FEATURE ARTICLE

2011 Transit Center construction, near Millennium Tower (left rear)

Soil Mixing Evolution in San Francisco

"San Francisco is 49 square miles surrounded by reality." So said Paul Kantner of the local '60s icons, Jefferson Airplane, and his words have still held true. The rate, scale and complexity of recent construction in this city has been remarkable, even compared to the Gold Rush or reconstruction after the 1906 earthquake. This article will address developments in soil mixing in San Francisco since 2011, and how the marked settlement of a downtown high rise has influenced this booming construction market.

Local Soil Mixing

Deep soil mixing has gained prominence in San Francisco for four reasons. First is the regional concentration of expertise. Japanese deep mixing technology was introduced to the U.S. in 1987 by S.M.W. Seiko. This pioneering company was based in the East Bay and some of its early employees still work at the eight soil mixing contractors now operating in the area.

Second, subsurface conditions here are well suited to soil mixing methods. The stratigraphy at city sites typically comprises urban fill, dune sand, young marine or marsh soils, Colma sand, and Old Bay Clay. The fill and dune sand are predominantly granular, forming well-blended soil cement. Although the young marine and marsh soils are mainly cohesive, their low strength allows for effective mixing, creating a reasonably consistent product. The stronger Colma formation, while predominantly dense well-graded sand, contains some silt and clay, which is mixable using shaft and end mixing methods. Typically, groundwater is within 15 to 20 ft (5 to 6 m) of grade, requiring cutoff walls for deep excavations. The Old Bay Clay unit, present at approximately 100 ft (30 m) below the downtown Transbay district, is an effective groundwater control layer, and cutoff walls are frequently keyed into this strata, or at least constructed with a deep toe within the Colma unit.

Third, the active seismicity of this region generates geotechnical challenges such as static settlement and liquefaction. Soil mixing offers efficient and cost-effective solutions for these situations. Finally, market demand has enabled contractors and consultants to rapidly evolve their expertise, as each successful project sets a new bar for complex support of excavation in tight, constrained urban sites. Although in

AUTHOR *Rob Jameson, Malcolm Drilling Company*

2012, 50 ft (15 m) was considered deep, by 2020, multiple excavations had extended over 70 ft (20 m), while being directly adjacent to existing buildings.

Approaches in Early 2000s

Back in 2011, the local soil mixing market predominantly involved multi-axis deep soil mixing (DSM) rigs operated by U.S. subsidiaries of Japanese companies, or single-axis mixing rigs operated by Malcolm Drilling Company and Condon-Johnson & Associates. San Francisco had seen limited new building since the 1980s. Construction projects were mainly infrastructure, structural retrofits, or relatively shallow excavations constructed with conventional pile and lagging or underpinning methods. Jet mixing had gained ground as being very fast and efficient; however, equipment constraints had limited this approach to about 70 ft (20 m) of total drilling depth. One unique project was the Sunset Reservoir, where multiple tiered soil mix cells provided slope stabilization and liquefaction mitigation. This project was constructed by Raito using a multi-axis rig. Cutter soil mixing (CSM) had not yet been used in San Francisco.

The Last Decade

After the Great Recession of 2008 and 2009, the city began a rapid growth trajectory fueled by the technology sector. Strong demand for state-of-practice soil mixing further concentrated local expertise among designers and contractors. Millennium Tower, completed and opened in 2009, became infamous for its post-construction settlement, resetting the risk perspective of many in the deep foundation industry.

Soil mixing has followed three tracks of development since 2011. An increased application of DSM grid systems has occurred for combined bearing support and liquefaction mitigation; secondly, the demand for larger, deeper, more complex excavations in an increasingly risk-focused environment led to widespread adoption of CSM as a preferred construction method. Within this heated, but maturing market, construction demands have also encouraged refinement and optimization of more conventional methods, such as single- and multi-axis and jet mixing.

San Francisco's Mission Bay, downtown in 2006

Constructed Mission Bay district in 2019, and Transbay District towers near downtown

Millennium Tower Impact

Millennium Tower is a 58-story luxury condominium whose opening in 2009 provided the first new downtown tower in almost 20 years. Its concrete frame construction is founded on up to 90 ft (27 m) long concrete piles driven into the Colma formation. The site is directly adjacent to the Transbay Transit Center,

whose construction from 2011 through 2018 included a secant pile buttress designed to limit deformation of Millennium Tower during excavation of the adjacent 60 ft (18 m) deep station. The buttress was keyed into the 250 ft (75 m) deep Franciscan bedrock, with installation costs exceeding $50 million (€44 million).

In 2016, it was publicly disclosed that Millennium Tower had settled 16 in (40 cm) in 7 years, compared to the predicted 20-year settlement of only 5.5 in (14 cm). The Transit Authority reported that 10 in (25 cm) of that settlement had occurred in the two years before their adjacent work started; by 2018, Millennium's total settlement was 18 in (45 cm). The residents, city, developer, Transit Authority and others initiated legal claims and counterclaims.

Settlements were reached without allocation or admission of fault. The Millennium Tower fallout has still impacted most contractors and consultants in San Francisco. In particular, the project highlighted the potential scale of liabilities surrounding deep foundation and excavation support work. Some repair schemes that were considered had estimated costs on the order of $300 million (€260 million). Heightened sensitivity to potential construction impacts on nearby structures has also occurred nationally, further emphasized by the recent Champlain Towers collapse in South Florida. One outcome is an increased focus on contractual risk management for all parties, notably the design professionals and specialist subcontractors, as has certainly occurred in San Francisco construction "Post-Millennium."

Another related impact of the Millennium has been an increase in regulation of geotechnical aspects of construction by San Francisco's Department of Building Inspection (DBI). In 2017, Interim Guidelines for Structural, Geotechnical and Seismic Hazard Design Review for Tall Buildings were issued, and then formalized in November 2018.

Although permitting previously relied solely on geotechnical engineer of record recommendations, the new guidelines require geotechnical peer review of projects over 240 ft (75 m) high. This requirement also applies to buildings constructed in seismic zones with soft soils, on sites overlying soft or compressible soils or on any other sites as directed by DBI. Specific considerations the peer reviewer addresses include ground improvement, effects of dewatering on site and nearby, and effects of construction-related activities on neighboring foundations.

In essence, Millennium has increased the focus on liability and risk transfer between parties engaged in geotechnical construction and created a new requirement for third-party peer review of support of excavation (SOE) and bearing support for critical projects. This means that design-build projects require earlier contractor engagement to determine the optimal construction approach and steer projects through permit approvals. Often, the peer review requires enhanced analysis, including finite element modelling of the geotechnical construction process, supplemental to the soil structure interaction studies that are conventionally run for completed structures under seismic loading. In consequence, complex projects now often have lead times of 6 to 18 months to break ground after a geotechnical construction team is selected.

These changes have afforded specialty contractors with an increased role in project development and participation in evaluating applicable solutions for risks. Another upside is that contractors are more frequently selected based on expertise, rather than solely on a low bid and potential willingness to accept challenging contract terms.

A cutter soil mix tool

Post-Recession Challenges

Construction of 350 Mission Tower kicked off the new, post-recession era in San Francisco. Its 50 ft (15 m) deep basement excavation was supported with internally braced CSM walls that extended through the Colma sands into the Old Bay Clay. Since this project's successful completion, increasingly deep, complex excavations have occurred in direct proximity to established structures. Several sites

have been excavated to over 70 ft (20 m) in the Transbay District, with shoring walls extending deeper than 100 ft (30 m); this depth allowed for structural embedment and sealing into the clay unit for groundwater control. Sometimes, walls have exceeded 130 ft (40 m) to seal off and depressurize confined aquifers for blowout mitigation, and for basal heave control in the underlying clay layers. Bedrock is too deep to contribute strength or stability.

Although traditional SOE schemes in San Francisco used the dense Colma sand to provide toe stability for shoring walls, the current, deeper excavations effectively remove this competent soil, and walls embed into the weaker, underlying clay. This increases the potential for basal heave effects that escalate the already significant ground movements predicted for these deep excavations. The CSM method has provided an effective solution to stiffen SOE systems by allowing thicker walls to accommodate larger, heavier steel sections than in traditional multi-axis soil mixing layouts. Also, buttress elements constructed perpendicular to the SOE wall can further stiffen shoring systems to manage deformation and effects on adjacent properties.

Project Example

Malcolm Drilling constructed SOE and deep foundations for Oceanwide Center, an L-shaped site that has a 61-level tower and a 53-level tower, over multilevel basements. The complex site footprint wraps around six adjacent structures, and required an SOE scheme that could allow tower excavation to progress without schedule constraints.

Overall, the mass excavation extended to 72 ft (22 m) depth, penetrating into the top of the Old Bay Clay. This uncharacteristic depth was further complicated by a thick sand lens within the underlying clay soils that required cut-off and depressurization. Due to the large depth and extensive removal of the Colma, the excavation had a relatively low factor of safety against basal heave.

The selected SOE approach was an internally braced, combined shoring and cutoff wall. Using a steerable, instrumented CSM mixing tool, Malcolm constructed a 140 ft (43 m) deep, 3.3 ft (1 m) thick, continuous perimeter wall. To minimize deformation effects, heavy W30 and W33 steel sections were placed at 4 ft (1.2 m) centers around the site perimeter. Structural beam lengths and other factors meant "over-the-hole" mechanical splices were employed during wet set placement of the reinforcement.

Two of the six structures adjacent to Oceanwide were high-rise towers founded on piles driven into the Colma formation. The planned excavation depth extended below pile tip of those structures. To further stiffen the SOE wall at these critical locations, soil cement buttresses were installed perpendicular to the perimeter alignment. The buttresses were constructed from original site grade by overlapping nominally reinforced soil cement panels end to end. They were removed in lifts as excavation progressed and bracing levels were installed, with the remaining length below final subgrade acting as a shear-key to resist lateral movement and basal heave. Finite element modelling of the shoring

The 72 ft (22 m) deep Oceanwide Center basement excavation

Soil mix buttress elements exposed during excavation

system provided deformation estimates, and the project was completed with actual movements within the predicted 0.1% to 0.2% of excavation depth.

Liquefaction and Bearing Capacity

DSM use for liquefaction mitigation in the U.S. dates back to Jackson Lake Dam in 1987, with multiple projects since then relying on its ability to construct below-grade shear structures to enhance slope stability and mitigate lateral spreading. These civil structures include dams, wharfs and reservoirs.

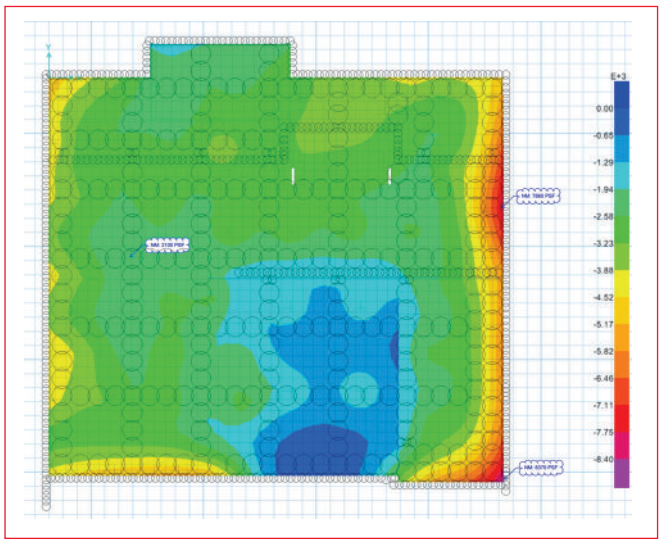
However, the last decade has seen rapid adoption of these methods for building projects, combining soil mixing grids for seismic mitigation and permanent bearing capacity support. Since soil mixing is often used for the perimeter SOE of these projects too, efficient combined systems have offered commercial advantages that have accelerated DSM grid adoption in San Francisco. The development of industry-wide design standards has also assisted nationally in applying this approach. Key references include a 2011 USACE design guide for levees and floodwall stability, an ASCE Grouting and Deep Mixing meeting paper in 2012 by Filz and colleagues, and a 2013 FHWA deep mixing design manual. Also the Boulanger and Shao keynote from DFI's 2021 Deep Mixing Conference presents a comprehensive review of recent developments in this field.

Market Street Example

Three blocks of San Francisco's arterial Market Street (5th to 8th) have seen 10 soil mixing projects this past decade. These mid-rise structures have used soil-mixed SOE walls for basement excavation, and are either founded on the Colma or on soil cement grids that transfer load down to this soil unit. The 12-story mixed use building at 1066 Market has three basement levels and imposes a peak load demand of 7 ksf (335 kPa). The site abuts double-stacked transit tunnels and multiple existing buildings. Its stratigraphy is comprised of undocumented fill materials and compressible marsh deposits overlying the Colma. Analysis predicted up to 3 in (8 cm) of liquefaction-induced settlement and up to 5.5 in (14 cm) of seismic densification of the fill.

Malcolm Drilling developed its bearing support design using 3 and 7 ft (0.9 and 2.1 m) diameter overlapped soil cement columns to create a combined bearing support and liquefaction mitigation grid extending through the fill and marsh soils, and 5 ft (1.5 m) into the underlying dense Colma formation. For the peak bearing pressure noted above, a 100% area replacement ratio (ARR) was used, with reduced coverage of 45-55% ARR elsewhere. Soil mix walls constructed around the site perimeter and to accommodate site grade changes were incorporated into the liquefaction grid pattern.

In a 2013 ASCE *Journal of Geotechnical and Geoenvironmental Engineering* article, Nguyen and colleagues shared the basis of the grid design, with predicted performance based on ARR, strength of soil cement, depth of the mixed columns, cyclic stress ratio and cyclic resistance ratio. The grid configuration reduces the shear strain imposed on enclosed soil and provides a barrier to excess pore pressure migrating from surrounding unimproved soils. The overlapped soil cement grid elements are configured to remain in compression, in



Market St. soil mix grid layout and applied loads of approximately 1 ksf (50 kPa, in blue) to over 7 ksf (335 kPa, in red)

contrast to the bending and cracking induced in individual elements subject to the same loading. The selected grid layout was integrated with the perimeter soil cement SOE walls for the Market Street project to provide completed enclosed cell elements.

Conclusion

Since 2011, San Francisco has experienced a massive surge in commercial and residential development. Millennium Tower issues and legal fallout triggered changes to business practices, local code and the review of geotechnical requirements.

As developers continued to pursue larger, deeper and more complex excavations in an increasingly dense, constrained environment, CSM has become the preferred system to successfully execute these works. Although typically costlier than conventional vertical multi-axis soil mixing systems, CSM's combination of direct down-hole monitoring, operator control and variable wall thickness provides significant technical advantages for most challenging SOE projects. The use of soil mix grid systems for combined bearing support and liquefaction mitigation has become more widespread, as new industry standard references provide an accepted design basis. In addition, the existing market for soil mixing with conventional tools (multi- and single- axis and jet mixing) has continued to thrive.

Excavated Market Street site

Rob Jameson has 30 years of geotechnical experience. Based in San Francisco, he oversees engineering and technical risk management throughout the U.S. for Malcolm Drilling Company, which celebrates its 60th anniversary thisyear.