flexible system would also allow considerable deformation compared to rigid concrete retaining structures.

The reinforced soil slope (RSS) scheme was composed of granular backfill, geosynthetic reinforcement (geogrid), and subsurface gravel drains. Considering the topography of the project site and the anticipated surface and subsurface flow of water during heavy precipitation, gabion facing was selected because of its better drainage characteristics.

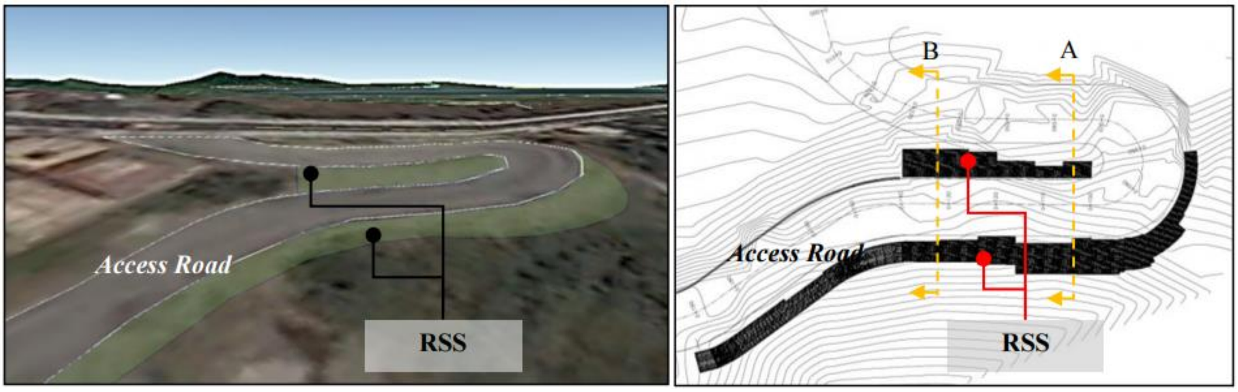


Figure 4. Hairpin access road with RSS structure

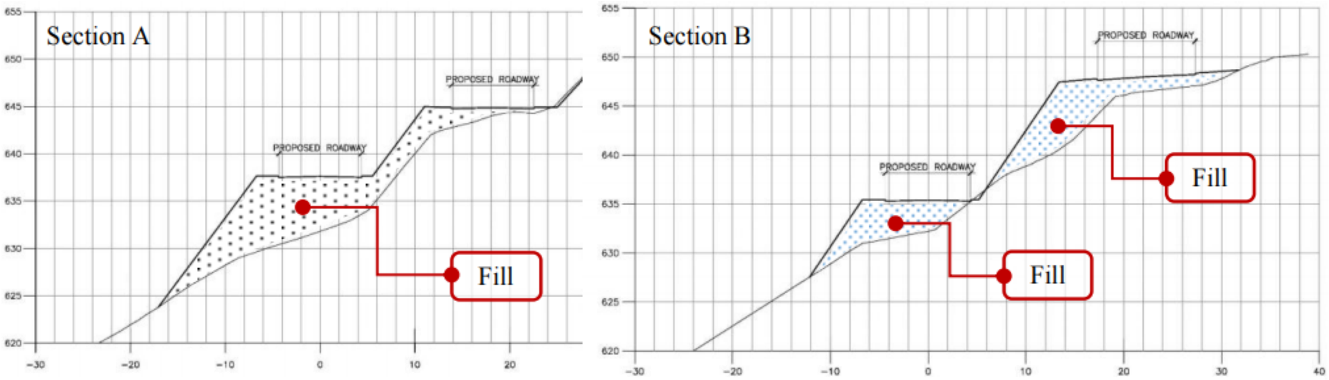


Figure 5. Sample road sections on hairpin access road

4.1 *Slope height*

Based on the proposed road alignment and topography of the project site, resulting RSS heights range from 18 m to 23 m within the hairpin area. Considering the offset distance due to road width, superimposed RSS wall design was considered in the analysis.

4.2 *Saturation*

Considering the rainfall record of the project area, it is essential to ensure that earth retaining structures would be able to accommodate additional pore water pressure due to saturation of the soil. Appropriate drainage management system, both for surface and subsurface water flow, was incorporated in the design of earth retaining structures. To simulate soil saturation in the design, pore water pressure ratio (Ru) was incorporated in the analysis.

$$R_u = \frac{u_w}{\sum(\gamma_t)_i h_i} \tag{1}$$

where u_w = pore water pressure
γ_t = total unit weight
h_i = thickness of each layer of overlying soil

Design Ru of 0.20 and 0.45 were assigned for partially and fully saturated conditions, respectively.

4.3 *Seismic Acceleration*

The project site is located in a seismically active region. As such, it is necessary to design the reinforced soil structure to withstand seismic acceleration. Deterministic approach using the attenuation model of Fukushima and Tanaka was utilized to evaluate the possible ground motion in the project area.

$$\log_{10} A = 0.41M - \log_{10}(R + 0.032 \times 10^{0.41M}) - 0.0034R + 1.30 \qquad (2)$$

where A = peak ground acceleration (m/s^2)
M = earthquake magnitude
R = distance of the seismic source

The nearest seismic sources, West Valley Fault (WVF) and Lubang Fault (LF), were considered in the analysis. Considering the assigned magnitude and proximity to the project site of these seismic sources, PGA values of 0.30g and 0.28g were computed for WVF and LF, respectively. Moreover, peak ground acceleration (PGA) values, were also verified from the PGA Acceleration Map of the Philippines published by PHIVOLCS. Based on this, the project site may experience PGA between 0.3g and 0.4g.

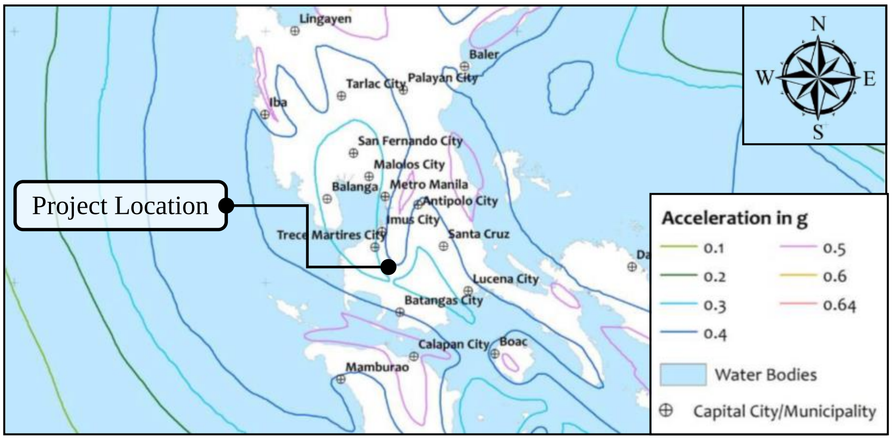


Figure 6. Extract from Peak Ground Acceleration Map of the Philippines for 500-yr Return Period on Stiff Soil (PHIVOLCS)

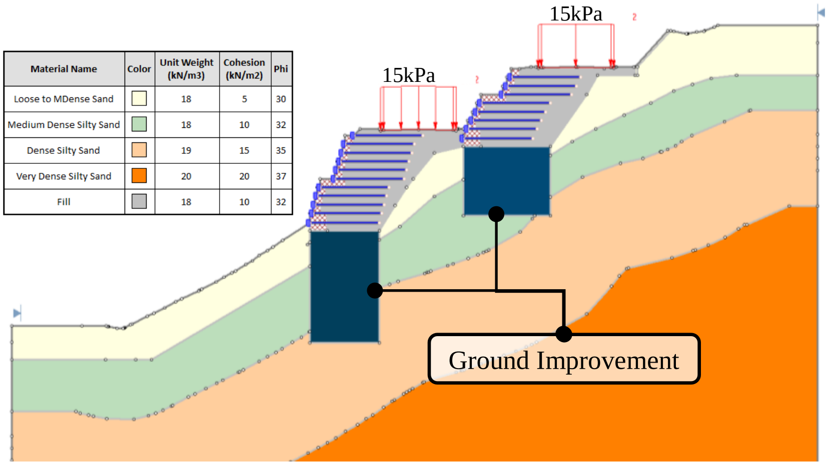
For prudence, PGA value of 0.4g was used in the analysis. Thus, for the design of the reinforced soil structures, a maximum horizontal (kh) and vertical (kv) seismic acceleration of 0.2g and 0.1g, respectively, were considered in the analyses. These seismic coefficients were based on the recommendations of Hynes-Griffin and Franklin to consider coefficients equal to 0.5 of the PGA.

5 STABILITY ANALYSIS

To verify the stability of the proposed scheme for different scenarios, slope stability analyses were conducted. Slope modelling and stability analyses were conducted using Rocscience Slide software.

5.1 *RSS model*

A slope model considering the existing topography of the project site and proposed road alignment was generated for analysis. The model includes the soil stratigraphy and corresponding strength parameters, soil reinforcements (i.e. geogrid), and ground improvement. Moreover, a traffic load of 15kPa, in anticipation of the heavy construction equipment that will utilize the road, was applied.



Material Name	Color	Unit Weight (kN/m3)	Cohesion (kN/m2)	Phi
Loose to MDense Sand	☐	18	5	30
Medium Dense Silty Sand	🟩	18	10	32
Dense Silty Sand	🟧	19	15	35
Very Dense Silty Sand	🟧	20	20	37
Fill	⬜	18	10	32

Figure 7. Slope Stability Analysis Model

5.2 *Global stability*

The stability analyses considered different soil saturation and seismic acceleration conditions. The following scenarios were analysed.

Table 2. Slope Stability Analysis Scenario

Case		Ru	kh	kv	Min. FS
1	Dry and Static	0	0	0	1.5
2	Partially Saturated and Static	0.2	0	0	1.5
3	Fully Saturated and Static	0.45	0	0	1.25
4	Dry with moderate earthquake	0.0	0.1	0.05	1.1
5	Dry with strong earthquake	0.0	0.2	0.1	1.1
6	Partially saturated with strong earthquake	0.2	0.2	0.1	1.1

The acceptable factors of safety are based on various considerations such as the recurrent period of heavy rainfall, seismic activity, as well as the assessment of risk or hazard brought about by the slope failure. With these factors considered, recommended factors of safety for static conditions range from 1.2 to 1.5, and a value greater than unity (>1.0) for earthquake conditions (Cheng, et. al., Duncan, et. al., Towhata).

The final design was based on the results of Case 6. The results of other cases were used as reference and guide for further optimization and evaluation depending on the risk appetite of the stakeholders.

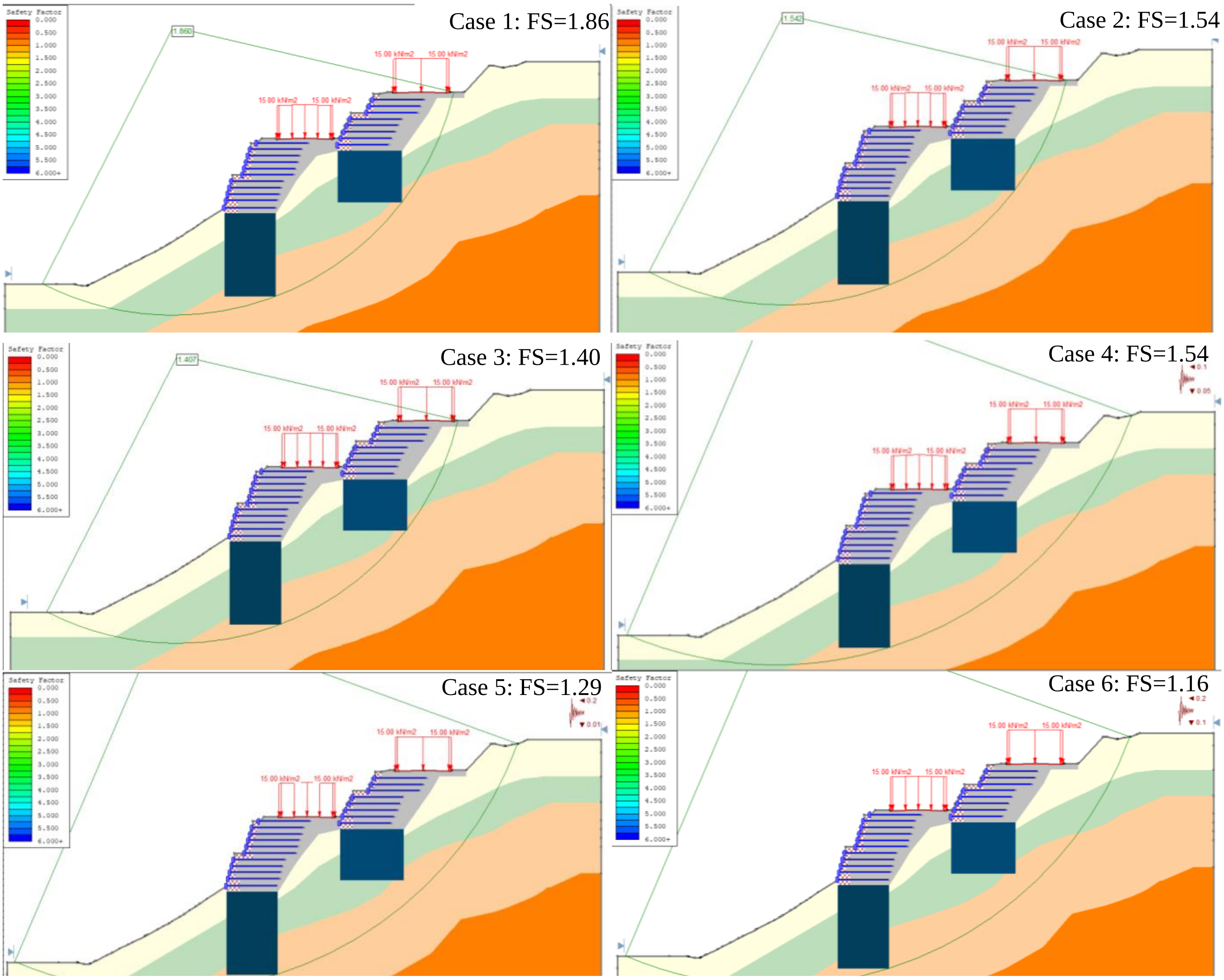


Figure 8. Slope Stability Analysis Results

5.3 *External and internal stability*

Further analyses, which involve the checking of external and internal stability of the RSS, were carried out for slope sections every 10 meters along the road alignment. Analyses were conducted to check the stability of each section against overturning, sliding, eccentricity, bearing capacity, and pullout resistance of reinforcement. The minimum factors of safety are based on the recommendations of Berg et. al.

Table 3. External and Internal Stability Check

1	Sliding minimum FoS	1.5
2	Overturning minimum FoS	1.5
3	Bearing Capacity minimum FoS	2.5
4	Settlement Limit	50 mm
5	Pull out minimum FoS	1.5

5.4 *Foundation and ground improvement*

Considering the height of the structure, it was anticipated that it will induce significant load on the slope. Based on the soil investigation results, the upper layers of the subsoil where the RSSs will rest, predominantly consist of loose to medium dense sand. As such, ground improvement techniques such as jet grouting and stone columns, were utilized to support the structures. Moreover, these were also employed to intercept deep seated failure surfaces.

Figure 9. Jet grouted piles and stone columns construction photos

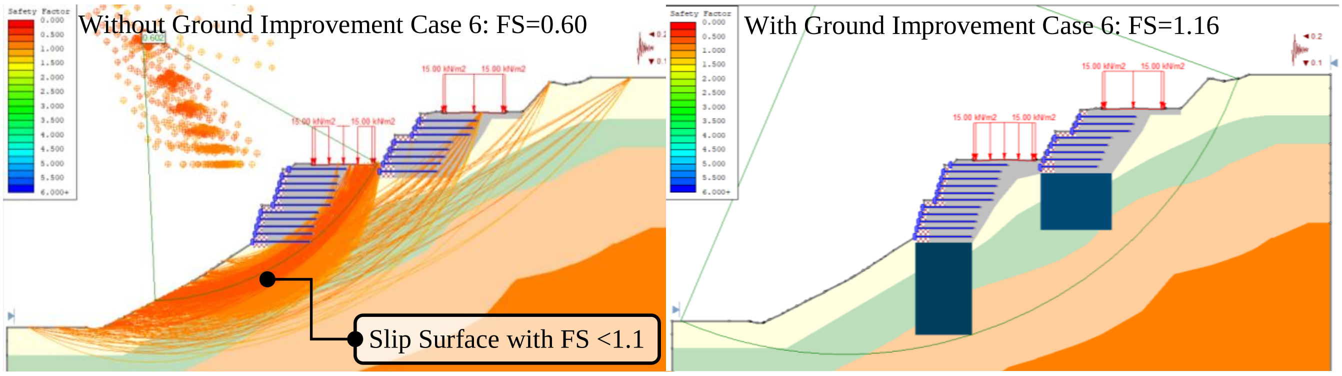


Figure 10. Slope Stability Analysis Results with and without Ground Improvement

5.5 *Drainage*

Considering the heavy precipitation the project site experiences during the monsoon seasons, proper drainage management system is essential. Subsurface drainage composed of gabion mattresses similar to a chimney drain were placed behind the reinforced soil mass. This was intended to collect and minimize water to enter the reinforced zone and allows it to flow downward and towards the gabion face of the wall.

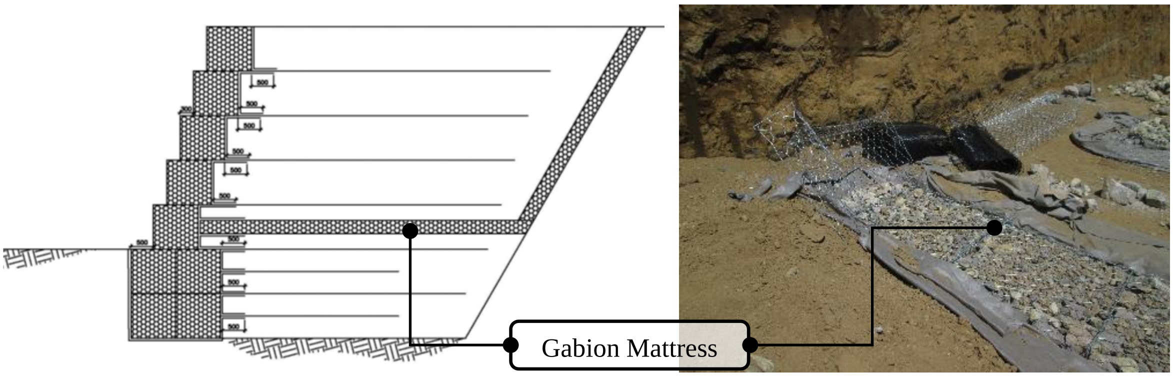
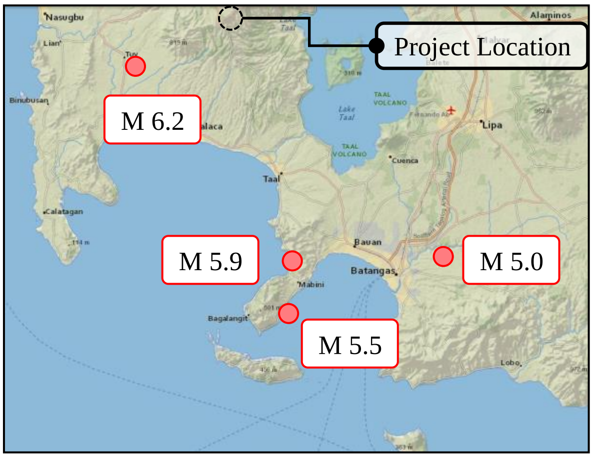


Figure 11. Typical RSS section with subsurface drainage and sample photo of gabion mattress

6 SEISMIC PERFORMANCE

Recently, several strong earthquakes occurred within the vicinity of the project site. At least four (4) major earthquakes were recorded in April and August 2017. The locations of the focus are within 20 km to 40 km from the project site. Considering these recent earthquakes, no deformations or damages on the constructed RSS were reported.



	Date	Magnitude	Epicenter
1	2017 April 08	5.0	4 km SSW of Ibaan
2	2017 April 08	5.5	3 km S of Talaga
3	2017 April 08	5.9	1 km NNW of Mabini
4	2017 August 11	6.2	1 km SE of Tuy

Figure 12. Location of earthquake epicenters and magnitudes

Figure 13. Photos of the RSSs after earthquake showing no damage (photo taken June and September 2017)

7 CONCLUSION

RSS Structures are deemed to be an effective and suitable scheme for high retaining structures in a seismically active region and in areas subjected to high rainfall. Considering the seismicity of the project area, it is essential to account the possible ground acceleration due to adjacent active seismic sources in the analysis. Furthermore, provision for proper drainage management system, for both surface and subsurface flows is also an important component of the system.

The constructed RSS structures show no deformation or damage despite the recent strong earthquakes within the vicinity of the project area with magnitudes ranging from 5.5 to 6.2.

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