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Innovative Soil Reinforcement Method to Control Static and Seismic Settlements

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ABSTRACT: With increasing levels of seismic awareness and design-level earthquake accelerations, Geotechnical Engineers are challenged to find cost effective solutions to address both static and seismically induced settlement in high seismic areas. In Salinas, California a relatively heavy, one and two-story structure was recently constructed in an area of relatively deep, intermittent, layers of liquefiable soil resulting in the potential for excessive total and differential settlements.

A traditional foundation system of driven piles with structural slab similar to the new surrounding buildings was initially considered. Although this option addressed static settlement control and the potential for excessive seismically induced differential settlements, the solution was not considered economically viable and posed a risk to adjacent historic, unreinforced masonry structures. Alternatively, an innovative soil reinforcement method consisting of a stiffened geo-grid reinforced engineered fill over reinforced soil utilizing an evenly spaced Rammed Aggregate Pier® system was used to support the building. The reinforced soil mat was designed to control static settlement from the building loads and reduce seismically induced differential settlements to within allowable project tolerances.

INTRODUCTION

Engineer's increased awareness of potential liquefaction and seismic settlement related damages to buildings and infrastructure are driving project costs to all new highs. Tough decisions are required regarding risk-based performance of structures after a major earthquake. Geotechnical Engineers have a limited database of proven and cost effective mitigation measures for damages caused by liquefaction and seismic settlements. Such mitigation measures include:

- Driven piles thru loose liquefiable soil bearing in deeper soil and rock,
- Mass excavation and replacement with engineered fill,

- Densification by dynamic compaction or vibration,
- Reinforcement by high modulus aggregate piers or cement columns,
- Stiffened grade-beam foundation systems with structural slabs,
- Drainage by wick drains or aggregate piers, and
- Rammed Aggregate Pier system support of a geo-grid reinforced fill.

A geo-grid reinforced fill supported over a Rammed Aggregate Pier system was used to support a structure in Salinas California which is the subject of this paper.

PROJECT DESCRIPTION

The structure is a theater building for the Maya Cinema 14-Plex in Downtown Salinas, California. Directly adjacent buildings consist of one and two story historic, unreinforced masonry construction on shallow footings, and a newly constructed adjacent parking garage founded on driven piles. The theater building has a footprint area of about 5,110 square-meters, with masonry wall loads of 8.8 kN/m and column loads of 445 to 1,232 kN. The design earthquake has a moment magnitude of 7.3 with a corresponding peak ground acceleration of 0.5g. The site is located within 22 km of the San Andreas fault, Monterey Bay-Tularcitos, and Rinconada faults.

Utilizing the design earthquake and bored soil conditions, the total earthquake-induced settlement as a result of liquefaction was estimated to be about 50 to 100 mm. Static and dry sand seismic settlements added to the concern of building damage.

LIQUEFACTION POTENTIAL, STATIC AND SEISMIC SETTLEMENT

The primary geotechnical concerns for this site were the presence of near surface undocumented sand fill and potentially liquefiable sand. The undocumented fills were found in the upper 5.2 to 6 m below the ground surface. The potential liquefiable soil consisted of loose sand below the groundwater table below about 8.2 m below the ground surface. Liquefaction potential was based on a design earthquake with moment magnitude of 7.3, with corresponding peak ground acceleration (PGA) of the site of 0.50g. The depth to which liquefaction is estimated to occur varies between about 7.5 to 15 m, and is discontinuous, varying in thickness, depth and lateral extent. Estimates of the resulting settlement should all of the various layers liquefy was performed based on the recommendations by Youd (1996 and 1998). Estimates from both the CPTs and borings performed at the site indicated an estimated accumulated settlement of 50 to 100 mm. Differential settlements were based on the difference in computed total settlement. Based on Martin and Lew (1999), differential settlements may be taken as half of the total settlements between adjacent supports.

In addition to potential settlement due to liquefaction below the groundwater level, settlement was also anticipated due to seismic densification of the dry sand fill above the groundwater level, as well as static settlement of the fill due to the planned buildings loads. It was estimated that the dynamic densification would range from about 6 to 12 mm, and the settlement due to the building loads could be about 50 mm. Potential total settlements could be on the order of about 100 to 165 mm.

DEEP FOUNDATION ALTERNATIVE

The initial approach to control settlements was to support the structure on a deep foundation that extended below the depth of the potential liquefiable soil. Typically, precast, prestressed concrete piles would be used with lengths of about 33.5 m with a 1,468 kN allowable load. Because of potential differential settlement between the pile supported building columns (limited settlement) and the subgrade supported building slab (potential for significant settlement), a structural slab would be required. Concerns were also expressed about the damaging impacts of pile driving on the adjacent historic, unreinforced masonry structures, as well as the additional foundation costs and the impact of the driven piles schedule on the aggressive project schedule.

ALTERNATIVE SOIL IMPROVEMENT / SOIL MAT SYSTEM

Due to high cost of piling, scheduling, and adjacent buildings, an innovative soil reinforcement method beneath the site was considered and subsequently used for foundation support, see FIG. 1. This reinforced soil mat system would need to address the undocumented fill in the upper portions of the site, reduce installation-caused settlement on the adjacent historic properties, and provide a mechanism to reduce differential settlement caused by potential liquefiable sands at the site. To address the effects of these potential damaging differential settlements, it was recommended that the Rammed Aggregate Pier (RAP) ground improvement system overlain by a geo-grid reinforced soil cap be installed to support a conventional shallow foundation system for the building. It was the intent of the RAPs and reinforced soil cap to both strengthen the fill soils beneath the floor slab and building columns, as well as to create a reinforced and stiffened soil mat over the potentially liquefiable soil layers to reduce damaging differential settlements.

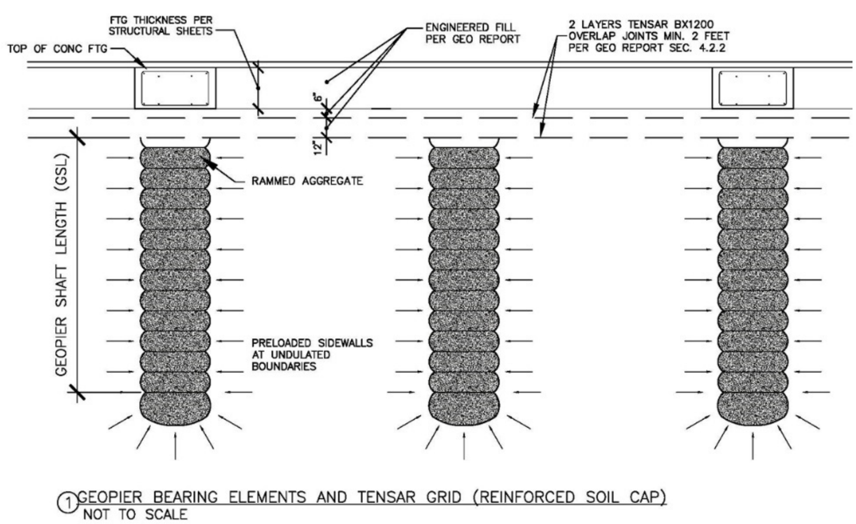

FIG. 1 Cross Section of the Installed Soil Mat System

REINFORCED SOIL MAT DESIGN

In designing a soil mat, the thickness and the method of the soil improvement is critical. The intent of the soil mat foundation system was not to eliminate total settlement, but to reduce differential static and seismic settlement to approximately 20 mm over 15 m~~s~~. For this project, the design of the soil mat consisted of the following components:

- Highly densified Rammed Aggregate Piers installed to depths of 5.5 m below the slab-on-grade to provide a stiffened and densified soil mass within the loose fill to reduce dynamic densification. RAPs were evenly spaced at 3.3 m on center and concentrated under walls and columns.
- Composite strengthening and densification of a substantial thickness of soil above the potential liquefiable soil layers with RAPs to increase the arching capability of the soil mat system.
- Installation of a geo-grid reinforced fill above the RAPs near the surface and just below the footings and below the slab-on-grade to reduce differential settlement between the RAPs.
- Increasing the tensile strength of the soil mat system by having a two layer Tensar BX1200 geo-grid reinforced fill near the surface of the site.

Given the above criteria, and using a Finite Differential Method (FDM) computer analysis to model the soil mat's effectiveness, a soil mat foundation system was installed as follows:

- Shallow foundations consisting of isolated and continuous footings embedded a minimum of 0.6 m below the bottom of the building slab,
- A 0.45 m thick geo-grid reinforced soil mat below the footings containing geo-grids at the bottom and in the middle of the compacted sandy soil,
- Installation of 0.75 m diameter RAPs on 3.3 m spacing throughout the entire building envelope. The RAPs extended a minimum of 4.6 m below the geo-grid reinforced fill. RAP ramming installation also increases the density of sandy soil below the RAP drill depth to an estimated depth of 0.9 m. As a result, the depth of RAP improvement extended about 5.5 m below the bottom of the geo-grid reinforced fill portion of the soil mat.

The depth and spacing of the RAPs were based on using the increased stiffness of the improved area due to the RAPs themselves, the increase in densification between the RAPs that would increase strength and strain characteristics with resulting increase in arching of the soil between the RAPs, the increase in density of the mass to reduce dynamic settlement above the groundwater level, and the decrease in settlement due to building loads. An iterative analysis using FDM was performed. In addition, reduction of the amount of differential settlement would be further reduced with the geo-grid reinforced mat. This was modeled based on the methodology by Han (1999), and Han and Gabr (2002). The geo-grid analysis resulted in an estimated reduction in by about half. In calculating the spacing and depth of the RAPs, consideration was given to soil arching as it relates to densification of the sand, the shear strength of the sand, and the shear strength between the RAPs and the sand. In the analysis, consideration was given to providing higher densification of the sands within about 1.5 diameters from the center of the RAPs. This distance is based on experience with stone columns and other ground improvement methods in sands, which are susceptible to ramming/vibration induced compaction. The increased densification allowed for shorter distances for arching of the soil. Typical values for soil arching are about three times the spacing. Given that the estimated distance (approximately of 1.8 m) of the unimproved portion of the soils between the RAPs, the vertical distance would need to be about 5.5 m.

RAMMED AGGREGATE PIER® SYSTEM

Rammed Aggregate Pier systems are a ground improvement technique that consists of replacing and/or displacing loose/weak soil with highly densified, thin lifts of compacted aggregate. RAP construction is well defined in the literature (Majchrzak, 2004, Farrell, et al 2008). RAPs provide for a stiffened, composite soil mass where higher concentrations of stress are attracted to the stiff RAP elements compared to the soft matrix soil. The stress to the RAP is a function of the relative stiffness between the RAP element and matrix soil and area replacement as shown in Eq. 1.

$$q_g = \frac{qR_s}{R_a(R_s - 1) + 1} \qquad [1]$$

Where q is the applied maximum footing bearing pressure, q_g is the stress to the top of the RAP, R_s is the stress concentration factor, and Ra is the area replacement of the RAPs. The stress concentration factor, R_s, is equivalent to the ratio of the RAP stiffness to the matrix soil stiffness at a given bearing stress. The matrix soil stiffness may be estimated through traditional geotechnical analysis. The RAP stiffness is confirmed by modulus load testing on an individual RAP (Fox and Cowell, 1998).

During ramming, the beveled hammer forces crushed rock laterally into the sidewalls of the drilled shaft. This ramming action increases the lateral stress and strengthens the matrix soil, thus providing additional stiffening and increased normal stress perpendicular to the perimeter shearing surface. In seismic areas, the stiffer RAP elements attract and absorb high shear stresses thereby reducing the cyclic shear stresses to the matrix soil (Green, et al 2008, Girsang, et al, Baez and Martin 1993).

The intent of the RAP element installation for this project was to control structural static load settlement, reduce seismic settlement of the loose sand fill, and to increase the composite soil mass stiffness to reduce surface manifestation of deep settlements below 7.6 m. The engineered fill and structural loads were supported by arching to the top of the RAP elements. Control of static settlement was determined using Eq. 2:

$$s_{uz} = \frac{q_g}{k_g} \qquad [2]$$

where q_g is the stress applied to the RAP and k_g is the stiffness modulus of the RAP (Fox and Cowell 1998). The stiffness of the RAP and the settlement within the RAP reinforced zone was verified by full scale modulus testing of an individual RAP using load testing procedures in general conformance with ASTM D-1143. The load test was performed on a concrete cap embedded a depth of 0.6 m, consistent with the average bottom footing elevation, and located directly over the RAP. The results of the modulus test, shown in FIG. 2, confirmed the stiff RAP element with 5 mm of deflection at the design test stress of 880 kPa.

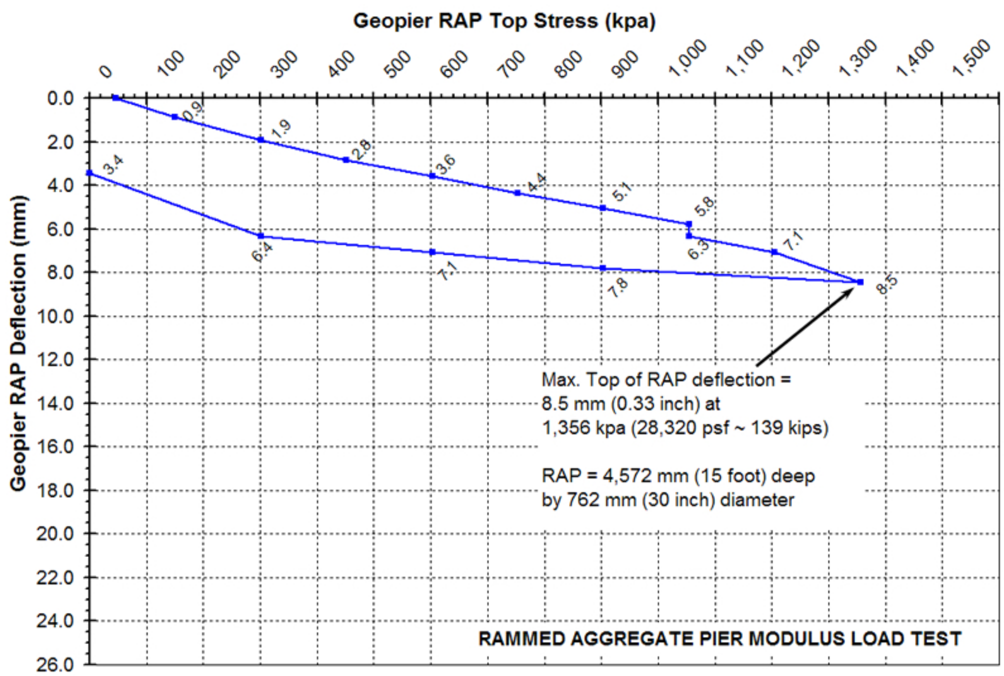

FIG. 2. Rammed Aggregate Pier Modulus Load Test

PRE AND POST CPT TESTING

Cone Penetrometer Testing (CPT) was performed before and after installation of the RAPs. The generalized soil profile and results of CPT testing are shown in FIG. 3. Prior to RAP installation, the Standard Penetration Test sampler had equivalent blow counts of less than 20 blows for 0.3 m to depths greater than 7.5 m. After installation of the RAPs, additional CPTs were performed to monitor the increase in density between the RAPs. The additional CPTs were located at 1 foot intervals between two adjacent RAPs spaced at 3.3m on center. The CPTs showed a significant increase of 150 to 200 percent of the original equivalent SPT N_{60} blow counts. The CPT results also showed significant increase in soil density between the RAPs.

CONCLUSION

The project site is underlain by loose sand fill above the groundwater level, and potential liquefiable sands below the groundwater level. The settlement from these soil layers could have a significant impact to the theater building. A typical

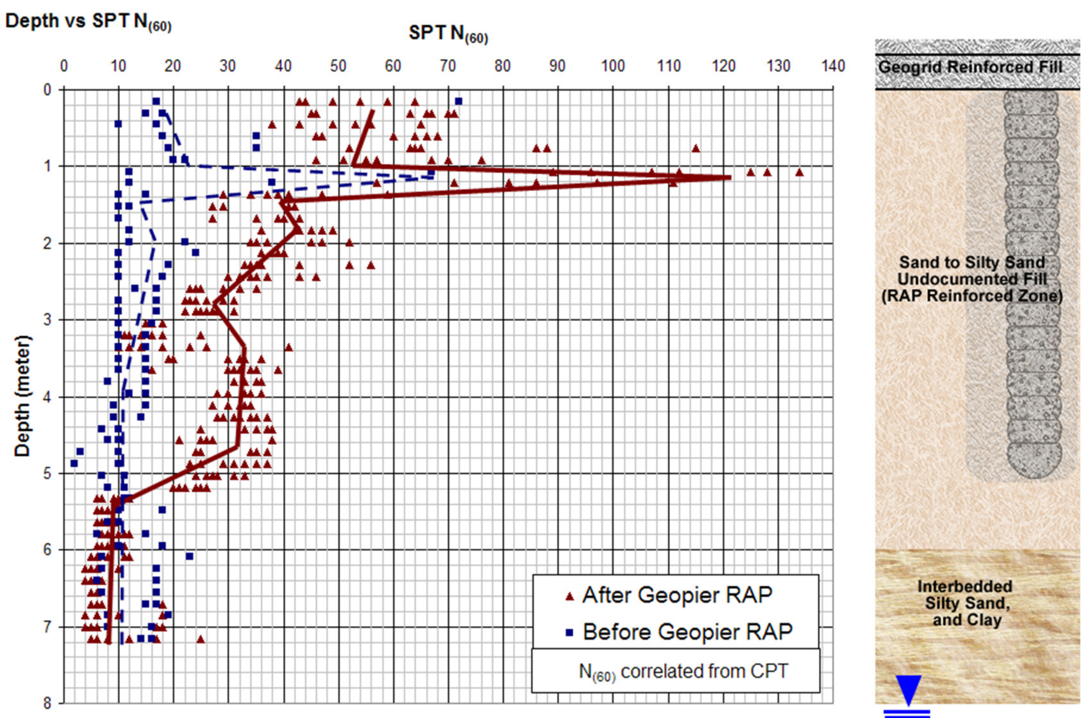

FIG 3. Pre and Post CPT Testing at Maya Cinemas in Salinas, CA

foundation system of driven piles was considered to support the building and slab. The deep foundation system was found to be costly, could not meet the aggressive project schedule, and could have a damaging impact on adjacent historic structures. An alternative system of a shallow foundation supported on a reinforced soil mat was considered and used. The soil mat consisted of two components that included a 0.45 m thick geo-grid reinforced fill supported on an evenly spaced Rammed Aggregate Pier system throughout the building footprint. The 0.75 m RAPs and resulting improvement extends to a minimum of 5.5 m below the geo-grid reinforced fill at an even spacing of 3.3 m on center. The design of the spacing and depth of the RAPs was based on the composite stiffness of the system and a conservative estimate of the lateral extent of densification resulting from installation of the RAPs.

The results of the modulus load test on a Rammed Aggregate Pier and the pre- and post- CPT testing of the soil demonstrated a significant improvement in the stiffened crust and higher than anticipated increase in soil densification between the RAPs. The improvements resulted in replacement of portions of the upper sands with stiffer and less compressible elements using the RAPs, increased density of the soils between the RAPs that increased its arching capability, stiff geo-grid reinforced fill above the RAPs, and finally lower settlement and higher shear strengths of the soil mat system. Specifically, the settlement due to the building loads would be reduced from about 50 mm to 5 mm (based on the improved stress/strain of the soil), the dynamic settlement above the groundwater level reduced to near zero, and the propagation of the liquefaction induced differential settlement estimated to be about 25 to 50 mm would be reduce to approximately 20 mm over a horizontal distance of approximately 15 m at the ground surface (based on further FDM evaluations; the RAPs would reduce the differential settlement by about 20 mm, and the geo-grid soil mat would reduce that by about 10 mm). It was concluded that this system would be capable of controlling static settlements and reducing the effects from dynamic densification in the sand fill above the groundwater as well as reduce the overall differential settlement associated with liquefaction occurring at depths below the reinforced soil mat system.

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