WHITEPAPER

Reduce the Risk of Foundation Settlement

Structural Mitigation for the Seismic Hazards of Liquefaction

Lou Scatena

Associate Vice President of Structural Engineering, Carollo Engineers, Inc.

Bentley
Advancing Infrastructure

INTRODUCTION

Structural methodologies for assessing and mitigating the seismic hazards of liquefaction differential settlement and lateral spread continue to expand. The author will summarize his own experience dealing with such challenges during design of a series of structures for a new water treatment plant in Southern California. The experience suggested that when the predicted displacements are not extreme, costly deep soil densification may be avoided. Instead, it can be replaced by less costly structural mitigation when approved by the geotechnical consultant. Soil improvements considered for this project included stone columns and compaction grouting. The structural mitigation alternatives were piling and/or thickened concrete mat foundations.

STRUCTURAL MITIGATION OF LIQUEFACTION DISPLACEMENT

The *California Geological Survey* (SP 117A) defines large-scale liquefaction displacements as those exceeding one foot horizontally and four inches vertically. As of July 2013, the Los Angeles County Department of Public Works specifies that structural mitigation is acceptable for up to one inch of seismic-induced differential settlement over a horizontal interval of 30 feet and total settlement up to four inches.

Seismic analyses and structural design were completed for all structures on the project using STAAD® structural analysis software from Bentley Systems. The models were essential to accurately assess structures for total static plus seismic settlement. Because only the electrical building would be occupied, and because of the high importance of two other non-occupied structures in the project, the owner requested that these three structures should be structurally mitigated for liquefaction. With concern for potential settlement, lightweight steel-framed structures were used for nonwater-bearing structures.

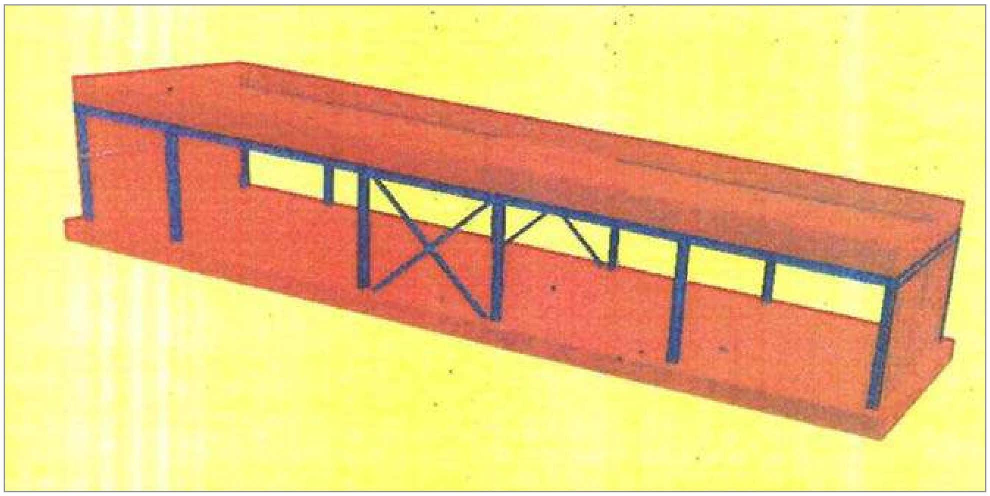

Figure 1 – 3D model for the electrical building (siding not shown).

Special moment frames are used to resist seismic forces in the short, north-south direction. Special concentric braced frames are used in the long, east-west direction. To accurately model the lateral stiffness of the corrugated steel roof deck, a trial model of the deck was run to determine the values for its thickness and modulus of elasticity. The selected values were based on the manufacturer's measured lateral stiffness resulting from their load tests. Models also include 32 separate seismic iterations for the equivalent lateral force (ELF) directional load cases, including orthogonal and torsional load combinations. For the electrical building, however, response spectrum analysis was used after scaling the initial dynamic results up to 100% of the ELF base shear, in accordance with the California Building Code.

The initial modeling objective was to identify the linear soil springs that would replicate the geotechnical consultant's original design assumptions and predicted total seismic plus static differential settlement. On previous projects, the author found that the consultant was able to provide these moduli. On this project, however, it was necessary to initially model the foundation by "trial and error" to arrive at the distribution of soil-spring values that yield the consultant's predicted settlement.

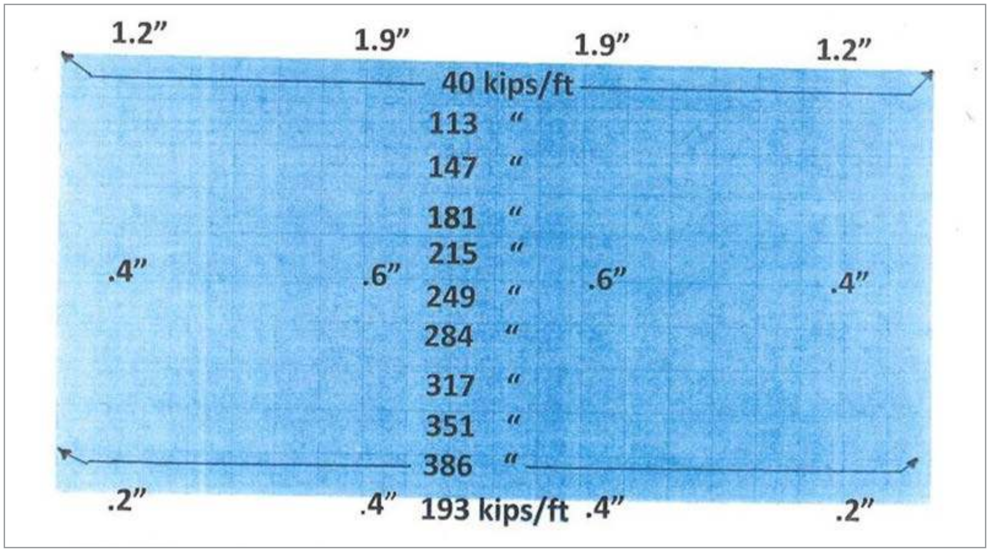

Figure 2 – Final distribution of nodal soil springs.

Figure 2 describes the final distribution of nodal soil springs in the north-south direction to duplicate the consultant's predicted differential settlement of 1.5 inches in 30 feet. Subsequently, the concrete mat in the final model employs the same soil springs. By trial and error, it was determined that a mat thickness of 30 inches yields an acceptable differential settlement for south-north seismic load, as shown in Figure 3.

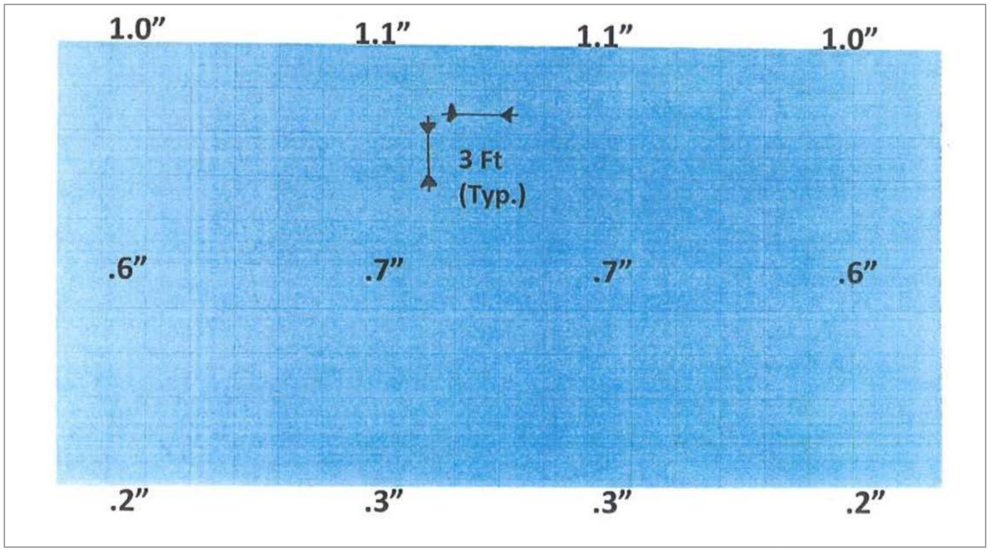

Figure 3 – Mat thickness for acceptable settlement.

Similar model extractions pictured the distribution of mat shear and bending stresses used in the final design. The model utilized specified values in ACI 318 for:

1. The reduced mat stiffness
2. The modulus of elasticity (E)

To the extent possible, concrete design strength was increased to elevate E to reduce settlement. A side benefit was that the increased strength also reduced the risks from corrosive soils that exist at the site. Fiber-reinforced concrete was also considered, but documented E values for such concrete were unavailable at that time.

It should be noted that in the north-south direction, increasing the mat thickness beyond 30 inches did not further reduce the final total static plus seismic differential settlement of three-quarters of an inch in 30 feet, as shown in Figure 3. As can be expected, the mat discontinuity in the short direction limits the benefits of thickening, as compared to the long direction. It suggests that when the geotechnical engineer can forecast the direction of differential settlement, narrow rectangular structures can be oriented to favor mitigation.

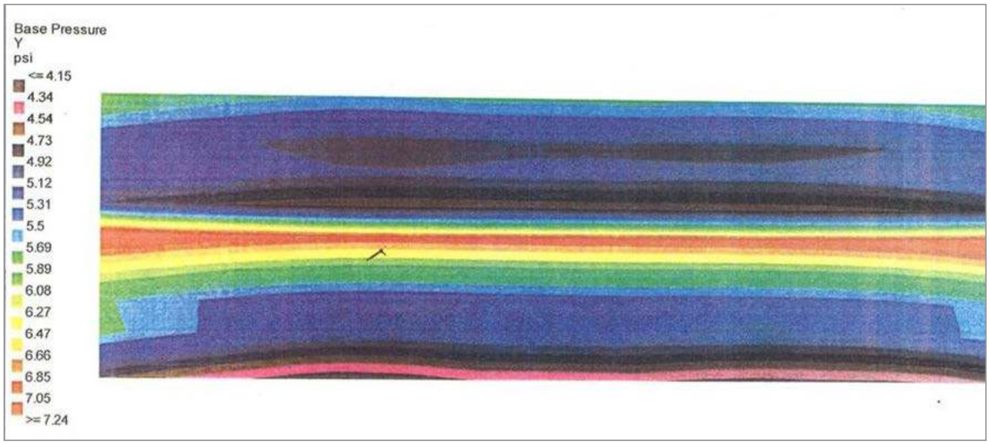

Figure 4 – Soil base pressure estimation.

Figure 4 estimates the soil base pressure with differential settlement in the short direction. It also describes the stiffness of the mat cantilevers beyond its central east-west axis to reduce settlement at the critical northern edge. Figure 4 utilizes a coefficient (Ks) of subgrade reaction (Bowles Foundation Analysis and Design); however, these values only approximate settlements and soil pressure, and are used here solely to depict the behavior of the mat. Soil pressures were accurately calculated from nodal spring deflections. These values were also used to estimate the additional reinforcing required in the concrete mat to resist the tensile effects caused by lateral spread. A soil/mat friction factor of 0.40 was used in the model.

ACCURACY BREAKTHROUGH

Carollo Engineers employs various Microsoft Excel spreadsheets to analyze and design concrete and steel structures in accordance with current design codes and technical practices. However, spreadsheets and manuals that are currently available today do not precisely assess certain critical design factors that are possible with STAAD. The STAAD models enabled an accurate identification of foundation settlements throughout a foundation system. It also enabled Carollo to identify seismic stresses and horizontal displacements throughout a framework, including the effects of flexible diaphragm deflection, stiffness, and torsion.

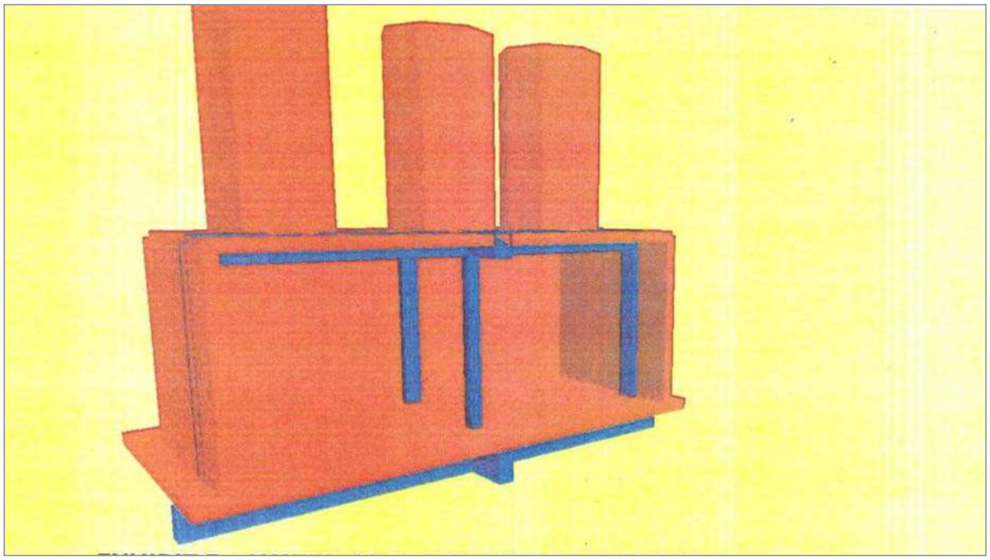

Figure 5 – Enclosed water containment basin.

For example, Figure 5 describes an enclosed water containment basin with large cylindrical water tanks anchored to the roof. The front half of the basin is removed to expose interior columns and beams. Since both structures are founded slightly below the existing ground surface, the same distribution of soil springs determined initially for the electrical building were also used for the containment basin. The hydrostatic and hydrodynamic loads were applied to the basin model in accordance with ASCE 7- 10, chapter 15.

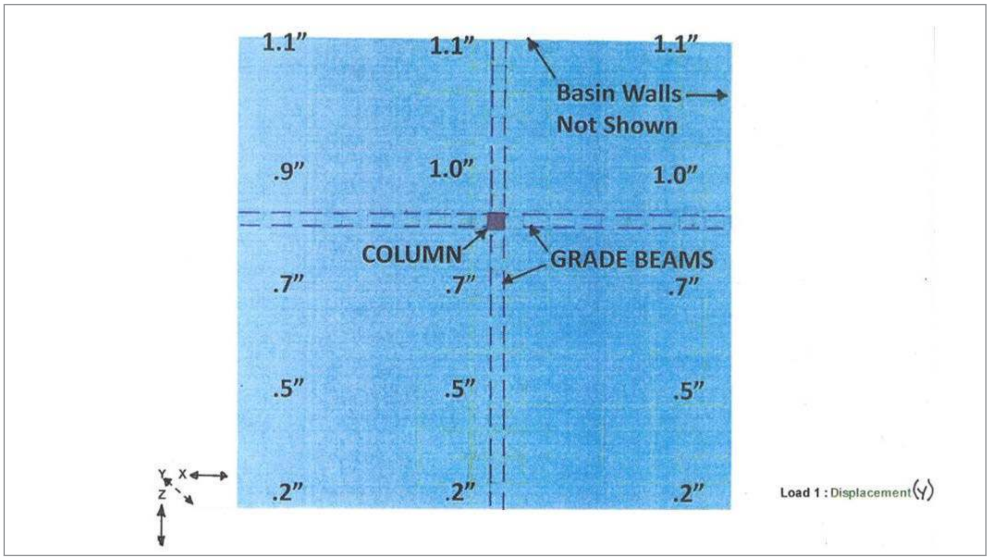

Figure 6 – Beams intersect under the single interior roof support column.

As expected, the governing load case for liquefaction settlement occurs when seismic acceleration is toward the north side where the basin structure is eccentrically loaded by the cylindrical tanks. Figure 6 describes the configuration of the four-foot-deep grade beams placed in each direction so that they intersect under the single interior roof support column.

It also describes the maximum differential settlement for the mat, which is 16 inches thick. Similar extractions from the model described the distribution of design shear and bending stresses used to design the reinforcement. Nodal spring values and settlements were used to accurately calculate liquefaction bearing pressures that varied from 900 to 2,000 pounds per square foot (psf), which was at the bearing pressure limit specified by the geotechnical consultant.

Past experiences with containment basins have shown that the concrete walls are instrumental in helping to stiffen the structure against differential settlement. This model, however, also suggested the economic benefits of utilizing ribs/grade beams on the underside of mats. Of course, such an approach is more reasonable when the mat is underlain by cohesive soils that can preclude the need for over-excavation and formwork. Since codes measure differential settlement in horizontal intervals of 30 feet, a 30-foot-by-30-foot grid layout for such ribs was implemented.

REDUCING COSTS ON A DIFFICULT PROJECT

Under certain soil conditions and when large seismic settlements are expected, soil densification methods are indispensable. Typically, however, this method of designing and building foundations can be very expensive, particularly if the soils targeted for improvement lay beneath other dense or semi-dense soil lenses that complicate the improvement by impeding the access of tools and materials used to improve the targeted stratum.

In these cases, if the anticipated differential settlement is not beyond code limits, structural mitigation can be considered. On some such projects, steel or concrete piling can also be considered; however, the drag-down loads from settling soils to the pile can be problematic and greatly elevate costs.

Where thick layers of loose soils exist near the surface (in any seismic zone), soil replacement can also be problematic and costly. The Valencia project demonstrated that STAAD structural models of thickened concrete mats, with or without ribs, could be considered and may provide an economical solution.

RELIABLE RESULTS

The project is in a high seismic area and involved the design of multiple structures that varied not only in dimension and framing, but also considered the owner's designated levels of risk and reliability for each structure. This wide variation in requirements emphasized the need for careful selection of:

- Seismic force resisting systems
- Foundation types
- Appropriate risk factors

Carollo Engineers used STAAD models to facilitate the fine adjustments required to meet those requirements for each structure. The models accurately calculated stresses, settlements, and lateral deflections—well above the level of reliability generated using spreadsheet analysis.

ON TIME AND ON BUDGET

Had the STAAD models not been used, it is likely that the construction cost for the project would have been substantially elevated due to the likely ultimate need for soil replacement and/or deep piling. The construction duration would have also been lengthened, leading to major negative impacts on the residential and commercial establishments that are served by the treatment plant and its product. The overall budget savings in terms of construction cost was estimated at 20%.

As a result of this project, Bentley's STAAD technical reference manual was redlined to create a template for use on future projects. In essence, the redlines enable users to quickly refer to appropriate data and design steps when finalizing input for the STAAD command file. The digital model for this project will serve to further improve collaboration between Carollo, Bentley, the geotechnical engineer, and the client.

REDUCE THE RISK OF FOUNDATION SETTLEMENT

Foundation settlement has been one of the largest concerns for all new structures ever since the Leaning Tower of Pisa was constructed. Efficient collaboration with Bentley and the geotechnical engineer can assist the structural engineer in utilizing STAAD to substantially reduce this risk.

About the Author

Lou Scatena is an associate vice president of structural engineering at Carollo Engineers, Inc. in Phoenix, Arizona. The firm specializes in the design of water treatment plants for major cities throughout most of the United States. Scatena has more than 50 years of experience in structural and civil engineering. He previously served as a structural engineer and technical consultant to the CEO at The Salt River Project Water & Power Co. Scatena graduated from University of Detroit Mercy College of Engineering and Science and is an accredited structural engineer in Arizona and civil engineer in California. He is the author of *Anthracite Boot Camp*.