



Performance-Based Design Review of a Reinforced Earth Retaining Wall for a Road Embankment Project in the Philippines

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Abstract. Several infrastructure projects such as light rail transit system, national roads, expressways, and underground rapid transit lines are currently being developed in the Philippines to address the huge gap in transportation infrastructure. One of the major infrastructure projects is an elevated toll expressway that connects several business districts in the southern areas of Metro Manila. Located near the coastal area of Manila Bay, the expressway alignment is underlain by soft clay and loose sand layers where long-term settlements and liquefaction are expected. In this context, a need to transition from conventional design methods to Performance-Based Design is essential in providing a cost-effective solution.

This paper presents the methodology utilized in evaluating stability and deformation of road embankment protection designs involving Mechanically Stabilized Earth walls. The assessment of the proposed ground improvement by Soil-Cement Columns to minimize settlements and to mitigate the onset of geohazards such as liquefaction are discussed. This paper also shows the instabilities observed by performing Slope Stability Analysis, and their corresponding deformations evaluated by Finite Element Analysis. Recommendations for optimization and design improvements based on Client's risk tolerance, and further studies to be undertaken are identified.

Keywords: Numerical modelling · Slope stability · Liquefaction · Deformation · MSE wall

1 Introduction

Several infrastructure projects are being built in the Philippines. These include light rail transit system, national roads, expressways, and underground rapid transit line. Therefore, a need for a more advanced design methodology, especially in the field of geotechnical engineering design is necessary. This paper focuses on an elevated expressway that aims to decongest city traffic, connect major business districts in the Southern Metro Manila area, and to provide faster and efficient regional movement of people and goods.

The project site rests generally on loose sand and soft clay materials. To address potential occurrence of geohazards, the contractor of the project proposed to improve the ground by means of Soil-Cement Columns (SCC). The resulting soil-binder composite material is expected to have higher soil properties relative to the properties of the native soil. This paper presents the general design methodology adopted in assessing the adequacy of the design of the resulting composite soil to increase bearing capacity, and to mitigate or minimize possible geohazards such as settlement, liquefaction, and slope instability.

Figure 1 shows the geometry of the critical section focused on this paper. The embankment height at this section is 6.5 m, and the road width is 11.2 m. The Soil Cement Columns spaced at 1.46 m have a diameter of 900 mm and length of 20 m.

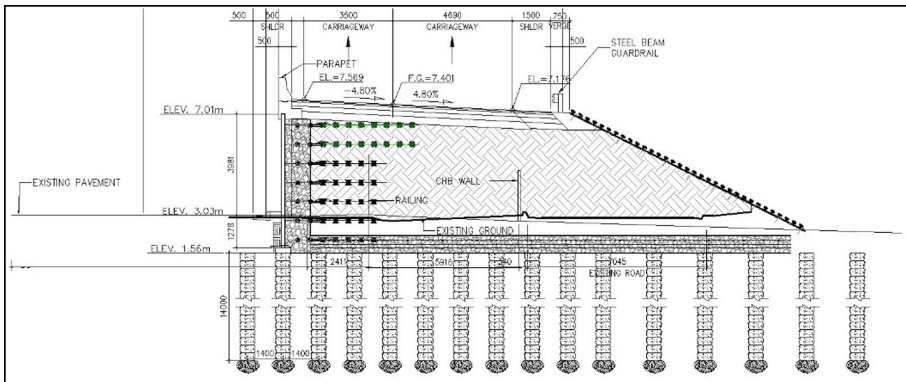


Fig. 1. Cross-sectional drawing of the expressway critical section

2 Design Review Methodology

Boreholes were drilled along the alignment of the project site to determine the local subsurface conditions. The materials encountered are composed of very loose to medium dense sand with some very soft to very stiff clay with varying thicknesses ranging from 20 to 25 m underlain by the bedrock. Geotechnical parameters of the native or untreated soil were then evaluated from correlating the SPT N-values with several published studies such as Bowles (1997) [1]. The soil-cement columns and surrounding native soil were characterized as a composite soil block. The equivalent geotechnical parameters of the composite soil are functions of the area replacement ratio and the geotechnical parameters of the native soil.

New Generation Attenuation Relationships was adopted in estimating the seismic demand on-site. The NGA-West attenuation models for active fault systems in 2008 and 2014 developed by the Pacific Earthquake Engineering Research Center (PEER) [2] was used in determining the Peak Ground Acceleration (PGA), needed for the analyses.

In the Philippines, it is common practice to adopt a k_h value taken as half of the surface PGA in accordance with the works of Kavazanjian et al. in 1997 [3]. On the other hand, k_v usually falls within one-fourth (25%) to two-thirds (66.67%) of its horizontal counterpart. For simplicity, the k_v value was taken as one-half (50%) of k_h .

With the presence of loose materials and shallow ground water table at the site, it is imperative to conduct liquefaction analysis. For this analysis, the Boulanger and Idriss 2014 [4] method was adopted; and, the liquefaction-induced settlement was estimated using the method Pradel developed in 1998 [5].

It is crucial that the strength properties of the composite soil would be able to resist liquefaction; hence, the composite soil materials were also evaluated for liquefaction susceptibility. The analysis was an iterative process wherein the SPT N-values of each liquefiable soil layers were refined until adequate safety factors against liquefaction are achieved.

The expressway project will be composed of high embankments for the ramps and elevated roads. Therefore, it is warranted to estimate the settlement of the subsurface after the placement of the embankment. Settlement analysis of both native and composite soil was carried out with the aid of Settle 3D software. Short and long-term settlements after the construction duration for the embankment of 12 months, and post-construction settlement were compared.

Slope stability analysis using Limit Equilibrium Method was conducted to determine the global stability of the MSE wall. The GLE/Morgenstern-Price Method was used for both circular and non-circular analysis of the slope. The table below presents the different loading cases used in the analysis.

Table 1. Global slope stability analysis scenarios

Case	Pore pressure ratio, r_u	Seismic coefficient		Minimum allowable FS
		k_h	k_v	
Normal and static	0.0	0.0	0.0	1.5
High pore water pressure and static	0.4	0.0	0.0	1.3
Moderate pore water pressure with strong earthquake	0.2	0.25	± 0.125	1.1

Considering the results of the SSA, deformation analysis by way of Finite Element Method (FEM) using the numerical analysis tool, PLAXIS, was carried out. This is aimed at establishing the earthquake-induced localized deformations, and assessing if these will be tolerable. The primary criterion for designing slope protection systems is the serviceability performance in terms of both vertical deformation (e.g. settlement, heaving) and lateral deflection. As such, deformation analysis was performed using Finite Element Method (FEM) to establish both static and seismic performance of the slope protection system. The main advantage of FEM is its ability to estimate the deformations

leading up to the failure or time point of interest. These deformations correspond to the movement of the soil mass showing how it will behave upon application of loads.

Section 11.10.4 of AASHTO LRFD 2012 [6] details the maximum deformation criteria for MSE walls. For MSE walls with full height precast concrete facing panels, total settlement should be limited to 2.0 in. (50 mm) for the pseudo-static condition. Since lower settlements are expected in normal condition, an allowable settlement of 1.0 in. (25 mm) is set for static conditions. The limiting differential settlement should be 1/500.

The maximum allowable lateral displacement of MSE wall, as prescribed by BS 8006 Code of Practice for Strengthened/Reinforced Soils and Other Fills [7], may be taken as 0.5% of the height of the supported embankment for the static condition. For the pseudo-static case, twice the allowable deflection for the static case or 1% of the height of the supported embankment may be set.

3 Results of Analysis

3.1 Subsurface Conditions

The succeeding table presents the geotechnical parameters of both native and composite soil evaluated from the SPT N-values obtained from field testing.

Table 2. Subsurface condition and geotechnical parameters of critical section

Depth, m	Soil classification	SPT N-value	Geotechnical parameters Native soil; Composite soil			
			γ (kN/m ³)	c (kPa)	ϕ (°)	E (MPa)
0.0–7.5	SM/SP-SM	2–8	17	0; 115	28; 29	5; 80
7.5–9.0	GM/SM	19	18	0; 115	32	2; 70
9.0–13.5	SC/CL/CH	0–2	12	6; 115	0; 9	5; 80
13.5–16.5	GM/SM	9–13	18	0; 115	32	10; 80
16.5–19.5	CH	7–10	17	40; 140	0; 9	30
19.5–23.0	CH/CL	26–36	20	200; 245	0; 9	75
23.0–25.5	Siltstone	‘coring’	20	200	30	80

3.2 Seismic Parameters

It can be surmised that the most influential seismic source for the project area is the West Valley fault (WVF) [8] which could produce a magnitude 7.2 earthquake. Based on the proximity of the alignment to the WVF, the expected surface PGA from the attenuation models is estimated to be 0.45 g. For prudence, PGA was rounded up to 0.50 g to be adopted in the analyses.

3.3 Liquefaction Analysis

The upper 19.5 m depth of the native subsurface is liquefiable, and the liquefaction-induced settlements is approximately 670 mm. However, once N-value of at least 25 is attained by the SCCs, liquefiable layers will be limited only at depths below the proposed SCC lengths. This is presented in Fig. 2.

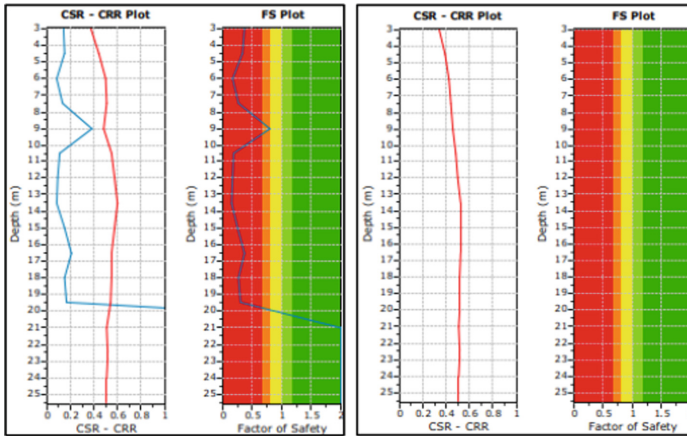


Fig. 2. CSR-CRR and FS plots (Left: Native soil; Right: composite soil)

3.4 Settlement Analysis

The results suggest that without SCC, settlement of 485 mm will take place upon application of load, and long-term post-construction consolidation settlement of 300 mm is expected because of the presence of clay layers. Upon application of embankment and traffic loadings at the ground with SCCs, the calculated settlements significantly decreased compared to the values considering native soil condition. Long term settlement of 55 mm is still expected to occur over a period of 4 years. This is presented in Fig. 3.

3.5 Slope Stability Analysis

Generally, for each section, there are several slip circles passing through the native soil having FS less than the allowable. Therefore, the embankment requires ground improvement of the underlying native soil to prevent slope instabilities under the loading conditions presented.

Based on the results of SSA (Fig. 4), ground improvement by SCC will be able to intercept the potential slip circles passing through the loose/soft soil layers as evident in the higher FS presented below. However, the FS is still lower than the established criteria in Table 1. In order to determine its performance once this condition is reached, FEM was conducted.

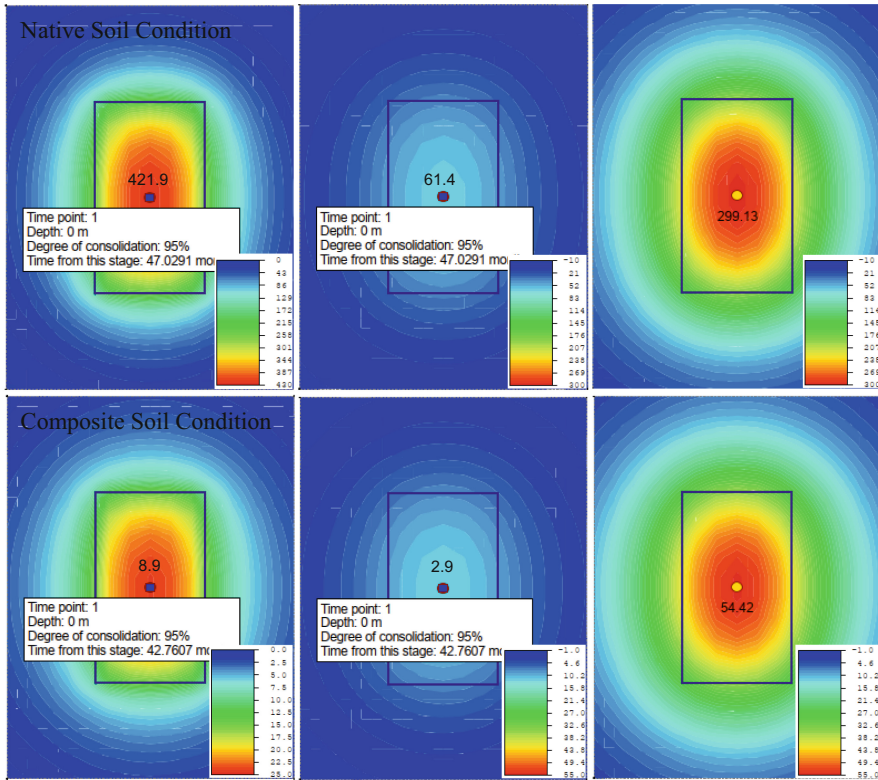


Fig. 3. Settlement analysis results

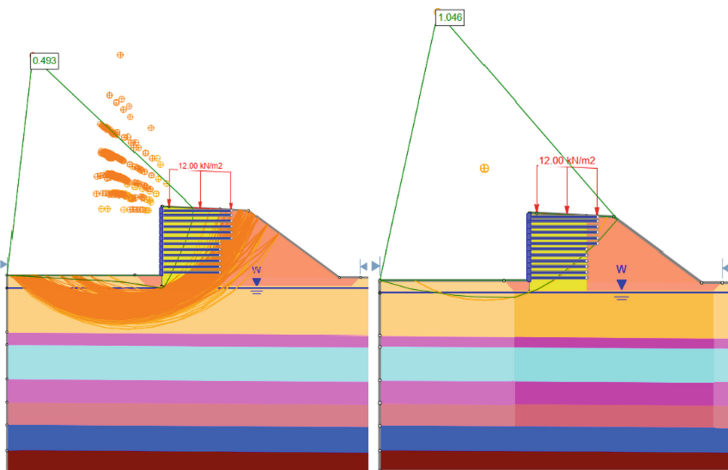


Fig. 4. Slope stability analysis results for the critical section. Embankment resting on native soil (Left); embankment resting on improved ground (Right)

3.6 Deformation Analysis

For all the FEM runs of the native soil with pseudo-static condition, the soil model collapsed due to excessive deformations. To illustrate, the deformation contours in Fig. 5 show the presence of a failure envelope cutting through the whole embankment and the upper soft layers of the existing ground.

At normal conditions, the fill settlements are generally unsatisfactory. Wall deflections exceeds the tolerable limits. In the event of an earthquake, excessive deformations are experienced. The tensile strength of the geostrips in all stations are adequate for the case of the unimproved soil. For static conditions, the maximum reinforcement tension experienced by the geostrips in each wall are all less than their pullout strengths.

In order to reduce the deformations to tolerable conditions, improvement of the soft and loose soils under the embankment with the use of soil cement columns is necessary.

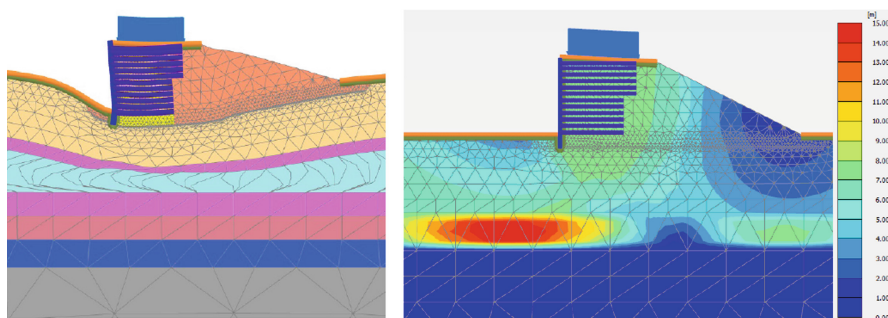


Fig. 5. Resulting exaggerated deformed mesh and deformation contour for the native ground (pseudo-static)

At normal conditions, the wall deflections and fill settlements resting on the improved ground are less than 10 mm and are within tolerable limits. This signifies the reduction of deformations upon improving the underlying soft and loose soil. However, for the pseudo-static cases, the computed deflections and settlements remain excessive (100–235 mm) at the upper portions of the wall, as shown in Fig. 6.

Geostrips have adequate strength against tensile failure for both the static condition and pseudo-static conditions. The pullout strength of the geostrips are generally adequate. However, the maximum reinforcement tension experienced by the geostrips in some of the upper layers at each location exceeds the pullout strength for the pseudo-static condition.

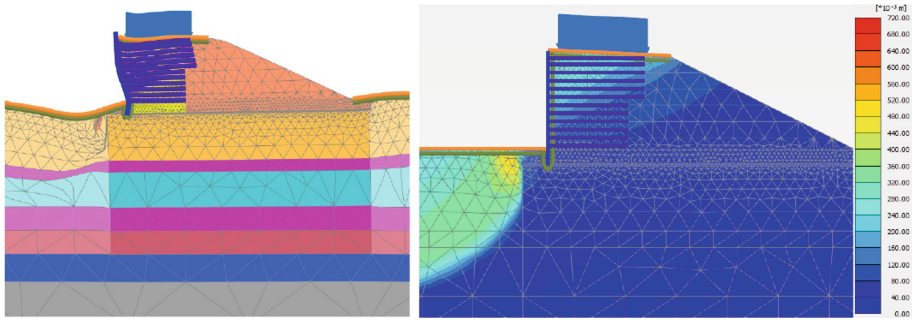


Fig. 6. Resulting deformation contour for the improved ground (pseudo-static)

4 Conclusions and Way Forward

Based on the results of the analyses conducted for the structure, Soil-Cement Columns will minimize liquefaction-induced settlements and layers with excessive settlements. The results of SSA for pseudo-static loading condition yielded inadequate factors of safety for global stability. Therefore, the deformation was analyzed using FEM to determine the performance of the embankment during seismic conditions.

In the context of performance-based design approach, improvement in the design may still be done by using the site-specific seismic parameters. Refinement of the established failure criteria may be done to optimize the design of both SCC and MSE wall.

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