Tall Building Foundations

The SF Millennium Tower Example

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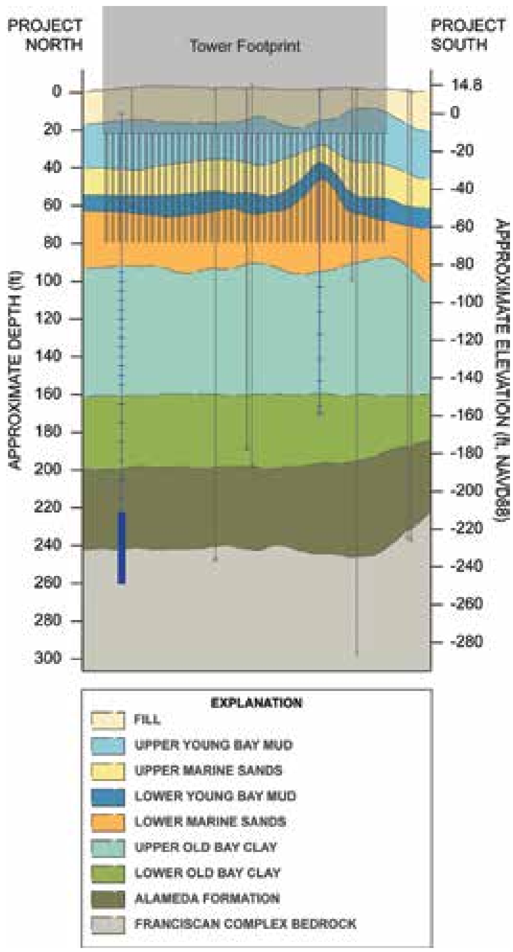
As new skyscrapers soar to increasing heights worldwide, the tip of the iceberg regarding potentially significant issues is hidden below the surface. For example, the Millennium Tower (Tower) in San Francisco, California, with a height of 645 feet and 58 stories, easily falls under the San Francisco Department of Building Inspection's (SFDBI) definition of a tall building. The Tower is one such case highlighting that communication among development team members, including engineers, architects, developers, and regulators, is imperative to achieving a successful project and illustrating how communication gaps can result in unanticipated issues. The entirety of a tall building ultimately performs as a single integrated system; its design team should strive for the same.

For decades, tall buildings in downtown San Francisco have successfully been supported on pile or mat foundations, bearing in dense late-Pleistocene sands that underlie artificial fill and soft Holocene sediments (known locally as Young Bay Mud [YBM]). Underlying the dense sands is a thick layer of Old Bay Clay (OBC) deposited before the last ice age. The OBC is a compressible soil that has become lightly overconsolidated due to erosion, aging, and lower sea levels during the late-Pleistocene glacial period. Very dense Alameda formation is found at the base of the OBC and immediately overlying Franciscan Mélange bedrock that is highly weathered and fractured due to the regional tectonic environment. Schematic representation of these subsurface conditions is illustrated in the *Figure*. Historically, extending foundations for tall buildings through the OBC to Franciscan bedrock at depths of 250± feet was not necessary. The Tower's foundation followed this trend by tipping the piles of its foundation in the dense sand, as depicted in the *Figure*. The Tower's settlement has altered the tenor of design practice and regulation in San Francisco toward only foundations that extend to bedrock being acceptable for tall buildings. Although bedrock-supported foundations may be necessary for acceptable performance for some tall buildings, such a requirement is not appropriate for every tall building.

Foundation design for tall buildings can be fraught with uncertainty, primarily due to limited knowledge of subsurface conditions underlying the site. Typically, geotechnical field exploration occurs early in the development process, sometimes even before full project conceptualization. Geotechnical engineers are always grateful for an additional investigative budget to improve knowledge of a site. Communicating the cost/benefit of reducing uncertainty to clients is difficult yet is not impossible. Whether the analyses are simple or sophisticated, the quality of the inputs is essential for accurate results; stratigraphy and soil properties are readily identifiable as critical inputs. Other information, such as the magnitude and rate of foundation loading, potential interactions of construction activities, and long-term foundation response with adjacent and nearby structures, are also crucial for such evaluations.



Subsurface stratigraphy beneath the Tower.

Communication

Like many other structural materials, soils are highly non-linear. However, soil is typically reduced to simple springs for use in structural models. Structural engineers need to appreciate the significance that such simplification may have on the results of their analyses. Many geotechnical engineering firms have advanced computational tools and can provide geotechnical inputs appropriate to and consistent with structural modeling sophistication.

It is essential to understand the intended demands on the soil supporting the foundation early in the design process. These demands generally stem from the structure's characteristics, including size, weight, depth below grade, foundation type, loading conditions, and spatial distribution. Performance objectives should also be developed to guide the level of detail required in the analyses. Once project demands are understood, a geotechnical investigation can begin with existing information such as geologic maps, previous geotechnical investigations, and awareness of and experience with historical building performance in the site vicinity. In addition, logs of previous borings and lab testing results are commonly helpful to identify the scope of further subsurface investigation. Still, many geotechnical engineers lament that existing boring logs frequently do not include information desired for today's problems. This highlights that communication issues can arise within the same discipline, and it is important to document one's findings fully and accurately.

After the general configuration of the project is understood, a proper field investigation is necessary. Geotechnical teams regularly have tight budgets and time constraints for characterizing the subsurface stratigraphy and its variability. Therefore, it is essential to invest in a subsurface characterization program that explores multiple locations distributed across the site to sufficient depths for designing tall building foundations. Using a combination of exploratory, sampling, and other testing methods, the soil's mechanical properties can be characterized, including stress history, compressibility, strength, and shear wave velocity. Geotechnical engineers must adamantly express (and justify) these needs to the development team; the team must then act appropriately in the interests of the developer/owner and the public that will use the building.

As discussed previously, communication within the project development team benefits from being intradisciplinary. The desired use, cost, and potential occupancy of the building should be considered from the first conceptual designs and with any design changes that occur along the way. Altering the structural materials, structural system, foundation system, or basement depth can create highly interactive issues if not factored into the design of each component of the structure (i.e., broadly, the superstructure and the foundation). Hence the typically iterative design process. For foundations, at a minimum, the bearing capacity, settlement, and factors of safety should be checked for potential configurations. In addition, the project team should address design objectives and performance criteria, including seismic and wind loading and anticipated settlements.

Design Evolution

For the Tower, documenting and communicating the effects of choices and/or changes to these components proved a challenge. The geotechnical engineers' experiences informed them that tall buildings in downtown San Francisco supported on pile or mat foundations bearing in dense to very dense sands at depths less than 100 feet had performed well for decades. At least a dozen buildings of 30 stories or more and heights of 400 feet or more within the general vicinity of the Tower fall into this category. Therefore, the initial field exploration for the Tower consisted of five borings with an average depth of 100 feet. After that investigation, the design was developed as a concrete structure when the price of steel rose dramatically. The Tower's use was intended as primarily residential, so the structural system was a stiff concrete core connected to outriggers for stability. During design, the foundation system evolved from a compensated foundation with multiple basement levels, initially below-grade levels to ≈35 feet and pile-supported, then levels extending ≈80 feet deep and supported by a thick mat, and ultimately to a single subsurface level underlain by a pile-supported mat. Accordingly, three years after the initial borings, two additional borings were drilled to depths of 200 and 220 feet to help characterize the deeper subsurface soil conditions. The geotechnical analyses were also seemingly robust, suggesting that settlements would occur primarily during and immediately following construction, comparable to the myriad other tall buildings in San Francisco. However, the choice of structural system and material (concrete) and changes of foundation configurations increased the expected foundation stress on the OBC underlying the bearing stratum from well-below to at-or-near its maximum past pressure. However, the OBC was still interpreted to be in the recompression range of stresses characterized by relatively low compressibility. During the design, the geotechnical engineer estimated the range of expected building settlement to be about four to six inches, even with a re-evaluation of the building changes.

Since tall buildings are commonly built in dense urban environments, the impact of the construction process and long-term presence on the surroundings is required by the building code. Effects of dewatering and excavation, both on-site and to adjacent/nearby structures, constituted significant and previously unconsidered contributions to the Tower settlement. In this case, there was an extended on-site groundwater drawdown during the construction of the project's adjacent below-grade parking and mid-rise structure. Re-evaluation of the settlement during construction to account for the on-site dewatering resulted in doubling the original estimated range. Subsequently, groundwater drawdown from dewatering at nearby construction sites and stress changes and ground movements from nearby deep excavations further increased the Tower's settlement.

It is understood that both activities can cause settlement to occur on and near a site; specifically addressing such concerns is repeatedly overlooked. Unfortunately, this is often inadequately communicated among the project team; settlements are implicitly considered negligible outside the building footprint as if the property lines are a rigid boundary isolating everything outside. When these effects are considered, the issue is communicated in terms of deflections, drawdown, and settlement, terms with which engineers are comfortable, rather than dollars, which is the language of potential damages (including attorneys' fees). Learning to think or translate measurements to dollars will improve communication with clients and their neighbors and tenants.

External Peer Review

While it is good practice for the design team to consider all potential issues, doing so is complex, and the contributions of independent parties should be appreciated. Independent peer review by a qualified interdisciplinary team of professionals should be a given for any unique structure. Considering the complexity, the project team should welcome the opportunity to review the consistency and applicability of the design to the site and surrounding environment. At a minimum, the peer review should ask and receive responses concerning awareness of possible issues, design assumptions, appropriate consideration of uncertainties, and the potential impact on nearby structures. As tall buildings continue to become taller, their foundations will consequently become deeper, and their zone of influence will expand. The peer-review teams must bring an independent perspective that helps expand the design team's focus beyond minimum code compliance to addressing the uncertainties that could affect the intended performance objectives.

Communication and transparency are crucial to the peer review process; it is imperative that the design team appropriately document and showcase the final design in a comprehensible manner that does not obscure details. The process itself should not be contentious but rather cordial with the intent of providing a safe product for the public. Structural peer review has been codified in San Francisco for tall buildings since 2008, although it was commonly implemented prior to that, including for the Tower. However, geotechnical peer review was not formally required of tall buildings until 2017, so it was not performed for the Tower. As a result of the settlement issues experienced at the Tower, the City now requires geotechnical peer review for tall buildings (SFDBI AB-082).

Performance Monitoring

When a building design becomes a reality, Mother Nature takes control. Performance monitoring criteria are enforced with quantifiable metrics and action limits to which they can be compared. As tall buildings become more complex and densely arranged, monitoring before, during, and after construction should be included both on-site and at adjacent properties. A baseline survey is a critical point of comparison to validate expectations or departure therefrom. This proved prudent in the case of the Tower as designers for subsequent neighboring construction projects continued to monitor and document settlement of the Tower before breaking ground at their own sites. However, quantifying things such as the amount of water extracted to keep excavations dry was complicated as gauges were regularly out of service while pumps remained active. Excavation and shoring wall movements should also be managed and appropriately documented. Any assumptions made to manipulate the data from ordinary interpretation should be thoroughly vetted and documented. The performance criteria and action levels should be set before construction. This is crucial in communicating within the project team, as well as with neighboring building owners. Monitoring ground movement is one thing; but, doing little or nothing to mitigate or prevent further movement can result in significant deleterious consequences.

"When a building design becomes a reality, Mother Nature takes control.

Conclusion

Communication, communication, communication! Case histories offer the engineering community an opportunity to revisit how we approach each project, how the project team interacts and responds to potentially adverse issues that arise during project conceptualization, design, and construction, and underscore the importance of constant communication in completing a successful project.

For the Tower, the choice of a concrete structure combined with a reduced number of basement levels resulted in expected increases in foundation stresses on the Old Bay Clay underlying the dense bearing stratum that was at or near the maximum past pressure. However, the soil was still interpreted to be in the recompression range of stresses characterized by lower compressibility. Additionally, Mother Nature got assists from several unanticipated sources, including extended groundwater drawdown on-site during construction and at nearby construction sites and stress changes and ground movements from nearby deep excavations. These events pushed the stress in the soil beyond its maximum stress into the level of greater compressibility, resulting in increased settlement beyond that originally estimated during design. Lastly, with the stress state having been pushed into virgin compression, secondary compression effects were triggered that contributed to the Tower settlement.

A voluntary upgrade of the Tower's foundation system is currently underway to arrest further settlement and mitigate some of the tilt that has occurred due to differential settlement across the Tower footprint.▪

See article on page 8 (Structural Repair) for additional information on the structural aspects for the upgrade of the Millennium Tower.

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