Proceedings of the 9th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2024)
Toronto, Canada – June 13-15, 2024
Paper No. 121
DOI: 10.11159/iccste24.121

Design for the improvement of soils with liquefaction potential using Rammed Aggregated Piers

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Abstract - This paper presents the use of Rammed Aggregated Piers (RAP) for soil improvement; this implementation gives the soil a greater load capacity and provides settlements lower than the admissible. In addition, it mitigates the liquefaction phenomenon in loose sands. The present project is an analytical study where calculations were made considering the construction of a building implementing soil improvement with RAP, which, in first instance, the settlements in the unimproved ground were evaluated using the methodology of Idriss & Boulanger (2008) considering the correction factor for depths of Cetin et al. (2009). Subsequently, the RAPs were implemented and the settlements in the improved soil were evaluated following the 3-step methodology proposed by Geopier. The implementation of the RAP presented a significant improvement in different aspects such as settlement, which was observed that in the results of the settlement calculations all the analyses were less than the admissible settlement (1inch).

Keywords**:** *rammed aggregated pier, liquefaction, settlement, soil, safety factor.*

1. Introduction

Throughout history, earthquakes have been and are the best-known geological events as they are so recurrent in various parts of the world. In certain places, these geological events are more likely to occur than in others, especially in South America, where there are various tectonic plates which can cause earthquakes when two plates collide or earthquakes within the same plate generating telluric movements on the surface.

When evaluating the seismic hazard, one must take into consideration not only the intensity of the historical telluric movements of the place nor only the tectonic characteristics of the area; but, in addition to this, the general conditions of the land where said event occurs must be taken into account since the characteristics of the soil, the presence of water in the building area (high water table) and a telluric event can trigger liquefaction of the soils. Soil liquefaction is a phenomenon that has been studied and continues to be a subject of study since it is highly dangerous and is an interesting topic in the field of geotechnical engineering. The presence of this event can be harmful to people since they have occurred in various parts of the planet, generating structural devastation and affecting the lives of a large number of people. A clear example of liquefaction, showing how damaging it was in construction and in community life, was during the earthquake in Niigata, Japan in 1964. (Fernandez, L. 2017).

Fig. 1: Liquefaction in Niigata, Japan (1964)

To avoid soil liquefaction, several engineers have used innovative solutions in buildings which are mainly based on the implementation of Compacted Gravel Columns and the implementation of Deep Mixing. These solutions generate an improvement in the safety factor (FS) increasing and decreasing the settlements (SS), however, when using the Compacted Gravel Piles (RAP), the results obtained in both indicators (FS and SS), were better compared to the solutions. The Compacted Gravel Piles are vertical semi-rigid elements formed by several layers of crushed gravel without the presence of fines, which will subsequently be tamped until compacted to achieve high rigidity. (De la Fuente, H., Nolasco, M. & Aguirre, J., 2022). Among the advantages of the RAP, in addition to generating and achieving a high lateral rigidity to densify the weak soil, it must be clear that it is a solution of great performance, low cost and fast construction, which speeds up the construction times in the building or work in which it is being used. (Barrera, C. & Valverde, H., 2012).

2. Contribution

The present research proposes the implementation of Rammed Aggregated Piers (RAP), in a shopping center that will have a foundation composed of footings and floor slabs, to mitigate liquefaction in soft soils considering 2 indicators: the security factor and settlement. Later, we will delve more specifically into the essential indicators mentioned above which play an important factor when analyzing the calculations to avoid liquefaction by providing greater carrying capacity.

3. Methodology

In this section, the steps to follow to design the implementation of the Rammed Aggregated Piers were established, considering the different stages and data necessary to follow a coherent and efficient order. Initially, the classification of the soil that the district of Lurín has, focusing on the study area and analyzing the seismic zone in which it is based on the E.030 standard. Next, data were collected on the liquefaction potential in the chosen district and soil profiles were made, from which the data obtained by the soil study (EMS) of the San Pedro project were taken as a basis. Input data for seismic magnitude (Mg), acceleration factor, water table and soil specific weight were determined with the help of the San Pedro Project's EMS.

Fig. 2: Project location, Lurin, Lima, Peru

The San Pedro project is a real estate project where road and building works were carried out, which, when presenting a soil study with predominant presence of loose sands (NSPT low < 10) and presence of water table near the surface, indicates that the soil where this structure will be cemented will have a high liquefaction potential.

a	0.45	g
Mg	8	Mw
D (N.F)	1.2	m
P.E (ENCIMA NF)	14.8	KN/m3
P.E (DEBAJO NF)	17.6	KN/m3

Fig. 3: Input Data

Subsequently, the NSPT was calculated, the N60 was calculated, the Cn of the Peck Cone, the SUCS classification was made, the Attenberg limits were found, and the percentages of humidity and percentages of fines were calculated. Similarly, the calculation of settlements will continue before soil improvement and will end with the calculation of settlements after the employability of Compacted Gravel Piles; thus, analyzing the settlements in a comparative table. It should be noted that the Idris & Boulander methodology established in 2008 is used. Finally, comparative analyses were carried out between the calculations carried out to verify the benefits obtained by the execution of Compacted Gravel Piles in weak soils such as in the present project located in the district of Lurin.

Although the EMS proposes some calculations to estimate the liquefaction in this area, in this article the FS and the post liquefaction settlements have been calculated independently. It was decided to implement a construction technique (the use of Compacted Gravel Piles) that will considerably improve the settlement of the structure and decrease the probability of liquefaction in the soil. In the following lines, the restrictions for the design of the execution of the Compacted Gravel Piles will be defined.

It is worth mentioning that, for the implementation of the Compacted Gravel Piles, the Geopier methodology was used, which consists of 3 steps. (Melo, A., 2016).

- Densification; consists of the densification of the soil by means of the increase in the number of blows N, where the blows will increase only in the strata where the % of fines is less than 15% and where the RAP is located.
- Increased lateral tension; where the RRC is increasing by 20% in the stratum where the RAP is located.
- Composite elastic modulus.

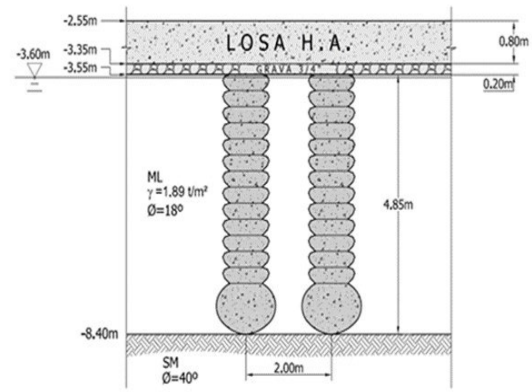

Fig. 4: Two rammed Aggregated piers supported on a slab.

- Constructability (use): The execution of Rammed Aggregated Piers is restricted according to soil classification; Because this technique improves the soil on which it is applied, that is, they are used in fragile soils or susceptible to liquefaction. These soils are mainly when there is the presence of sand or silt (SM, SM-SP). Similarly, it can be used when there is a surface water table.

- Safety: To use the Rammed Aggregated Piers technique, a settlement analysis must be performed to determine if it can be applied, since if the settlement is within the range established by the E.050 standard, it is counterproductive to use them.

In accordance with the E.050 standard, it must be considered that a soil study must be carried out in buildings that present any of the following characteristics.

- Constructions where they are going to build from 1 to 3 floors with more than 500 m2 of surface.
- That are 4 or more stories high.
- Buildings intended for industries, factories, workshops, etc.
- Special buildings with danger of breakdown.
- Buildings that require piles, pillars, or foundation plates.
- Buildings with unstable soils or that are adjacent to slopes.

Exploration techniques

The studies carried out in this project to study the soil, were calicatas, standard penetration tests (SPT) and dynamic penetration tests of Peck Cone. Based on this, it is observed that these studies were used based on the regulations in force today in Peru.

For the use of calicatas, ASTM D 440 applies.

For the standard penetration test and for the use of dynamic Peck Cone penetration, NTP-339.133 and ASTM D 1586 apply, which indicates and describes the procedure to be used to perform a sampling with the implementation of these tests.

Unified Soil Classification (SUCS)

It is a system of classification of the characteristics of the soils which can influence the design of a building. It should be noted that for the present project the SUCS classification method was used, since this method is used in a general way while the AASHTO method is more commonly used on roads. The standard which governs this system is ASTM D 2487.

Standard Tests

After obtaining the study of the soil characteristics, we proceeded to obtain the geodynamic data, which were present in the soil study of the San Pedro project. To obtain such data, it is necessary to implement ASTM standards which were applied in the study of soils for foundation and paving purposes for the San Pedro Project.

- Plastic limit and liquid limit, ASTM D 4318 was applied.

Design of RAP

Rammed Aggregated Piers are soil reinforcement elements designed to control settlements. The configuration of the design of the RAP according to the Geopier methodology, is divided into two parts: the upper zone and the lower zone. (Geopier, Technical Bulletin No. 12, 2016).

- The upper zone is defined by the depth of the Geopier element to the bottom of the RAP bulb.

- The lower zone is the area below the RAP where the soil has not been reinforced.

Employability study of RAP

For the design proposal of Compacted Gravel Piles, the AutoCAD program was used, which is a multifaceted program that allows the development of architectural, industrial, mechanical, and engineering projects.

We start by choosing the area where the RAPs will be used, so we can optimize costs and use the necessary RAP; the spacing between stack and stack, its diameter, and the parameter Ra (relationship between the stack area and the shoe area) must be considered.

DIAMETER	0.61	meter
SPACING	2.5	meter
Ra	0.047	

Fig. 5: Essential Rammed Aggregated Piers Data

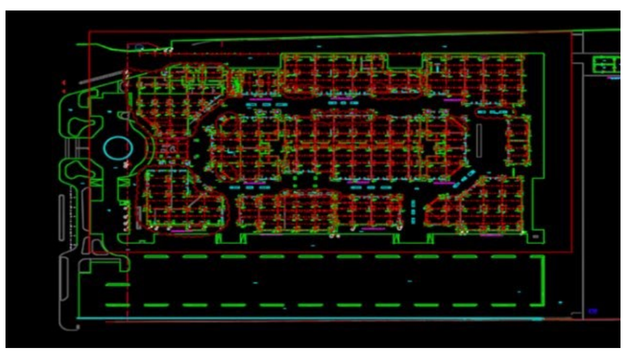

Fig. 6: San Pedro Project Floor Plan

After that, we clean the surface of any object other than foundation and create the piles. It is important to delimit the work area well so that in this way the meters to be made are optimal and not size the structures or increase prices.

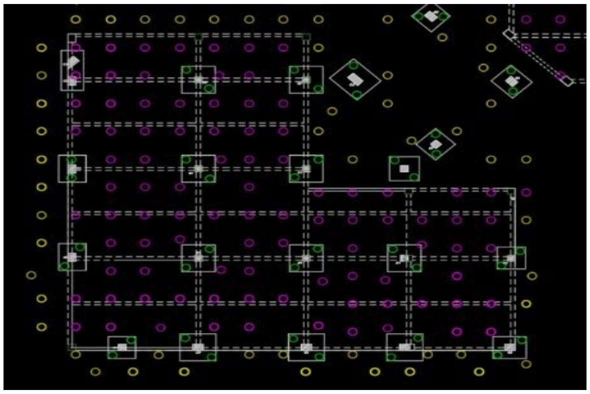

Fig. 7: Workplace

Finally, we separate with different layers and determine a color for each function of the stack. The green batteries located in the shoes fulfill the function of resisting static charges in addition to liquefaction. The fuchsia piles, which are in the floor slab, are used to prevent liquefaction, it should be taken into account that if in any slab it is determined that there will be no liquefaction it is not necessary to implement said pile. Finally, yellow batteries are confinement batteries which fulfill the function of mitigating liquefaction.

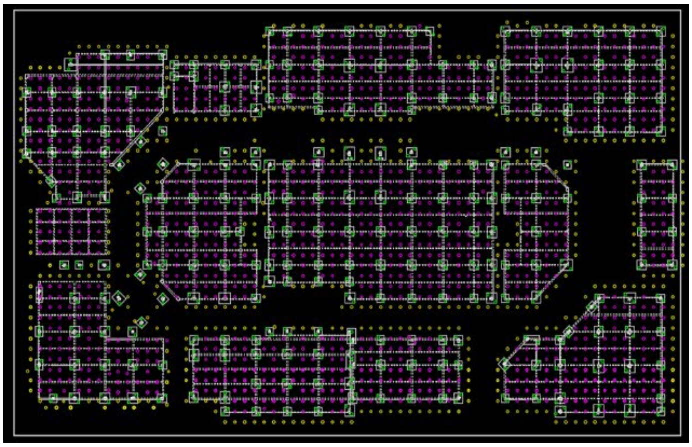

Fig. 8: Total Workplace area

4. Results

Based on the calculations made and taking into consideration the graphs and results obtained from the EMS of the San Pedro Project, the following summary tables were obtained using the Rammed Aggregated Piers as a solution, demonstrating the reduction of settlement.

Table 1. Summary of settlements before and after the implementation of RAP

1 inch =	2.54	cm

RESUMEN DE ASENTAMIENTOS				
TEST	SETTLEMENT BEFORE IMPROVEMENT (cm)	SETTLEMENT WITH INCREASE OF N AND Ko (cm)	SETTLEMENT WITH INCREASE OF N, Ko AND Ecomp (cm)	VERIFICATION OF MAXIMUM ADMISSIBLE SETTLEMENT (<1 INCH)
SPT 1	3.55	2.16	0.91	OK
SPT 2	7.16	4.17	1.86	OK
SPT 3	3.73	3.06	1.19	OK
SPT 4	7.47	5.62	2.15	OK
SPT 5	1.37	1.37	0.32	OK
SPT 6	4.21	2.37	2.43	OK
SPT 7	2.30	0.65	0.66	OK
SPT 8	No licuation	No licuation	No licuation	
SPT 9	No licuation	No licuation	No licuation	
SPT 10	No licuation	No licuation	No licuation	
SPT 11	No licuation	No licuation	No licuation	
SPT 12	No licuation	No licuation	No licuation	

4. Conclusions

Through the standard penetration test (SPT) analyses carried out and with the help of the settlement summary table, where the results of the tests prior to and after the use of the Compacted Gravel Piles are analyzed; It is concluded that, in the San Pedro Shopping Centre Project, there is great potential for liquefaction since when analyzing the settlements for each SPT test (12 tests in total), it was verified that 7 settlements were greater than the admissible settlement proposed by the Study of Soil Mechanics (EMS) carried out prior to the implementation of any soil improvement method.

With the application of the Compacted Gravel Piles in the SPT tests, taking into consideration the calculations carried out in each SPT for the analysis of the settlements post implementation of the soil improvement and by the settlement summary table, it is denoted that the use This semi-rigid element considerably benefits the mitigation of liquefaction since taking these analyses into account, the settlement decreases considerably compared to the analyses prior to the implementation of the proposed solution; which leads to an increase in the safety factor in the strata where the piles were implemented.

Through the analyses carried out in the Soil Mechanics Study (EMS) of the construction of the CC. San Pedro, it was submitted that the maximum allowable settlement was less than 1 inch. Therefore, through the analysis in each SPT, it was highlighted and corroborated that through calculations carried out to obtain the settlements implementing the Compacted Gravel Piles, all the settlements carried out are less than what was specified. Having a maximum value of 2.15 cm which is equivalent to 0.85 inches.

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