

AN OUTSTANDING PROJECT AWARD RUNNER UP

Shoring Design of Historic LA Metro Station

FEATURE ARTICLE

The Regional Connector Transit Corridor (RCC) is the Los Angeles Metro area's ambitious light rail project, running under the city's main thoroughfares, Flower and 2nd streets. When completed, it will alleviate traffic and parking congestion downtown, while connecting thousands of residents living in the bedroom communities of Inland Empire and Long Beach to their jobs there. The rail line of 1.9 mi (3 km), which involves a $1.756 billion (€1.545 billion) budget to construct the underground rail line, including three new stations. They are the Grand Av Arts/Bunker Hill station at 2nd and Hope streets, Historic Broadway Station at 2nd Street and Broadway, and Little Tokyo/Arts District Station at 1st Street and Central Avenue, which will offer riders their first "one seat/one fare" ride option from Azuza to Long Beach.

Regional Connector Transit Corridor including Historic Broadway Station



Regional Connector Constructors JV is led by Skanska USA Civil West California District Inc. (Skanska), in partnership with Traylor Bros., Inc. (Traylor), to deliver RCC to the Los Angeles County Metropolitan Transportation Authority (Metro). PB&A was the structural engineer of record (SEOR) responsible to design the shoring systems for the Grand Av Arts/Bunker Hill Station at 2nd and Hope streets, and Historic Broadway Station at 2nd Street and Broadway.

The temporary shoring design for Historic Broadway Station is the focus of this article, and why the project received special recognition as a runner up for DFI's 2021 Outstanding Project Award. Two main challenges are discussed in particular: design of the shoring system considering all construction stages, and design of an underpinning system where the Los Angeles Times Building (Times Building) protruded into the station footprint.

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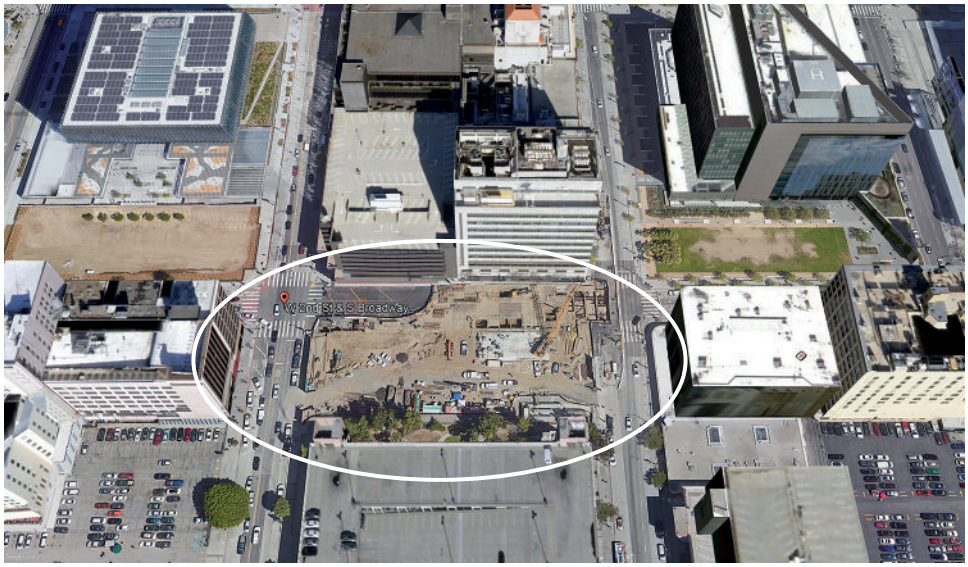


Surrounding buildings next to Historic Broadway Station

All construction stages including internal bracing removal and tieback detensioning for station construction were modeled to capture the maximum possible load during construction. These loads were then used to design all structural elements of the shoring system, such as soldier pile, tiebacks, struts/walers, and to develop action plans in case greater loads were experienced during construction.

A unique underpinning system, which consisted of precast concrete blocks with ground anchors, was designed and incorporated into the shoring system to support the Times Building foundation and prevent settlement. Rigorous comprehensive finite element analyses were conducted at different sections to calculate shoring wall deflection and surface settlement, and to develop action plans in case of excessive movement.

Project Description

The Historic Broadway Station has a cut-and-cover excavation, 500 ft (152.4 m) long by 97 ft (30 m) deep, underneath 2nd Street. The shoring system was comprised of internal bracings and tiebacks. The shoring system design was made challenging by the depth of excavation and the need to maintain the traffic on 2nd Street during the excavation, along with the proximity of existing buildings, underground utilities, Metro's requirement for tieback detensioning, and the protrusion of the Times Building into the station footprint, which required underpinning.

The stratigraphy analysis of the station site revealed 15 ft (5 m) of artificial fill and alluvium underlain by the Fernando Formation. The Fernando Formation is essentially a bedrock that consists of siltstone and claystone. Since the depth of excavation for the project was almost 100 ft (30 m), the majority of the excavation was within this Formation.

Support of Excavation (SOE) Design

Metro required that live traffic be maintained on 2nd Street during the construction. To achieve this, a decking system consisting of W-shaped beams was designed and incorporated into the shoring system. The decking system not only provided support for the traffic but also acted as the first level of lateral support (i.e., the strut) for the shoring system.

The soldier beams were required to be modeled as a simply supported beam between lateral supports (i.e., tieback or struts). This assumption ignored the presence of negative moments generated at the lateral support location, which reduced the positive moments occurring between lateral supports. To account for positive moment reduction due to negative moment at lateral support locations, the positive bending moment from the simply supported beam model was allowed to be reduced by 20% at intermediate stages until excavation reached the bottom of the final excavation. That is, $wL^2/10$ was used instead of $wL^2/8$ for moment calculation in the simply supported beam, where w is the lateral pressure and L is the distance between two lateral supports.



Underground utilities below 2nd Street

When a structural slab was poured against the SOE during station construction at backfill stages, it was allowed to reduce moment based on the simply supported beam model by 33% ($wL^2/12$ instead of $wL^2/8$) to account for fixity provided by the structural slab.

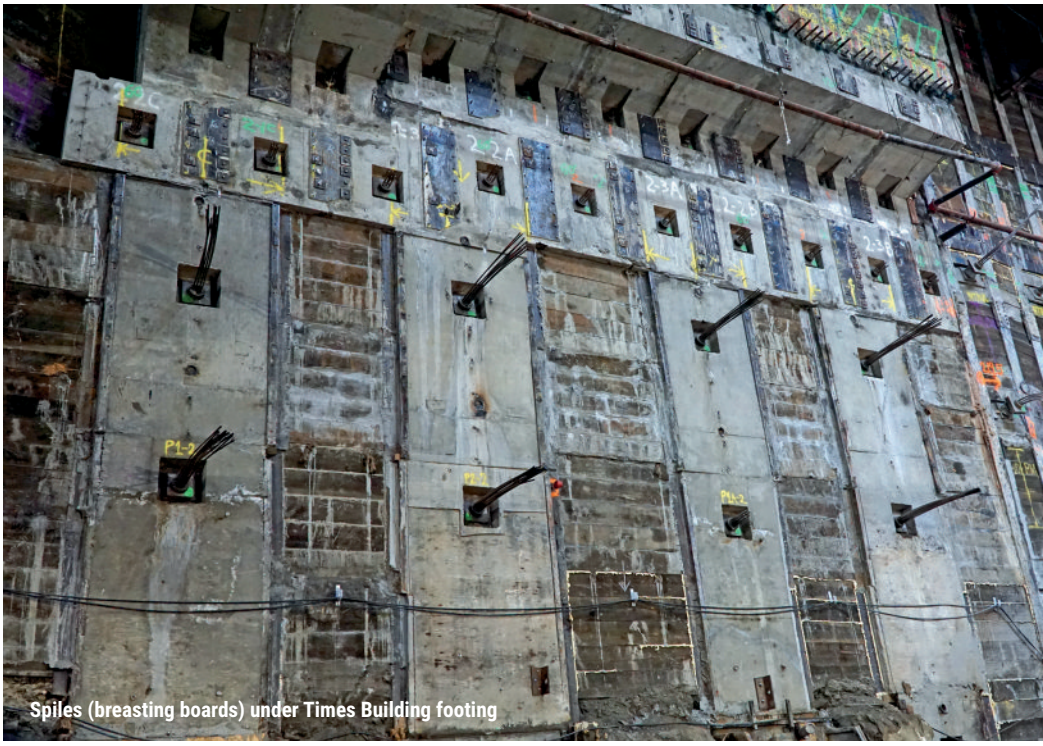
The limit equilibrium method was adopted to design the SOE system. Since the SOE lateral bracings needed to be removed and/or detensioned during main station construction, all construction stages needed to be modeled to capture the highest possible load exerted to the SOE. The DeepEX software program (Deep Excavation, 2019) was extensively used to model all construction stages and to design the SOE system. Lateral bracing (i.e., strut and tieback) loads were extracted at each construction stage and used as benchmarks to make sure actual loads did not exceed calculated loads. This helped to verify the assumptions that were made during the design process for the SOE in terms of lateral pressures being valid. Also, the results were used to develop contingency plans in case an excessive load was observed during construction.

In one of the models with internal bracing, it was observed that the strut load at the second level would experience a 26% higher load (42.76 kip/ft vs. 33.78 kip/ft, or 58 kN/m vs. 45.8 kN/m) once the third-level bracing was removed for roof-level construction. This proves how important it is to model all intermediate construction stages to capture the maximum possible load and to design the SOE accordingly.

Building Underpinning

The Times Building is a 10-story building that sits next to the station, with part of the building at the basement level protruding into the footprint of the station. Therefore, an underpinning system was integrated into the SOE system to support the vertical load from that building's basement wall and to prevent lateral movement and settlement due to surcharge from the building's foundations behind the underpinning system.

The challenging underpinning system consisted of ground anchors with precast concrete panels/diaphragms that were designed to support the Times Building's vertical and lateral surcharges. The first two rows typically consist of 5 ft by 6 ft (1.5 m by 1.8 m) precast concrete panels to expedite the construction procedure. Since a higher lateral surcharge from the Times Building was expected based on the Boussinesq Equation, ground anchors were installed on every panel at the first two rows. The excavation was conducted locally under the basement wall to install only one panel at a time, which assured minimum settlement occurs during underpinning construction.



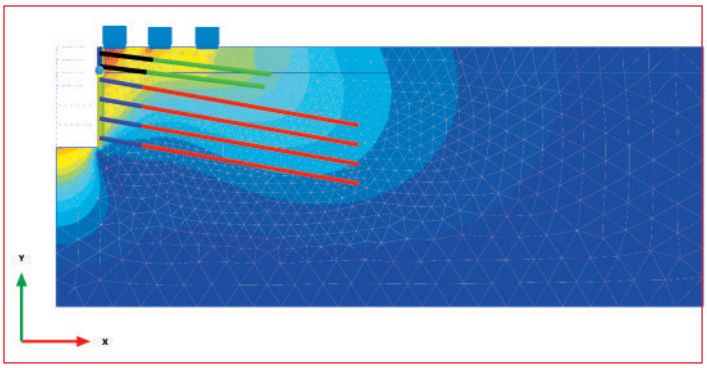
Spiles (breasting boards) under Times Building footing

The first two rows were followed by a hand-dug pit where reinforced concrete was constructed before excavation, and then ground anchors were installed once the excavation reached almost 3 ft (0.9 m) below each ground anchor elevation.

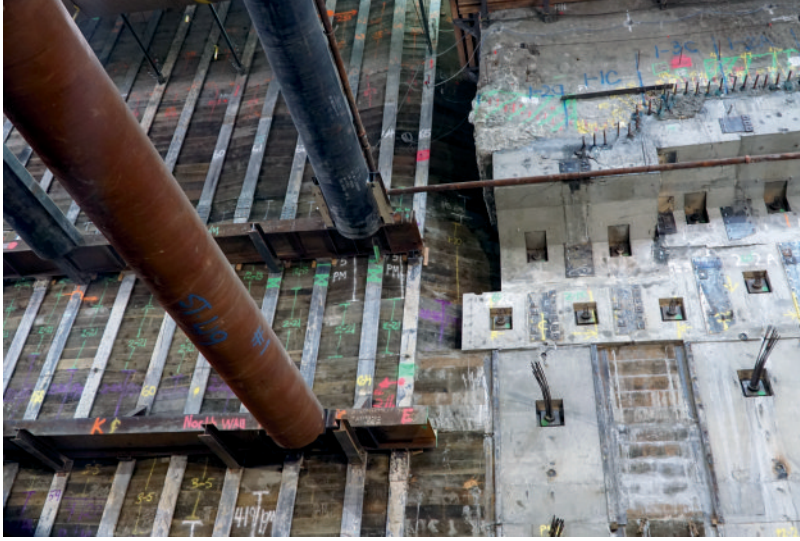
In addition, the first row of the panels formed an inverted L shape to support the bottom of the basement wall footing and to transfer the vertical load into the ground anchors. Each concrete panel was also connected with a series of plates and bolts to make sure the loads from the Times Building were distributed evenly and that the whole system works together as a single unit.

Spiles (breasting boards) were installed before excavation for the concrete panels to prevent soil behind the wall footing from collapsing into the excavated area for the panels. *Spiles* are closely spaced steel bars that are mainly used in tunneling to provide temporary protective support for soil.

A limit equilibrium model with DeepEX was generated for the underpinning system based on the criteria provided by Metro. The lateral surcharge from the building was calculated with the Boussinesq Equation, which showed a maximum lateral surcharge of 4.8 kip/ft^2 (230 kN/m^2) at 3 ft (90 cm) below the top of the underpinning. Although the lateral surcharge can dissipate rapidly by depth based on the Boussinesq Equation, the minimum lateral surcharge was limited to 1.9 kip/ft^2 (91 kN/m^2) per Metro criteria for the building to achieve a conservative design.



Finite element PLAXIS model for underpinning



Times Building underpinning

Calculated loads from the DeepEX model were then used to design concrete planks/diaphragms and to determine the number of strands required at each ground anchor elevation. Based on the Metro criteria, the anchors were tested for two times the design load and locked off at the design load.

Finite element analysis with PLAXIS 2D (PLAXIS, 2019) was conducted to evaluate the deflection of the proposed underpinning system. All intermediate construction stages were modeled to calculate the cumulative deflection of the underpinning system. Based on geotechnical information, the top two rows were located within the layer of the Fernando Formation that was moderate to highly weathered, while the rest of the underpinning was within the slightly weathered Fernando Formation. The unbonded and bonded lengths of anchors were modeled with node-to-node anchor and embedded beam row elements. Hardening soil conditions were used to model the soil behavior.

The soil deflection profile was extracted and saved at each stage of the construction. The soil showed positive deflection (i.e., backward) at the initial stages of excavation and, as excavation proceeded, the deflection became negative (i.e., inward). This was because anchor design loads were based on the maximum possible load during construction stages, which in the underpinning system, occurred at the final excavation stage. Therefore, the anchor lock-off load was higher than the actual load at the initial stages, which theoretically would push the wall back into the soil.

The maximum calculated deflection of 0.41 in (1 cm, and 0.07% of the wall height) occurred at the final excavation stage, which was less than the allowable deflection of 1 in (2.5 cm). The data from the inclinometer and tilt sensors at the top of the Times Building showed minimal settlement and movements during and after construction.

Conclusion

The support of the excavation (SOE) system for the Historic Broadway Station was designed based on Los Angeles County Metropolitan Transportation Authority (Metro) criteria using the limit equilibrium method. It was shown how extremely important it is to model all construction stages to calculate the maximum possible loads on the SOE system. Calculated lateral bracing loads at every construction stage were used as benchmarks to verify assumptions made during the design process. They also helped in developing contingency plans in case excessive loads were observed.

The challenging underpinning system used consisted of ground anchors and concrete panels/diaphragms. The system was designed and constructed to support part of the Los Angeles Times Building that protruded into the station footprint, as well as building foundations that sit adjacent to the station. The underpinning elements were designed based on results from the limit equilibrium method, and then the deflection was checked with finite element analysis (FEA). Data from settlement and tilt sensors showed minimal movement, which aligned with FEA model outputs. Also, data from multiple monitoring points positioned around the station, which captured wall deflection and surface settlement, showed minimal movement.

Excavation reached the bottom of the station in January 2019, and structural walls in front of the shoring system have been completed. Currently, the mechanical and architectural elements are being installed, with the project on track to open to the public in fall 2022.

Babak Mamaqani, P.E., is the project manager with PB&A. He is a certified project management professional with over 15 years of experience in designing a wide variety of structures, including retaining wall systems and deep foundations. Mamaqani has published several technical papers for deep foundation conferences and structural engineering journals.

Pirooz Barar, S.E., is the principal engineer and founder of PB&A. He has over 40 years of structural engineering analysis and design experience, with the last 30 years devoted to the development of advanced technical methodology for the design of shoring, underpinning and earth retention.