Assessment and mitigation of earthquake-induced landslides in Philippine infrastructure

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ABSTRACT

A case study of an industrial facility located in the Visayas Region in the Philippines is presented. A magnitude 6.5 earthquake hit the province on 6 July 2017. The tremor was an extreme event such that even slopes with moderate landslide susceptibility ratings failed. Major facilities, such as power plants, pipelines, and access roads were heavily damaged.

Hazard assessment was conducted in several facilities to determine post-earthquake conditions of the surrounding terrain (slopes, waterways, etc.) and of the structures. Among the areas inspected, nine (9) areas within the reservation were tagged as "high" risk areas. Thus, detailed engineering was done to mitigate the recurrence of hazards. Structural measures such as soil nailed wall system, mechanically stabilized earth (MSE) walls, and, micropiles as cut-off wall were proposed as landslide mitigating measures. Moreover, non-structural measures were also proposed in order to minimize the risk of further landslide.

Keywords: earthquake-induced landslides, risk reduction, hazard mitigation, slope protection measures

1 INTRODUCTION

The Philippines, being located in the Pacific Ring of Fire, is one of the countries most exposed to seismic hazards. An archipelago of more than 7,100 islands, the country has high seismicity with 58,000 instrumental records of earthquake from 1900 to 2015 according to the Philippine Institute of Volcanology and Seismology (PHIVOLCS).

The country consists of islands which are mostly mountainous, and volcanic in origin, with relatively young geological, and geomorphological features. These mountainous terrains are located above one of the major active tectonic features of the country, the Philippine Fault Zone (PFZ) that transects the whole archipelago. The country also has 23 active volcanoes, 21 of which have historical eruptions according to PHIVOLCS.

As such, the country is highly susceptible to catastrophic events such as landslides, liquefaction, debris flows, etc. The highly-altered geologic formation of the Philippines also influences the hazards associated with the catastrophic events.

Most of the seismic activities in the country is confined to the Philippine Mobile Belt. This refers to the portion of the Philippine Archipelago that is sandwiched by the Manila-Negros-Cotabato Trenches on the west, and the Philippine Trench-East Luzon Trough on the east and traversed along its entire length by the 1,200-kilometer long Philippine Fault. The Philippine Mobile Belt corresponds to the complex plate boundary between Eurasia and the Philippine Sea Plate.

Aside from seismic activities and geological formation, climate also influences the susceptibility of the Philippines to such catastrophic events. With a climate generally characterized by predominantly rainy season, high amount of precipitation is experienced by the country year round, with strong typhoons occurring frequently.

With a fast-growing population and being a developing country, the Philippines has a huge gap in public infrastructure, which the government has been addressing for the past several years. Implementation of major infrastructure projects has been a priority through government funding, private undertaking or public-private partnerships, such as road expansions, bridge rehabilitations, and mass transport system. Power plants, transmission facilities and water supply system improvement are likewise essential in sustaining the country's economic growth.

With the design and construction of these major infrastructures come the challenge of ensuring that these structures and facilities are earthquake resistant and disaster-resilient.

2 EARTHQUAKE-INDUCED LANDSLIDES IN THE PHILIPPINES

The Philippines, having a high seismicity, experiences a relatively large numbers of earthquakes every year. Table 1 shows the list of strong earthquakes in the country from 1990 to 2018. The magnitudes range from 5.1 to as high as 7.7 (Luzon earthquake 1990). Most of these earthquakes occurred offshore, and as such, also posed tsunami threats.

Table 1. The list of strong earthquakes in the Philippines from 1990 to 2018.

Year	Region/ Area	Magni-tude	Year	Region/ Area	Magni-tude
1990	Bohol	6.8	2010	Moro Gulf	7.3
	Panay Island	7.1	2011	Ilocos	6.4
	Luzon	7.7		Bukidn-on	5.2
1994	Mindo-ro	7.1	2012	Negros	6.9
1995	Samar	7.3		Surigao	5.9
1996	Bohol	5.6		Samar	7.6
1999	Agusan del Sur	5.1	2013	Mindan-ao	6.2
	Zamba-les	6.8		Bohol	7.2
2001	Minda-nao	7.5	2014	Moro Gulf	6.6
2002	Minda-nao	7.5	2015	Siargao	6.1
	Sultan Kudarat	6.1	2016	Tamisan	6.3
2003	Masba-te	6.2	2017	Sarang-gani	6.9
2004	Mindo-ro	6.5		Leyte	6.5
2009	Moro Gulf	6.6	2018	Dinagat Island	5.7

From these strong earthquakes, some occurred on-land and posed landslide threats. Table 2 shows the list of earthquakes that caused landslides and debris flows. The most well-known was the Luzon 1990 earthquake, which caused multiple landslides along the major road going to Baguio City, one of the areas that suffered the most. The most recent documented earthquake-induced landslides took place on July 2017 in the island of Leyte. Major infrastructures located on the mountainous area in Leyte were severely affected. Multiple landslides occurred and damaged several facilities and blocked major access roads.

Table 2. The list of earthquakes from 1990 to 2018 that caused landslides.

Year	Region/ Area	Magnitude
1990	Panay Island	7.1
	Luzon	7.7
2002	Mindanao	7.5
2012	Negros	6.9
2017	Leyte	6.5

3 CASE STUDIES: LANDSLIDE ASSESSMENT AND MITIGATION

Following the July 2017 earthquake in Leyte, an industrial facility in the mountainous area was severely affected by several earthquake-induced landslides. The slope failures caused damages on several power facilities such plants, transmission lines, pipelines, and access roads, causing disruption and power outage for several days.

Prior to the recent earthquake, several landslide mitigating measures were earlier implemented for these facilities. These landslide-mitigating measures have not been subjected to considerable seismic loadings until the July 2017 earthquake. The pre-earthquake and post-earthquake designs are discussed in the succeeding sub-sections.

3.1 Geohazard Assessment

Immediately after the earthquake, a team of geotechnical engineers, geologists, and hydrologists carried out the inspection and assessment of the affected areas. Geohazard assessment was conducted, leading to the formulation of cost-effective and practicable measures for hazard mitigation and risk reduction.

The geohazard assessment involves site reconnaissance and inspection, and subsequently, risk ratings were assigned considering three (3) parameters: hazard that can cause loss of life or damage to property; exposure or the element at risk such as roads or buildings; and vulnerability which is the capacity of the element to survive a hazard. Considering the three parameters of risk, the site will then be classified as having low, moderate, or high risk.

Low Risk is defined as an inconvenience that is easily corrected, not directly endangering lives or property such as a single block of rock causing blockage of a small portion of roadway that can be easily avoided or removed. Moderate Risk is defined as a more severe inconvenience, corrected with some effort, but not usually directly endangering lives or structures when it occurs such as debris slide affecting one lane of a roadway and causing partial closure for a brief period until such is removed; High Risk is defined as complete loss of roadways, important structures or complete closure of the roadway for some period of time. Lives are endangered during failure.

Out of the seventeen (17) sites inspected after the earthquake, nine (9) locations were tagged as high-risk areas, necessitating long-term slope stabilization measures.

3.2 Formulation of Mitigating Measures

Geotechnical investigation was carried out for each site to characterize the subsurface conditions. The geotechnical investigation program generally consisted of drilling boreholes or excavation of test pits, and the samples were brought to the laboratory for routine testing such as Particle Size Analysis, Atterberg tests, and Unconfined Compressive Tests for rocks. The results of field and laboratory testing were also supplemented by geologic characterization and secondary data such as results of previous studies and assessment. Back-analysis were also carried out, as well as sensitivity analyses, to establish the geotechnical parameters for subsequent design of mitigating measures.

Based on the results of geotechnical investigation and topographic survey, slope stability analysis was carried out using Limit Equilibrium Approach.

The analysis considered the existing slope conditions and loadings, and based on the results, appropriate mitigating measures were formulated, considering two (2) loading conditions: (1) static condition with high pore water pressure, and (2) pseudo-static seismic condition. Minimum Factors of Safety (FoS) adopted for Case 1 is 1.2, while for Case 2, 1.1.

The pore water pressure build-up was considered by considering pore water pressure ratio. For the seismic loadings, the seismic coefficient was taken as one half of the peak ground acceleration (PGA). In the absence of a site-specific Probabilistic Seismic Hazard Assessment (PSHA), the PGA was obtained using deterministic approach, using the Fukushima and Tanaka attenuation model (Thenhaus, 1984).

Other loadings such as structure surcharge and road traffic near the slope were also taken into account.

The slope stability analysis was undertaken using a proprietary software Rocscience Slide 6.0©. Several sections identified as critical were generated from the topographic survey, and were used in the analysis. Geotechnical parameters were determined from the results of investigation and testing, supplemented by geological assessment and secondary geotechnical data.

3.3 Case Studies

3.3.1Existing Design (Pre-earthquake)

Several landslides were triggered by typhoons prior to the earthquake, and power facilities, roadside cuts, and pipelines near the failed slope were at risk. Therefore, there is a need to provide the structures with engineering measures to mitigate further slope failure.

One of the sites is a portion of the road that was cut-off due to a landslide approximately 50.0 meters high and 80.0 meters long. The subsurface consists of hydrothermally altered clay, which is unstable and highly susceptible to landslides. Soil nailing was chosen as a practicable slope protection measure for the site. After the earthquake, no major damages were observed on the road. Only minor cracks were observed on the shotcrete surface, an indication of slope movement. Without the soil nails, the landslide could have progressed.

Another site is a major outfall below a power plant facility previously decommissioned due to slope failures. The side slopes of the outfall were regraded and benched to remove the unstable soil material, and to provide a gentler slope. Adequate drainage system was also provided to minimize infiltration, and mitigate pore water pressure build-up. The design was able to withstand the earthquake, with some localized scouring and erosion at the slope and at the interface of the concrete drainage and soil.

These slope protection measures were able to sustain the seismic loads they were subjected to, proving the effectivity of the designs. Minor damages were experienced, but can be easily repaired. Using the observations and experience from these sites, the designs for the areas damaged by earthquake were formulated.

3.3.2 Post-Earthquake Design

Long-term landslide mitigating measures were formulated for nine (9) sites tagged as "high risk" areas. The slopes to be protected are near critical facilities such as pipelines, roads, towers, and buildings. Two (2) sample designs are discussed in this paper: MSE wall and cut-off wall using micropiles.

Some sites where the roads were damaged and cut-off by a deep-seated landslide also needed to be rebuilt. In these cases, mechanically stabilized earth (MSE) walls were proposed (in lieu of conventional reinforced concrete walls. Rigid walls are evidently costly for slopes with high and steep geometry; hence, flexible retaining structures were adopted.

The models in the succeeding figure present the slope stability analyses carried out for the landslide section with slope protection. A portion of the roadway was rebuilt by placing engineered backfill materials on the failed section of the slope. The backfill is then retained by using MSE wall with gabion facing. The summary of the MSE wall geometry is presented in Table 3, while Table 4 shows the recommended bond strength (adhesion and friction angle) for the type of engineered fill.

Table 3. Recommended bond strengths.

MSE wall height (m)	Reinforment length (m)	Reinf. spacing (m)	Reinf. tensile strength (kN/m)	Strip coverage (%)
4.0	4.5	0.5	86	100

Table 4. Recommended bond strength.

Soil Type	Relative Density / Consisten-cy	SPT $(N_1)_{60}$ Range	Adhesi-on (kPa)	Fricti-on Angle (deg)
Engineer-ed Fill	Medium Dense	15 – 30	2	31

Stability checks were also conducted for the section. ReSSA 3.0 was then used to calculate the factors of safety against rotational and sliding failure. Factors of safety for sliding (FS=1.5) and rotational slip (FS=1.5) were used to check the external and internal stability. Figure 2 shows the results from the ReSSA runs.

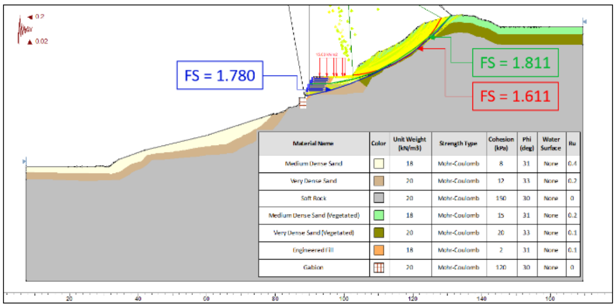

Figure 1. Slope Stability Analysis for a landslide section with MSE wall.

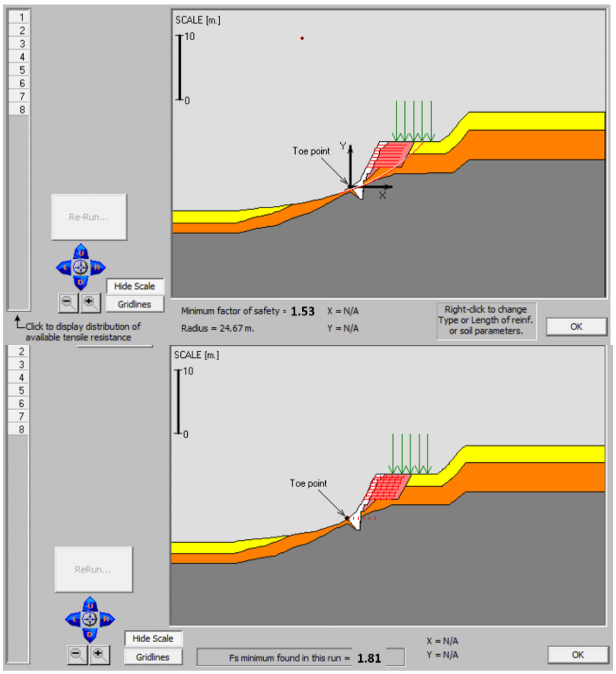

Figure 2. Stability checks for the MSE wall. (a) Rotational (b) Sliding.

Some slopes were observed to have tension cracks, even as no slope failures have taken place. For these sites, and for sites where constructability is an issue (due to the sheer height of slopes), cut-off walls by utilizing micropiles were recommended. The succeeding figure shows the analysis of a slope with tension crack near a structure.

The design consideration is to confine the slope movements outside of the cut-off wall, and the protection of the existing structure as the primary consideration. Deformation analysis using Finite Element Method (FEM) was undertaken, to approximate the slip circular planes at several stages leading to the failure of the slope. Figure 4 presents the effect of the micropile (b) on the slope. The micropile was able to act as a cut-off wall such that the slope movement was confined outside of the structure. The resulting deformation at the top of the micropile was kept at tolerable limits (approximately 30mm), mitigating damage on the structures and plant operations.

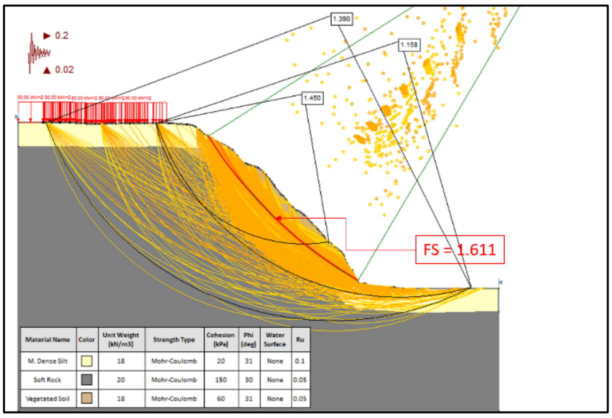

Figure 3. Slope Stability Analysis for an area with tension cracks.

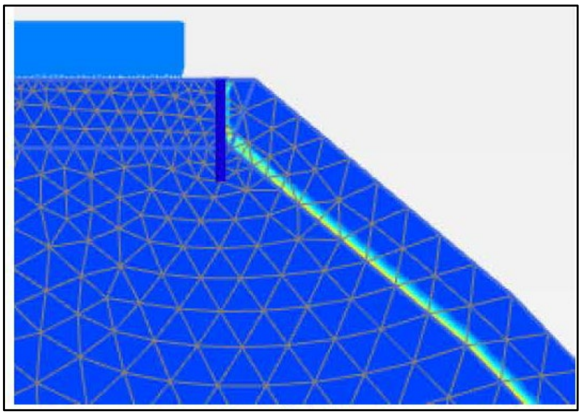
Figure 4. FEM results of engineered slope.

Moreover, non-structural measures, such as slope benching or trimming, hydroseeding, and surface drainage improvement, were also proposed in order to minimize the risk of further landslides. In some areas, a hybrid, or a combination of slope protection measures, were adopted.

For areas tagged as "low" to "moderate" risk areas, short-term recommendations were provided. These include sealing of cracks, removal of loose materials on the slope, traffic regulation, and slope monitoring. These immediate or 'stop-gap' measures were undertaken to address safety issues and accessibility, immediately after the earthquake.

4 CONCLUSION AND WAY FORWARD

Mainly utilizing available technology for testing, analysis, design and construction, complemented by multi-disciplinary hazard assessment approach, slope protection measures were formulated and were effectively implemented for various infrastructure projects in the Philippines. These measures performed well and were found effective when a major earthquake occurred in July 2017.

Further monitoring is being undertaken, aimed at further contributing to earthquake-resistant and cost-effective design.