Liquefaction mitigation of silty sand and sandy silt soils with rammed aggregate piers

Mitigación de licuefacción de arenas limosas y limos arenosos con pilas de agregado apisonado

Xavier VERA-GRUNAUER[1], Kord J. WISSMANN[2], Miriam SMITH[3], Jorge ARROYO-ESQUEDA[4]

[1]CEO, Geoestudios / Professor, Universidad Católica de Guayaquil, Guayaquil, Ecuador
XVG@geoestudios.com.ec, Calle José Assaf Bucaram, mz 704 villa 3, Guayaquil, Ecuador
[2]President, Chief Engineer – Geopier Foundation Company, Davidson, NC, USA
KWissmann@geopier.com, 130 Harbour Place Drive, Suite 280, Davidson, NC 28036
[3]Lead Engineer – Geopier Foundation Company, Davidson, NC, USA
MSmith@geopier.com, 130 Harbour Place Drive, Suite 280, Davidson, NC 28036
[4]Project Manager – Geopier Foundation Company, Davidson, NC, USA
JArroyo@geopier.com, 130 Harbour Place Drive, Suite 280, Davidson, NC 28036

ABSTRACT: Ground improvement for liquefaction mitigation typically focuses on densifying the subsurface materials to achieve a relative density greater than that which corresponds to liquefaction triggering. The densification of potentially liquefiable silty sands may be difficult, however, because of the inability of the ground to drain rapidly during treatment. Recently, Rammed Aggregate Pier elements were recently installed at a project site containing sandy silts and silty sands materials in Ecuador subject to a major earthquake. The Ecuador site was subject to the Mw = 7.8 earthquake that induced accelerations of greater than 0.3g at the project site. This paper describes the test results collected for this site and provides a description of the mechanisms involved in liquefaction mitigation.

RESUMEN: El mejoramiento de suelo para la mitigación de la licuefacción se enfoca típicamente en la densificación de los materiales del subsuelo para lograr una densidad relativa mayor que la que corresponde al desencadenamiento de la licuefacción. La densificación de las arenas limosas potencialmente licuables puede ser difícil, sin embargo, debido a la incapacidad del suelo para drenar rápidamente durante el tratamiento. Recientemente, elementos de Pilas de Agregado Apisonado fueron instalados en un proyecto que contenía materiales de arenas limosas y limos arenosos en Ecuador sujetos a un terremoto de gran magnitud. Este proyecto en Ecuador estuvo sujeto al terremoto de Mw = 7,8 que indujo aceleraciones de más de 0,3 g en el sitio del proyecto. Este artículo describe los resultados de las pruebas recopiladas para este sitio y proporciona una descripción de los mecanismos implicados en la mitigación de licuefacción.

1 INTRODUCTION

On April 16, 2016 Ecuador suffered a devastating Mw 7.8 earthquake that generated peak ground acceleration values of approximately 0.35g at the Briceno River embankment site located along the coastline south of the epicenter. Many buildings and embankments collapsed, and more than 600 lives were tragically lost. Prior to this earthquake, the Ministry of Transport and Public Works of the Province of Manabí approved soil improvement project to reduce the potential for soil liquefaction of a layer at the approach embankment of the Briceño river bridge. The work included the installation of more than 6,300 Rammed Aggregate Piers (RAP's).

RAPs mitigate liquefaction through four mechanisms: a) densification of the matrix soil, b) increasing the lateral stresses in the matrix soil, c) drainage, and d) increasing the shear strength and stiffness of the composite ground during and after the seismic event. This paper presents a summary of the Briceno river approach embankment post-earthquake performance, provides an overview of how RAPs are designed to provide the means of liquefaction mitigation and presents the results of analyses that show the benefits of RAPs for increasing global stability.

2 CONSTRUCTION PROCEDURE OF RAMMED AGGREGATE PIERS (RAPS)

RAPs are a ground improvement system that has steadily gained acceptance around the world. The construction procedure of the RAPs using the displacement system is shown in Fig. 1, a method that is commonly used in soils prone to caving of the matrix soil during drilling, such as non-cohesive granular soils, and under conditions of shallow groundwater table (ICC-ES 2017).

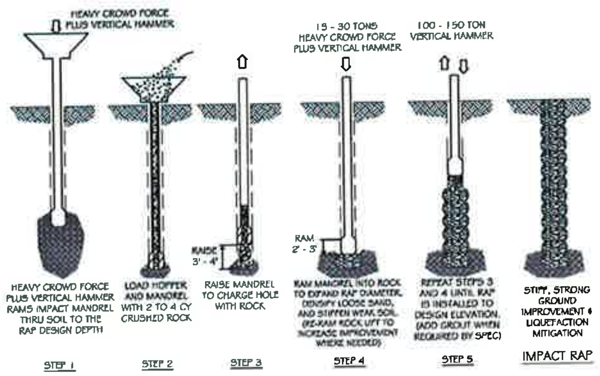

Figure 1. RAPs construction process using the displacement system.

3 PROJECT SITE LOCATION

The Briceño River bridge is located at the Manabí province, western Ecuador (UTM Coordinates 562269 m E, 9942519 m S). The area improved with RAPs on the approach embankment is south of the Briceño River bridge, and comprise a length of approximately 725 m. Fig. 2 shows the site location.

Figure 2. Briceño River Bridge site location.

4 PROJECT SITE SOIL CONDITIONS

The soil conditions at the Briceño River bridge approach embankment consists generally of loose silty sands and sandy silts, identified through direct exploration and laboratory testing, from 2.5 to 5m below natural grade elevation. The groundwater table at the moment of the earthquake was located at the natural grade elevation. Pre-improvement SPT N-values ranged from 2 to 13 in the upper 5 m and were generally greater than 40 below a depth of 5 m (Figure 3). Fines content values in the upper 5 m ranged from 10% to 40% for silty sands, and upt o 90% for fine soils. These soil conditions resulted in a high liquefaction susceptibility for the project seismic parameter values (Magnitude, Mw=8 and Peak Ground Acceleration, PGA=0.4g).

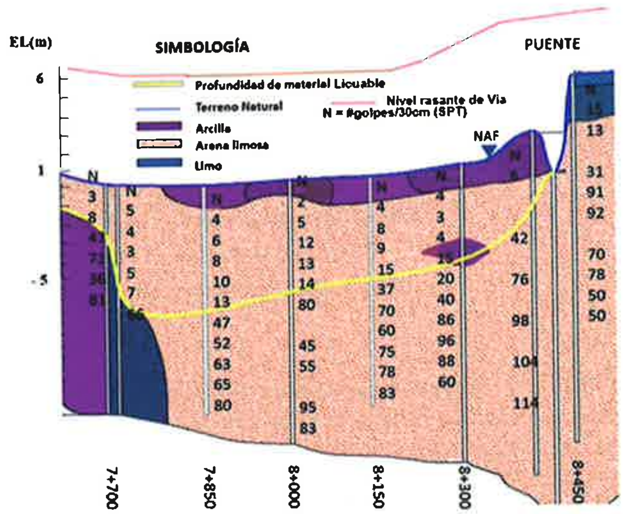

Figure 3. Soil profile along embankment alignment.

5 BRICEÑO EMBANKMENT GROUND IMPROVEMENT SOLUTION

The ground improvement solution for the Briceño embankment project consisted of using 0.51 m diameter RAPs to depths of 2.5 to 5m and center-to-center spacings varying from 1.65 m at the edges of the embankment, to 3 m beneath the center of the embankment. The purpose of the ground improvement was to reduce the liquefaction potential and increase the global stability conditions.

6 BRICEÑO EMBANKMENT PERFORMANCE AFTER THE EARTHQUAKE

The RAPs reinforced Briceño approach embankment showed a favorable performance after the April 16, 2016 Muisne earthquake, resulting in only minor repairable surficial tensile cracks and no observable embankment settlement. Unlike Mejia, an embankment with similar stratigraphy conditions that suffered large to catastrophic damage, the Briceno embankment's serviceability was never compromised. Fig. 4 shows the Mejía bridge approach embankment, which is not RAPs supported. Fig. 5 shows the Briceño approach embankment, which is supported on RAPs, after the April 2016 earthquake. Fig. 6 shows sand boils that occurred adjacent to the Briceno embankment evidencing the liquefaction susceptibility of the Briceno embankment foundation soils.

Figure 4. Mejía River Bridge Approach Embankment not RAPs supported (Nikolaou et al. 2016).


Figure 5. Briceño River Bridge Approach Embankment supported on RAPs after the earthquake.


Figure 6. Sand boils adjacent to the Briceño River Bridge Approach Embankment.

7 LIQUEFACTION MITIGATION

Rammed Aggregate Pier elements reduce the potential for soil liquefaction by: densifying the granular materials, providing drainage for the dissipation of excess pore water pressure, increasing confining stress, and increasing the strength and stiffness of the reinforced ground thereby providing for increased resistance to shearing and decreased shear deformations (Fig. 7).

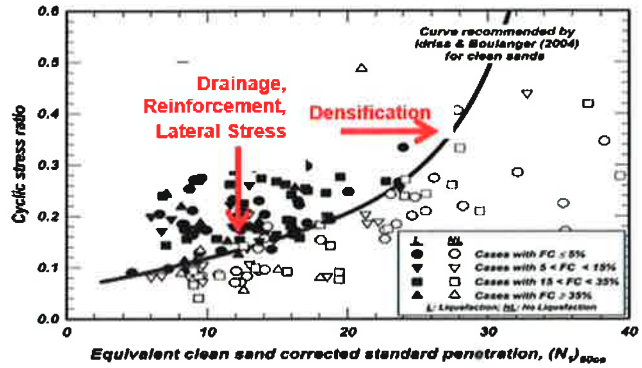

Figure 7. Effect on CSR, CRR from Densification, Drainage, Reinforcement and Lateral Stress increase.

The influence of densification on the reduction of liquefaction susceptibility is well accepted and understood in the community and is regularly applied to loose, clean, cohesionless soil deposits subject to shaking. However, densification is often not achievable in soils with fines content values greater than about 15% such as those encountered at the Briceño embankment site. The remainder of this paper investigates the influence of confinement and reinforcement mechanisms at the embankment site. The influence of drainage is not considered because of the low permeability of subsurface materials.

7.1 *Liquefaction Susceptibility in Free Field*

Fig. 8 shows CPT tip resistance values for free-field conditions for SP/SM and SM/ML soils and plots of Cyclic Stress Ratio (CSR) for the site conditions. The plot shows that 100% of data points for SP/SM and SM/ML soils are computed to liquefy when subject to loading by the design event. These results are consistent with the sand boils observed at the embankment tow (Fig. 6).

7.2 *Influence of Confinement*

The confining pressures applied by the constructed embankment reduce the potential for liquefaction triggering. This is shown in Fig. 9 that presents CPT tip resistance values for free-field conditions and associated plots of CSR whereby the computed CSR values have been corrected for embankment confinement. The plot clearly shows a reduction in CSR from confinement (90% and 100% of data points are computed to liquefy for SP/SM and SM/ML soils, respectively, when the above-mentioned correction for embankment confinement is applied). These plots suggest that, absent any other liquefaction reduction influence, most of the subsurface alluvial materials are computed to liquefy during the applied seismic event.

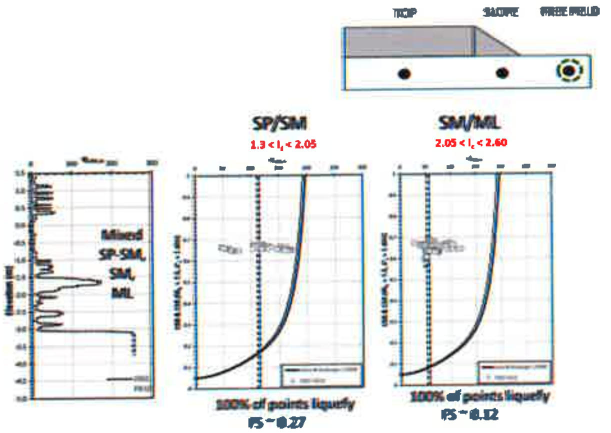

Figure 8. Unreinforced, Unimproved Free-Field CPT tip resistance data without correction for embankment confinement.

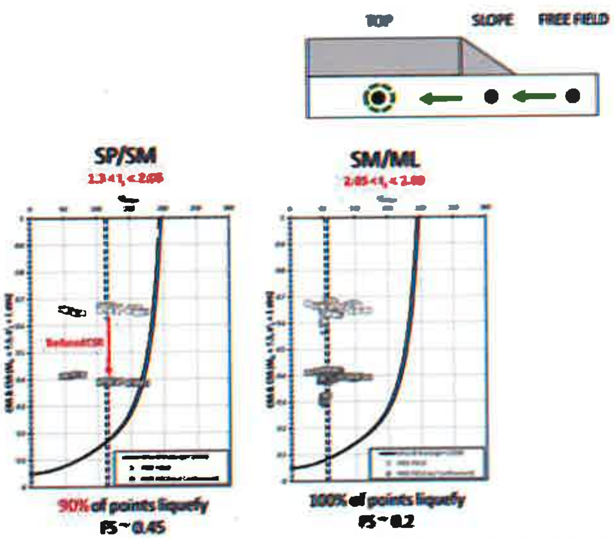

Figure 9. Unreinforced, Unimproved Free-Field CPT tip resistance data corrected for embankment confinement.

7.3 *Influence of densification and confinement*

Fig. 10 shows CPT tip resistance values for reinforced, improved soil conditions beneath the embankment and associated CSR profiles, whereby the computed CSR values have been corrected for embankment confinement. The plot shows that approximately 50% and 100% of measured values are computed to liquefy when loaded by the applied earthquake. These computations suggest that the combined benefits of increased confinement and increased density are not sufficient to preclude liquefaction below the embankment as a result of loads applied by the earthquake.

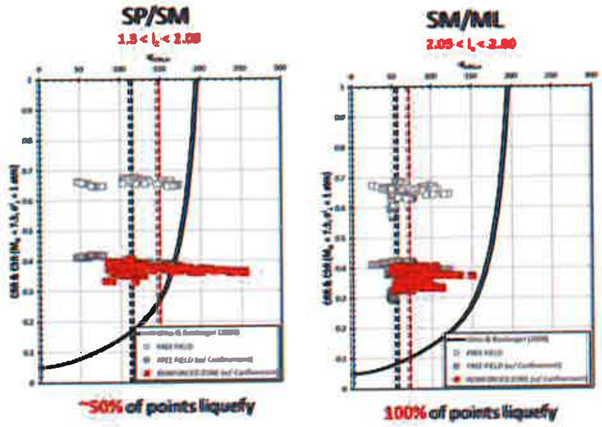

Figure 10. Reinforced, improved CPT tip resistance data beneath the embankment corrected for embankment confinement.

8 EMBANKMENT STABILITY

Fig. 11 shows the results of pseudo-static embankment stability calculations performed for the embankment when subject to the applied earthquake loading conditions (assumed k_h = 50% of PGA) and for a variety of foundation soil residual shear strength conditions computed using the method described by Idriss and Boulanger (2008).

As shown in Fig. 11, a Factor of Safety of 0.97 is computed for an embankment soil shear strength value that corresponds to the unconfined free-field conditions depicted in Fig. 8. The Factor of Safety is then increased to 0.98 when the embankment soil shear strength value corresponds to free field conditions corrected for confinement (Fig. 12). These factors of safety both correspond to embankment failure such as that experienced at the Mejia site (Fig. 4). When the benefit of densification is further included for the embankment soil shear strength conditions then the Factor of Safety increases to 1.08 (see Fig. 13). While this computation suggests that the embankment would be stable, factors of safety of less than 1.1 are typically associated with embankments that have experienced much more dramatic deformations. This was not the case of the Briceno embankment (Fig. 5).

To add insight into the reasons for stability, additional analyses were performed with reinforced conditions. Soil reinforcement is the broad concept that the installation of the piers increases the strength and stiffness of the foundation soils. The increase in shear stiffness as provided by RAP elements were demonstrated by researchers that applied vibroseis shear stresses to reinforced ground in New Zealand (Wissmann et al. 2015).

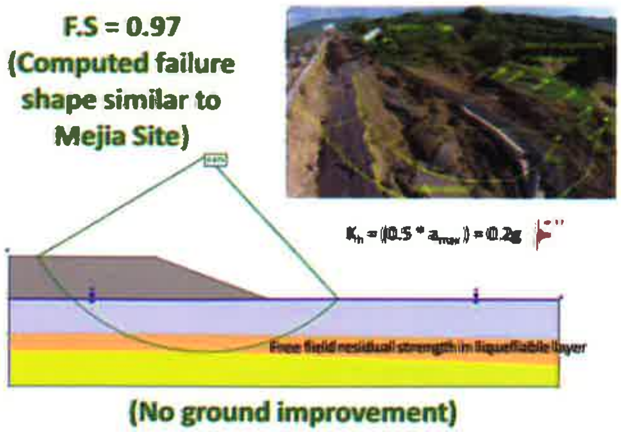

Figure 11. Unreinforced, Unimproved, Unconfined, Free-Field pseudo-static limit-equilibrium stability analysis.

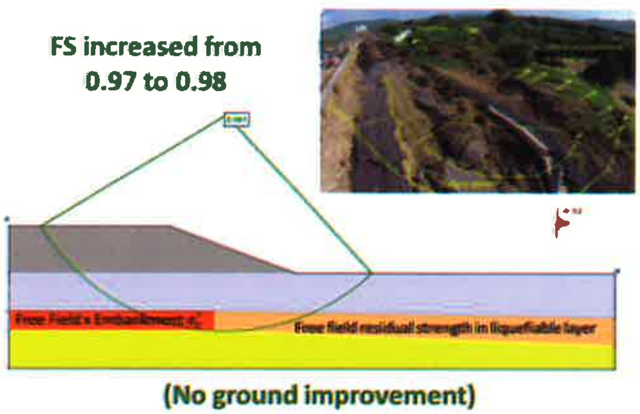

Figure 12. Unreinforced, Unimproved, Confined, Free-Field pseudo-static limit-equilibrium stability analysis.

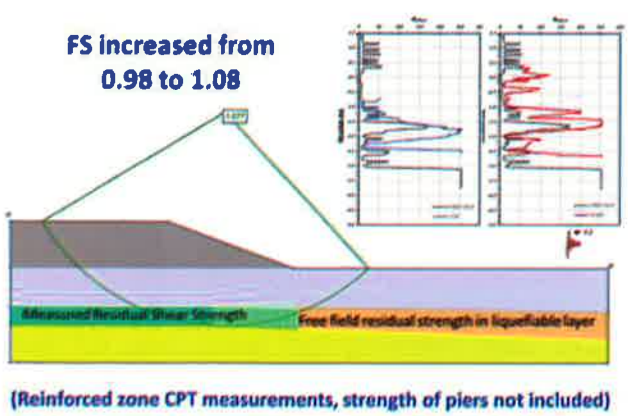

Figure 13. Improved, Confined, Free-Field pseudo-static limit-equilibrium stability analysis using densification of the matrix soil from RAPs reinforcement.

While it is possible to compute the decrease in liquefaction susceptibility that results from shear stiffening, this mechanism is somewhat controversial because of flexural bending mechanisms that were initially described in Goughnour and Pestana (1998). Yet the presence of soil improvement elements is well known to greatly reduce liquefaction settlements (Martin et al. 1999). For this reason, a direct computational approach was used for the Briceño embankment: the reinforced conditions simply incorporated the weighted average of the shear strength value for the liquefied natural soils and the unliquefied aggregate piers. A Factor of Safety of 1.38 (Fig. 14) was computed using this simplified reinforced approach. This factor of safety corresponds well to the observations obtained at the Briceno embankment site.

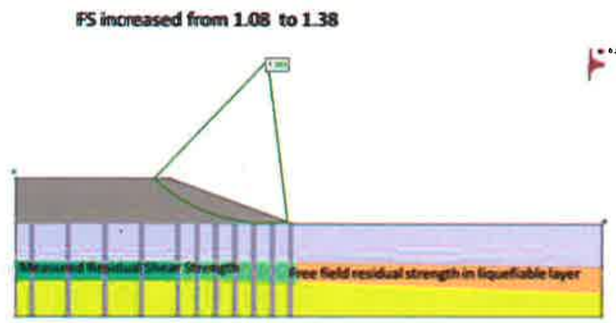

Figure 14. Reinforced, Improved, Confined, pseudo-static limit-equilibrium stability analysis showing increased factor of safety using weighted average shear strength values from RAPs and matrix soil beneath embankment.

Table 1. Summary of analyses and factor of safety obtained.

Analysis Condition	Factor of Safety
Unreinforced, Unimproved, No Confinement	0.97
Unreinforced, Unimproved, with Confinement	0.98
Improved, with Confinement	1.08
Reinforced, Improved, with Confinement	1.38

9 CONCLUSIONS

The Briceño Embankment Case History provides an opportunity to gain much insight into the benefits of RAP ground improvement method for liquefiable sandy silts and silty sands soils. This paper shows that, like the Mejia site, the embankment would have likely been unstable had the embankment soils been unreinforced. The RAP elements provided for densification of the foundation soils, but this densification is unlikely to explain the lack of embankment displacements during the earthquake. When the benefits of soil reinforcement are included, however, the computed factor of safety corresponds well to the observed conditions.

REFERENCES

Goughnour, R.R., and Pestana, J. M. (1998) "Mechanical Behavior of Stone Columns Under Seismic Loading", *Proceedings, 2nd International*

Conference on Ground Improvement Techniques, Singapore; October 1998; p. 157-162.

Idriss, I.M., and Boulanger, R.W. (2008), "Soil Liquefaction During Earthquakes", *Earthquake Engineering Research Institute (EERI) monograph MNO-12*, Oakland, California.

International Code Council Evaluation Service (2017) (ICC-ES) (2017). "ESR-1685. Rammed Aggregate Pier Intermediate Foundation/Soil Reinforcement System", *International Code Council (ICC) Evaluation Service, LLC*; 2016. 4 pp.

Martin, G.R. and Lew, M., eds. (1999). "Recommended Procedures for Implementation of DMG Special Publication 117 Guidelines for Analizing and Mitigating Liquefaction Hazards in California", *Couthern California Earthquake Center*. University of Southern California. 63 pp.

Nikolaou, S., Vera-Grunauer, X., and Gilsanz, R., eds., (2016). "GEER-ATC Earthquake Reconnaissance: April 16 2016, Muisne, Ecuador", *Geotechnical Extreme Events Reconnaissance Association Report GEER-049, Version 1. Accessible at the GEER website:* www.geerassociation.org

Wissmann, K.J., Ballegooy, S. Van, Metcalfe, B.C., Dismuke, J.N., Anderson, C.K., (2015). "Rammed Aggregate Pier Ground Improvement as a Liquefaction Mitigation Method in Sandy and Silty Soils", *Proceedings of the 6th International Conference on Earthquake Geotechnical Engineering*, Christchurch, New Zealand.