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ABSTRACT

The two underground stations and portals of Metro Gold Line's East Los Angeles extension were excavated in heavily over-consolidated alluvium. The excavations were supported with heavy soldier piles with pre-loaded steel-pipe struts. When measured strut loads increased to up to 3 times the design value, and strut-waler connections began to buckle, the contractor was directed to install additional struts. Maintaining that the problem had been caused by inadequate construction means and methods, the owner denied a change-order request for this work. This paper describes the contractor's investigation into the cause of strut overloading in preparation for a formal hearing by a Dispute Resolution Board. The study concluded that the extremely high bracing loads were caused by high in-situ stresses in the region, which had not been accounted for in the shoring-pressure diagrams provided in the contract drawings.

INTRODUCTION

The Metro Gold Line East Los Angeles Extension project is located in a generally compressional tectonic region of the Los Angeles Basin (Fig. 1) where high horizontal in-situ stresses have caused strut-overloading in braced excavations in the past (Roth et al. 1993; and Terzaghi et al. 1996). Figure 2 shows the tunnel segment of the alignment along First Street with two underground stations at Boyle and Soto Streets.

Subsurface conditions consist of heavily overconsolidated coarse- and fine-grained Older Alluvium with the groundwater table 60 and 30 ft deep at Boyle and Soto Street, respectively. Station and portal excavations were supported by soldier piles and timber lagging with multiple tiers of pre-loaded cross-lot bracing (typically wide flange wales with steel-pipe struts.) Strut loads and shoring deflections were monitored at designated instrumentation zones shown in Fig. 3 for the Boyle Street station.

Each zone consisted of strain gages mounted on three consecutive struts at each support level below the deck beam, and inclinometer casings installed behind the shoring. The main box for the Boyle station was excavated ahead of the Soto station. When measured strut loads at Boyle increased to up to 3 times the design value (Fig. 4), and strut-waler connections exhibited visual signs of distress (Fig. 5), the contractor was directed to install additional struts. Maintaining that strut overloading had developed due to excessive shoring movement caused by noncompliance with the shoring construction provisions of the contract documents, the owner/designer denied a change-order request for this work. Specific factors alleged to have contributed to strut overloading included the following:

1. Over-excavating between strut levels (Fig. 6) – considered to be the "most serious" factor;
2. failing to keep the groundwater table 5 ft below the excavation grade; and
3. inadequate toe embedment of the soldier piles.

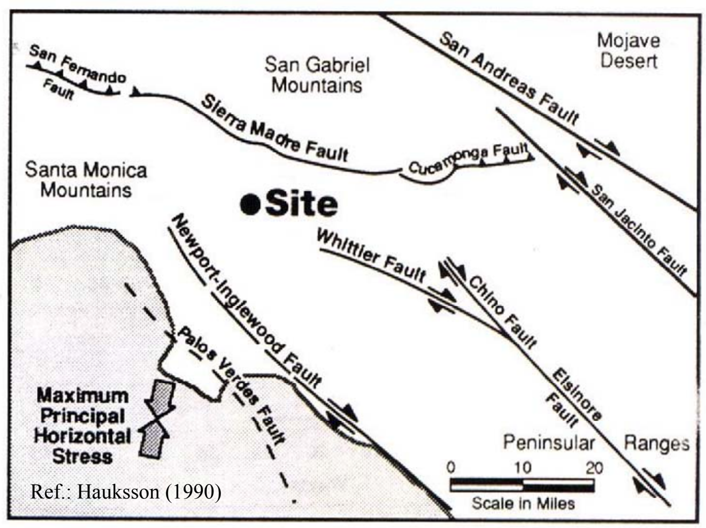

Fig. 1. Site location in the Los Angeles Basin

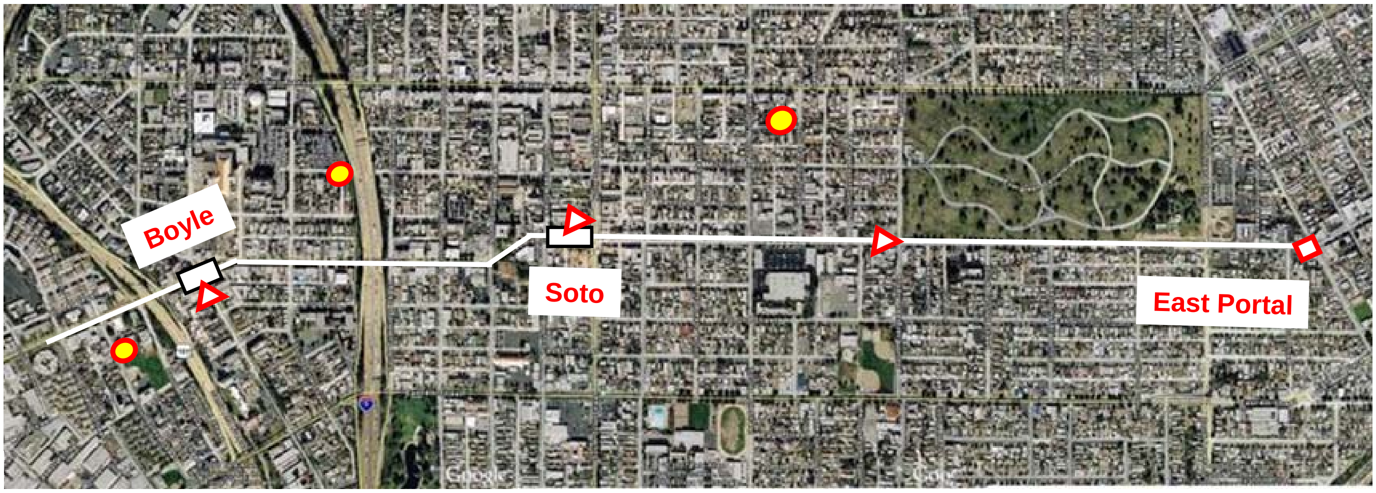

Fig. 2. Tunnel alignment

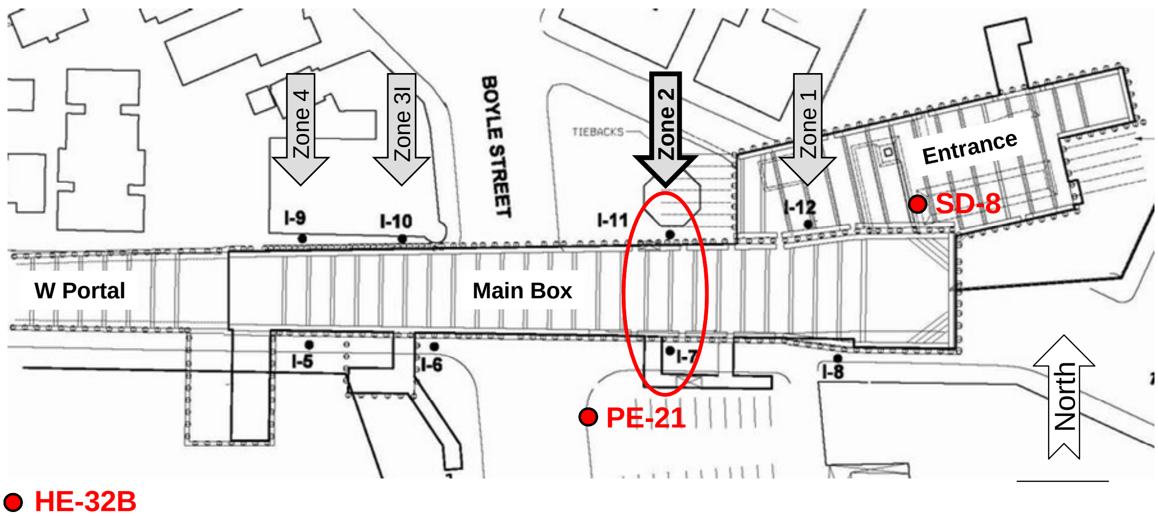

Fig. 3. Instrumentation zones

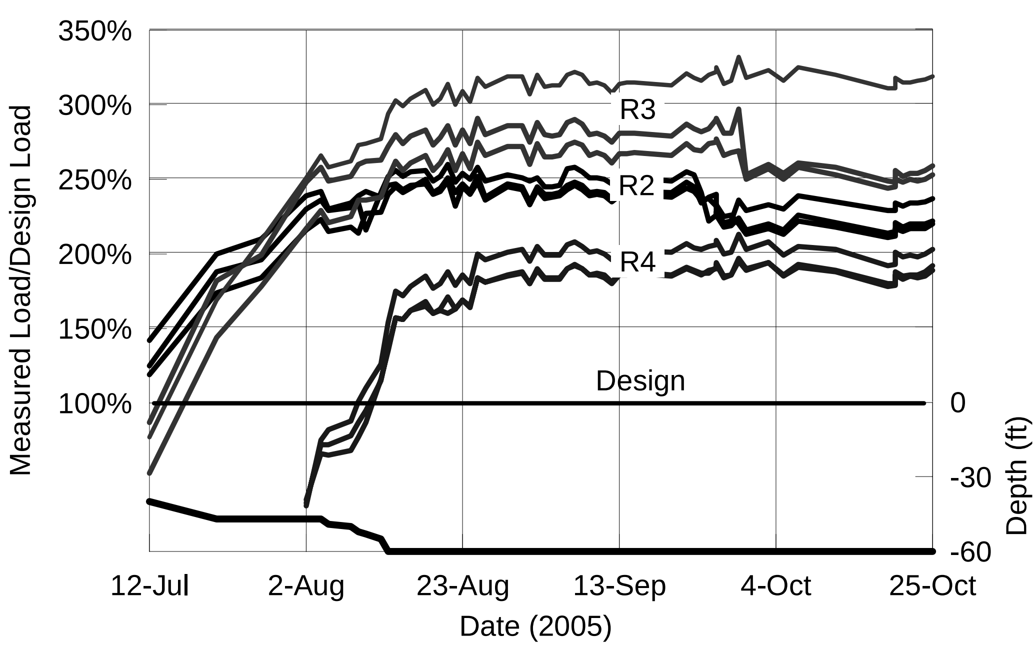

Fig. 4. Boyle Station Zone 2 strut loads

Fig. 5. Bent waler flange at strut connection point


Fig. 6. Notch cut prior to installation of third level of bracing

Even though excess strut loads later also developed at the Soto station, where over-excavation was specifically avoided, the change-order request continued to be denied, and the matter was brought before a Dispute Resolution Board (DRB). This paper discusses the investigation into the probable cause of strut overloading, which was performed for the contractor in preparation for a formal DRB hearing. The study focused on the 420 ft long, 45 to 66 ft wide, and 52 to 59 ft deep Boyle station excavation (Fig. 3) as a representative example for all braced excavations of this project.

TECHNICAL APPROACH

Due to earlier incidents of strut-overloading in the compressional geologic/tectonic region of the Los Angeles basin (Roth et al. 1993), the investigation focused on high in-situ stresses which had been measured at the subject site (GDR 2003). These stresses had not been considered in the specified earth-pressure diagram which served as the basis for the contractor's shoring design.

Finite-Difference Soil-Structure Interaction Analyses

The effect of excess in-situ stresses on lateral wall pressures and resulting strut loads was investigated by performing soil-structure interaction analyses with the nonlinear finite-difference code FLAC (Itasca 2005). Soils were simulated using an elastic-plastic constitutive model with Mohr-Coulomb yield criteria; and soldier piles and struts were represented by elastic-plastic structural elements with the capability of plastic yielding in bending. FLAC and its predecessor codes have been verified for static and dynamic loading conditions with closed-form solutions, centrifuge model tests, and field measurements. Examples of particular relevance to this investigation include both after-the-fact and predictive analyses of braced excavations where computed shoring performance was successfully verified with field measurements (Roth, et al. 1993, 1997, and 2002).

Establishing an "As-Built" Baseline Model

For the purpose of this investigation, Instrumentation Zone 2 of the Boyle station excavation was chosen for numerical simulations. A plan view and section of the shoring are shown in Figs. 3 and 7, respectively, and the model mesh established for this study is presented in Fig. 8. The first step was to establish a Baseline Model representative of actual ("as-built") conditions for comparison with various "what-if" scenarios simulating those factors alleged to have caused strut-overloading. The Baseline Model was developed with iterative back-calculations simulating the actual excavation sequence that was carried out by the contractor. Computations were repeated while varying soil properties and pre-excavation in-situ stresses (Ko values) within the range of geotechnical laboratory- and field-test data provided in project geotechnical reports. The combination of these data which most closely matched computed with measured strut loads and shoring deflections, was then taken as the Baseline Model.

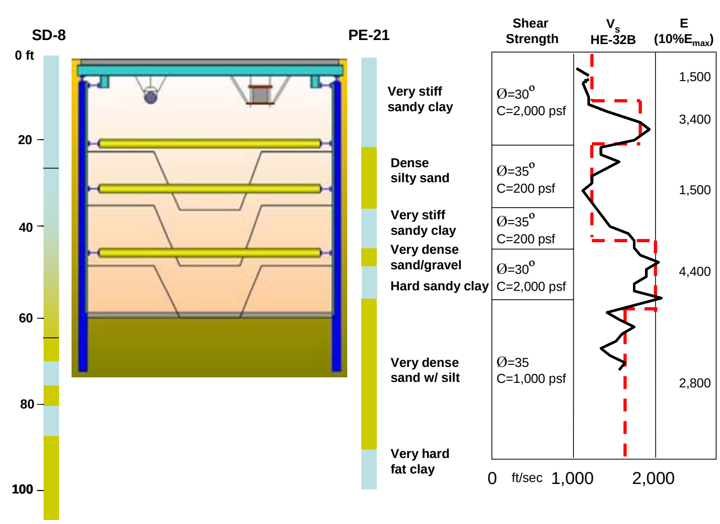

Fig. 7. Section at Boyle Station Zone 2

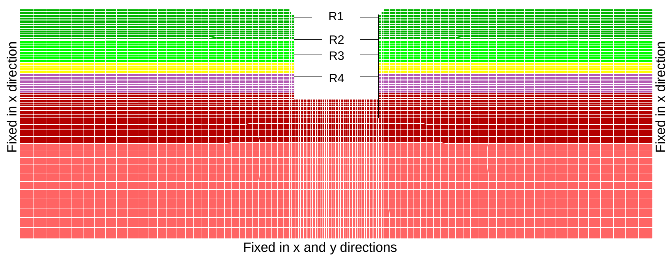

Fig. 8. Boyle Station Zone 2 FLAC model mesh

Analyzing the Effect of Construction Means & Methods

Using the soil properties and Ko values of the Baseline Model, the following "what-if" scenarios were analyzed in order to investigate whether, and to what extent, the contractor's means and methods may have contributed to the development of the high bracing loads:

1. What if excavation had been carried out as specified (i.e. no over-excavation)?
2. What if groundwater had been kept at 5 ft below excavation grade as specified in the contract documents?
3. What if the toe penetration of soldier piles had been increased from 12 ft to 15 ft?

AVAILABLE DATA

Even though the makeup, thickness and sequence of soil layers vary over short distances, overall subsurface soil conditions at this site are best described as extremely competent (i.e. very stiff to hard silts/clays alternating with dense to very dense sandy layers). The model for analyzing the shoring section at Zone 2 was constructed based on information obtained from the Geotechnical Baseline Report (GBR 2003) and the Geotechnical Data Report (GDR 2003), both of which had been part of the bid package.

Soil Stratigraphy

The soil layers in the model closely mirror the boring log of PE-21. The location of this boring on the south side of the excavation, near Zone 2, is shown on the plot plan in Fig. 3, and a simplified boring log of PE-21 is presented in Fig. 7. Also shown in this figure is Boring SD-8, which is located on the north side of the excavation; it exhibits the same competent soil types, but with a somewhat different stratigraphic make up.

Pre-Excavation In-situ Stresses (Ko)

Stiff shoring systems in competent soils are strongly affected by Ko, the ratio of horizontal to vertical effective stresses in the ground before excavation. Fig. 9 presents the Ko values measured in the general project area in the course of three separate subsurface investigations performed in 1995, 1996, and 2001 (GDR 2003). The dashed lines indicate the various Ko distributions assumed for the iterative back-calculations performed for calibrating the Baseline Model.

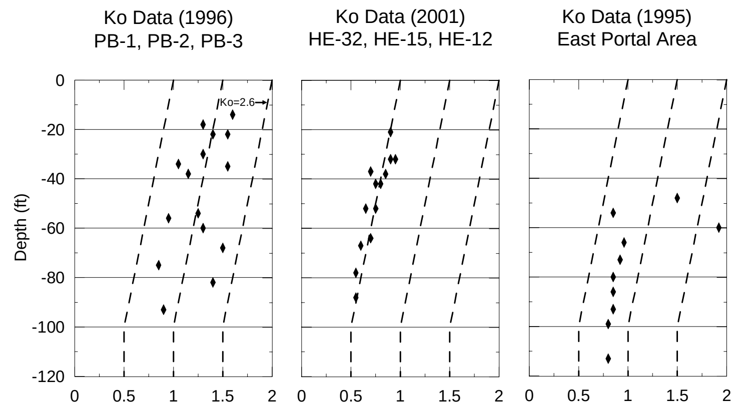

Fig. 9. Ko values in project vicinity

Based on these Ko values, the pre-excavation horizontal in-situ stresses in the general site region were 1.5 to 4 times higher than was implied by Ko=0.45 given in the GBR (2003). With a friction angle of ø=34 degrees, this low Ko value quoted in the GBR satisfies the empirical relationship (Ko=1–sinø) introduced by Jaky (1948) for estimating horizontal in-situ stresses of normally consolidated granular deposits.

Elastic Modulus

For braced excavations in competent soils, relatively small wall deflections tend to keep soil shear strains within the elastic range. Hence, the conventional concept of (active) earth pressure as a function of the soil's shear strength, does not apply. Rather than shear strength, the single most important soil property governing lateral wall pressure for stiff shoring systems, which inhibit elastic deformations of the retained soil, is the Elastic Modulus, E (Terzaghi et al. 1996). The overriding significance of E for stiff systems was also pointed out by Clough and O'Rourke (1990) who investigated construction-induced movements of in-situ walls.

For the subject analysis, the distribution of E vs. depth was based on the shear-wave velocity profile from Boring H-32B (Fig. 7), the location of which is shown in Fig. 3. Assuming a Poisson's Ratio of 0.35, dynamic E_{dyn} values were computed from these velocities and adjusted for static conditions with reduction factors varying from 5% to 20% for the iterative analyses.

Strut Loads and Wall Deflections

Figure 4 shows measured strut loads vs. time for Zone 2 at the Boyle station, expressed in percent of "design loads" based on the shoring-pressure diagram provided in the contract drawings. Figure 11 compares the specified shoring-pressure diagram with the average earth pressure derived from strut loads measured at Zone 2, and Figs. 12 through 14 show similar diagrams for Zones 1, 3 and 4 at Boyle Station. All four zones show loads that greatly exceed the contract-specified values. Figure 15 shows measured wall deflections at this Zone 2. (The light lines in Fig. 15 are inclinometer measurements from the other 3 instrumentation zones). Wall deflections varied significantly, even though shoring walls were identical - a reminder that soil behavior in the field should never be expected to be uniform, no matter how uniform subsurface conditions might appear to be in adjacent borings. This fact of "*outstanding practical importance*" (Terzaghi et al. 1996) must be kept in mind when trying to match computed values with those measured in the field.

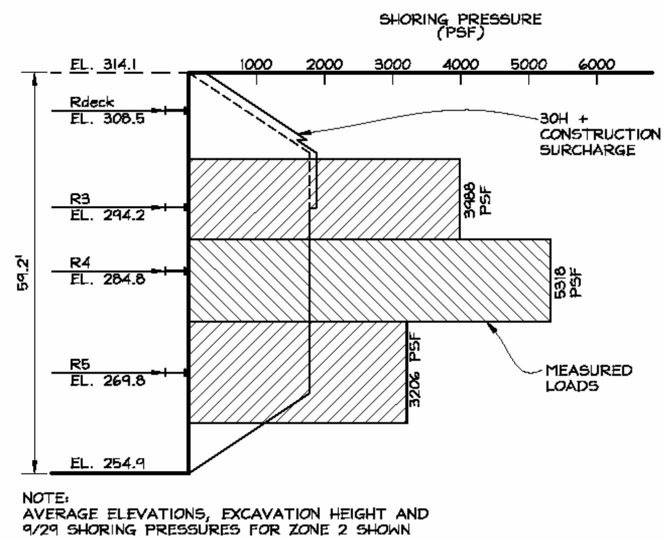

Fig. 11. Zone 2 bracing loads at Boyle Station

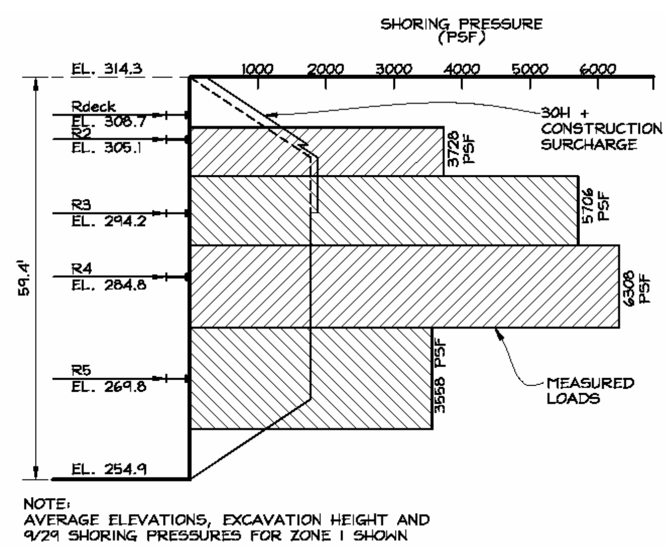

Fig. 12. Zone 1 bracing loads at Boyle Station

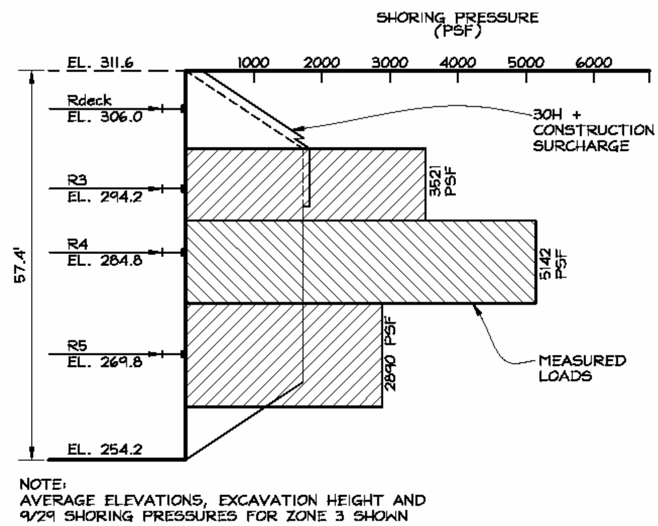

Fig. 13. Zone 3 bracing loads at Boyle Station

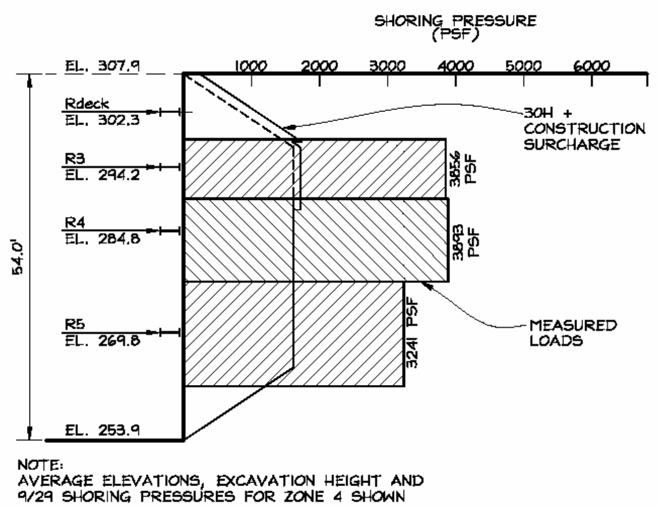

Fig. 14. Zone 4 bracing loads at Boyle Station

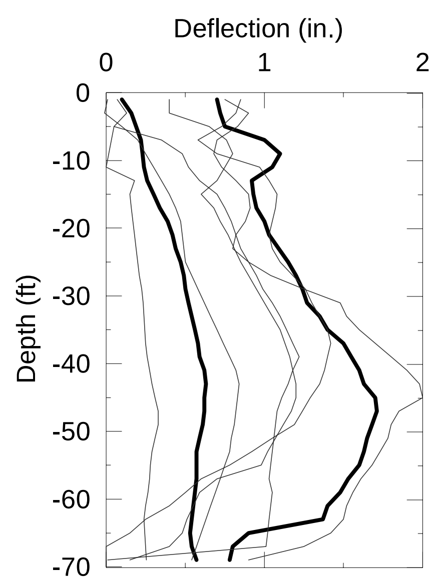

Fig. 15. Inclinometer measurements at Boyle Station

"AS-BUILT" BASELINE CASE

The Baseline Model was calibrated by simulating actual, "as-built" construction stages (Fig. 16) assuming various combinations of Ko distributions and reduction factors applied to E_{dyn}. Computed strut loads and wall deflections at full-depth excavation for 8 different combinations of Ko and E are compared with actually measured data in Fig. 17.

Comparison of analysis results from Cases A through C indicate that, for the same Ko conditions, increasing the E modulus produces lower strut loads and smaller wall deflections. On the other hand, comparing Cases B and C with E and F, respectively, shows that, for the same E modulus, increasing Ko results in higher strut loads and larger wall deflections.

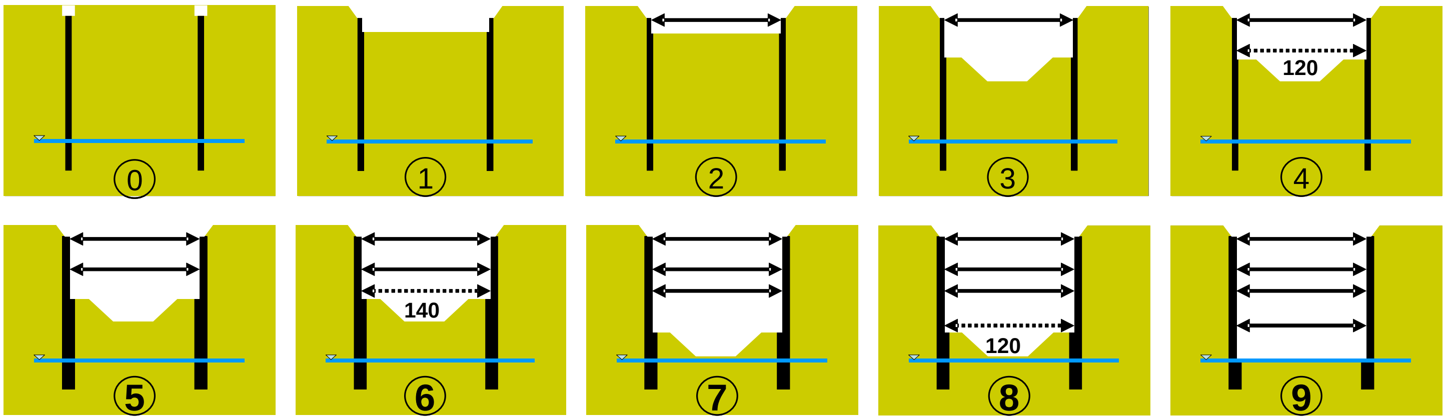

Fig. 16. Boyle Station Excavation Sequence

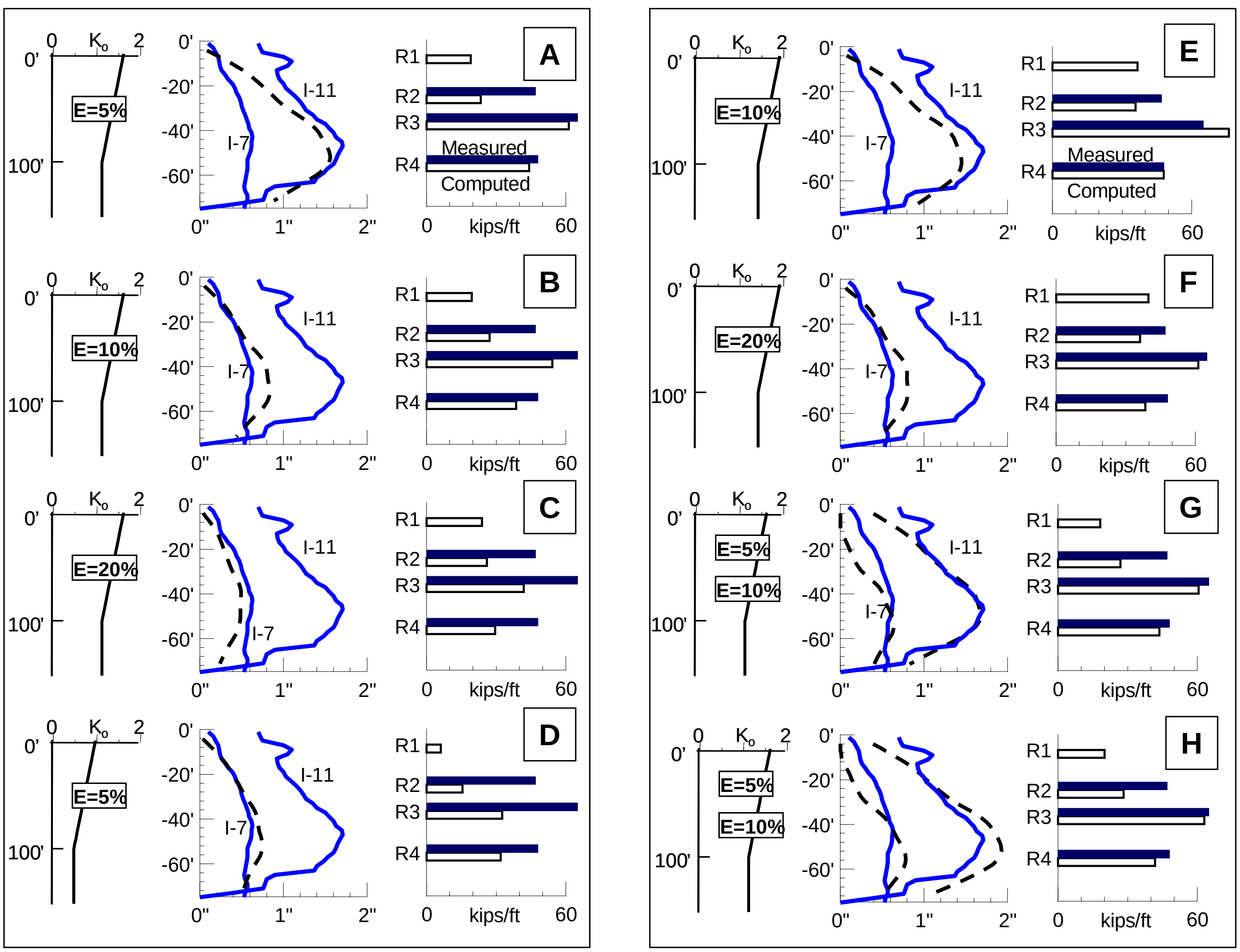

Fig. 17. Iterative FLAC analysis to identify Baseline Model

With respect to computed strut loads, Cases C and D produced the worst matches and, therefore, were excluded at the outset. Case D showed that with Ko<1.0 it was impossible to produce strut loads as high as had been measured in the field – even when E was reduced to only 5% of E_{dyn}. Acknowledging the large difference in measured wall deflections on opposite sides of the excavation (see I-7 and I-11 in Fig. 15), two additional cases (G and H) were analyzed assuming different soil stiffness (E) across the excavation. Case G was then selected as the "as-built" Baseline Case to be compared with the "what-if" scenarios discussed below. It is noted that the moduli used for the various soil layers on either side of this particular model range between E=750 ksf to 4,400 ksf (E=5% and 10% E_{dyn}), which falls within the range of E values obtained from Pressuremeter tests conducted in the typical alluvial soils along the alignment (Fig. 18).

EFFECT OF CONSTRUCTION MEANS & METHODS

A series of "what-if" scenarios were analyzed in order to investigate whether, and how much, the contractor's alleged deviations from specified excavation procedures had contributed to strut-overloading. To this end, computed strut loads and wall deflections of the following hypothetical scenarios were computed and the results compared with the "as-built" Baseline Case:

1. excavation depths between strut levels limited as specified (no over-excavation);
2. groundwater table maintained at 5 ft below excavation grade as specified in the contract documents; and
3. toe penetration of soldier piles increased from 12 ft to 15 ft.

As shown in Fig. 19, only Scenario 1 (no over-excavation) had any impact on the performance of the shoring system. Note, however, that rather than making the strut loads lower, eliminating the over-excavation actually increased the strut loads.

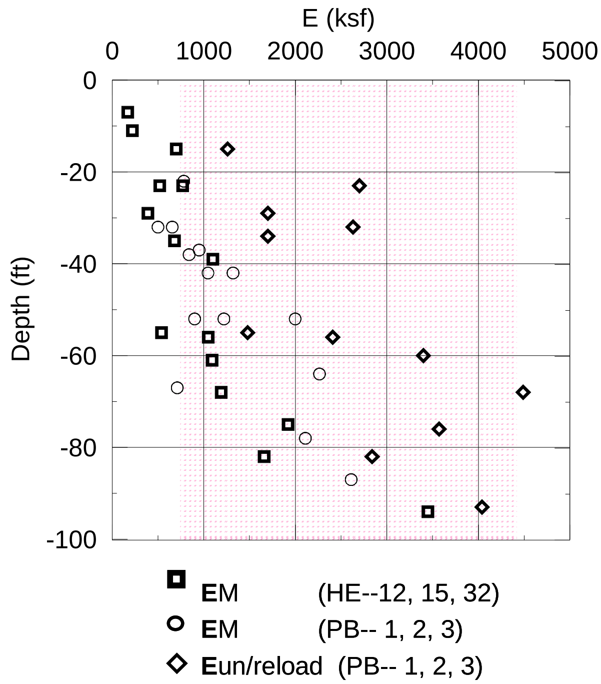

Fig. 18. Range of E-modulus for Baseline Case

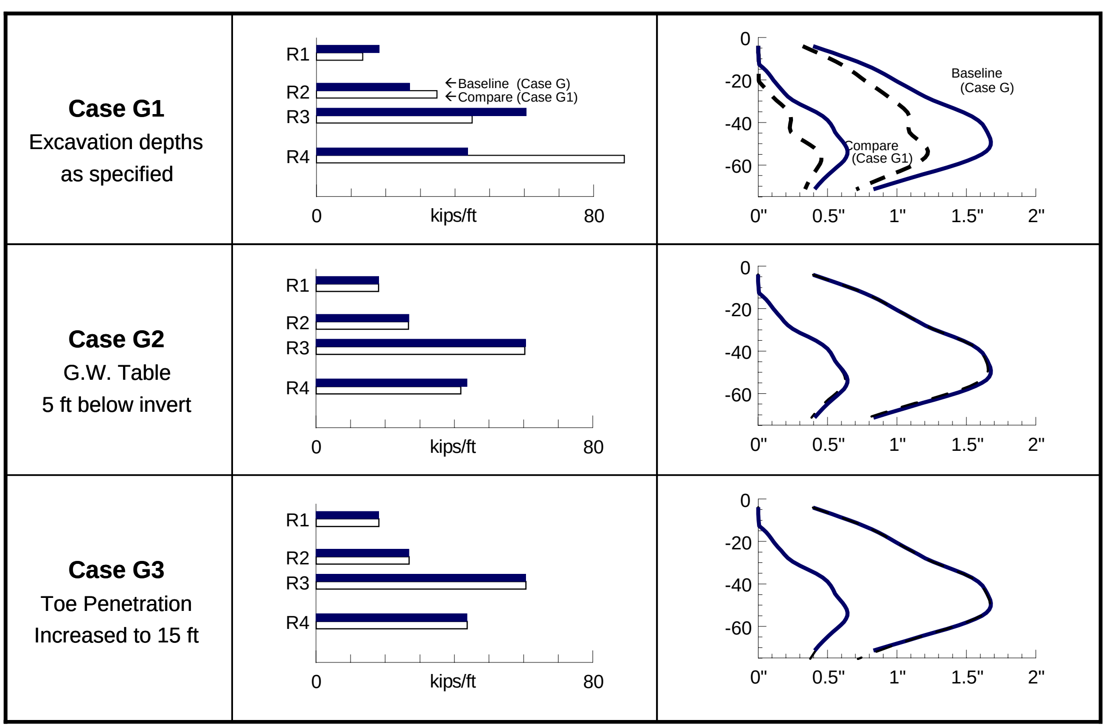

Fig. 19. Results of "what-if" analyses

EARTH PRESSURE AS A FUNCTION OF WALL DEFLECTION

That over-excavation should produce lower strut loads, might appear counterintuitive at first glance. After all, incremental loads in the last (lowest) strut installed at any given excavation stage are certain to increase with over-excavation. But increasing the excavation depth also increases wall deflection, which then lowers the earth pressure for the next strut level to be installed, and so on. In the end, overall wall movements are slightly larger than they would have been if incremental excavation depths had been less. By allowing the in-situ stresses to relax, the final total strut loads accumulated throughout the excavation stages end up being lower when excavation reaches full depth. This outcome is consistent with the most basic principle of classic earth pressure theory illustrated in Fig. 20.

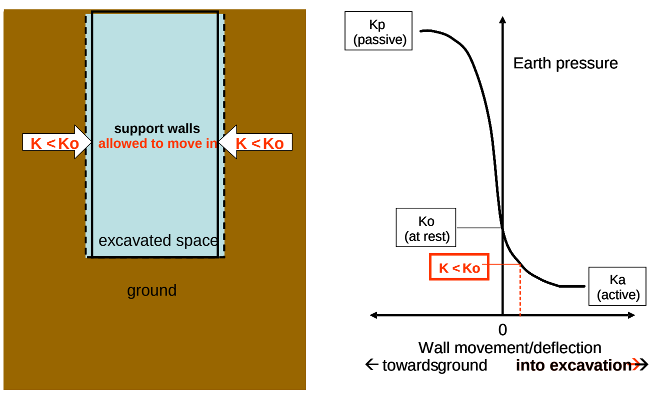

Fig. 20. Support pressure decreases as walls are allowed to move/deflect (Ref.: Lambe & Whitman 1969)

The trapezoidal earth-pressure diagram shown in Fig. 21 had been provided as part of the contract drawings. Apparently aiming for a stiff shoring design to minimize excavation-induced settlements, the commonly used empirical relationship for braced excavations (Terzaghi et al 1996) had been slightly modified to:

$$e = 0.8*\gamma*K_a*H \qquad (1)$$

where "e" [psf] is the earth pressure; γ [pcf] is the soil density; K_a [-] is the active earth pressure coefficient (a function of soil shear strength); and H [ft] is the excavation depth. Lacking any provision to account for Ko, this equation works well for "normal" in-situ-stress conditions with Ko values around 0.5. For the compressional geologic/tectonic environment of the subject site region, however, the situation changes drastically. For these conditions, Equation (1) is bound to underestimate earth pressure, unless wall movement/deflection - sufficient to relieve the high horizontal in-situ stresses - is permitted.

In order to demonstrate the effect of in-situ stress conditions on shoring behavior, comparisons of "as-built" excavation staging (i.e. with over-excavation) vs. "as-specified" staging (i.e. without over-excavation) were analyzed for both actual conditions with excess in-situ stresses (Ko=1.0 to 1.5) and hypothetical "normal" conditions characterized by Ko=0.45. Examining the analysis results presented in the form of computed wall pressures plotted in Figs. 21 and 22, respectively, the following observations are made:

- For the actual (Ko=1.0 to 1.5) condition, the beneficial effect of over-excavation is most pronounced for the lower strut levels, where wall pressures are significantly reduced by increased wall deflection that relieve the high in-situ horizontal stress;
- for the hypothetical "normal" (Ko=0.45) condition, over-excavation has no appreciable effect on the wall-pressure distribution at the end of excavation; and
- the trapezoidal pressure distribution defined by Equation (1) works quite well for the hypothetical "normal" in-situ stress conditions (Ko=0.45), but grossly understates wall pressures for actual conditions with high in-situ stresses (Ko=1.0 to 1.5).

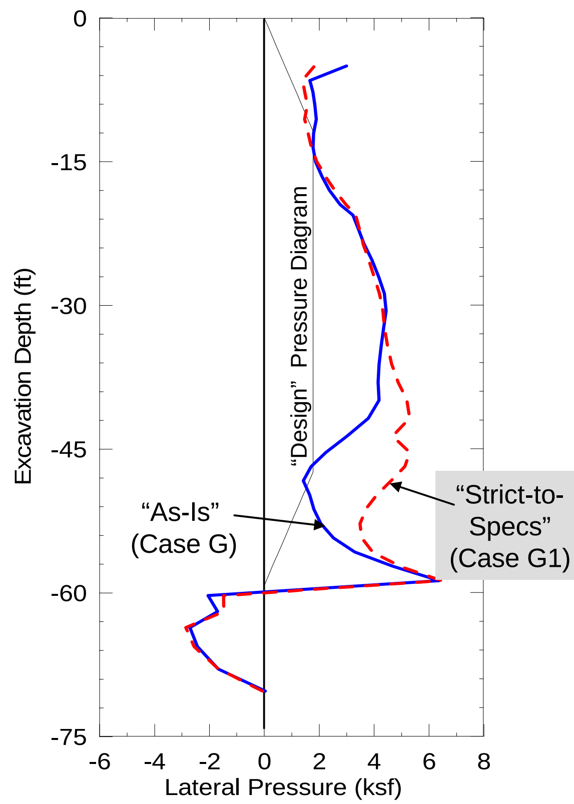

Fig 21. Computed shoring pressures for Ko = 1.0 to 1.5

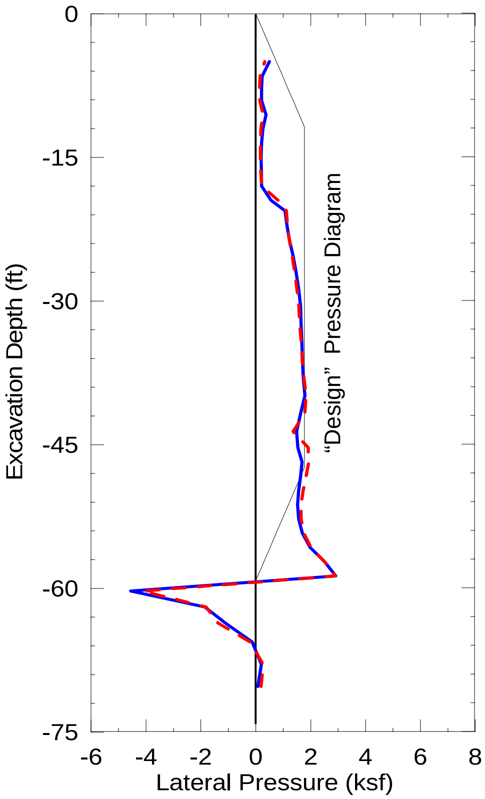

Fig 22. Computed shoring pressures for Ko = 0.45

ULTIMATE CONFIRMATION

A rare opportunity for demonstrating the strong interdependency of earth pressure and wall deflection for the subject site conditions was provided during excavation of the entrance/mezzanine levels for both the Boyle and Soto stations. These excavations were carried out after the main station box had been fully excavated, so that existing strut loads had to be transferred across the adjacent mezzanine excavation.

The Soto Station shoring developed high loads that were of a similar magnitude as those measured at the Boyle Station excavation. Figure 23 illustrates the bracing loads measured at Soto Station in comparison to the contract-specified loading. The bracing layout and typical section at the mezzanine excavation at Soto Station is shown on Fig. 24.

Fearing that already elevated strut loads would increase even further, due to inevitable shoring movement induced during load transfer, there was considerable concern about this construction stage on the owner/designer side. As it turned out, strut loads at both stations actually dropped drastically as shoring deflections increased by merely ¼ inch in response to entrance excavation. Figure 25 shows the drop in the strut loads recorded at the Soto Station.

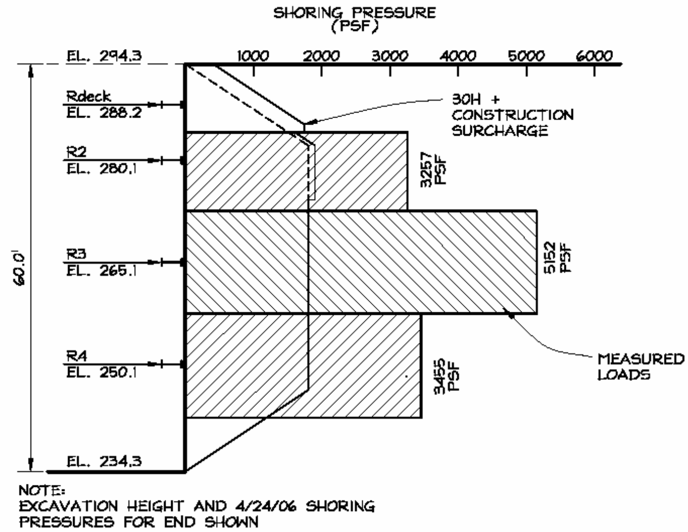

Fig. 23. Bracing loads at Soto Station (Zone 4)

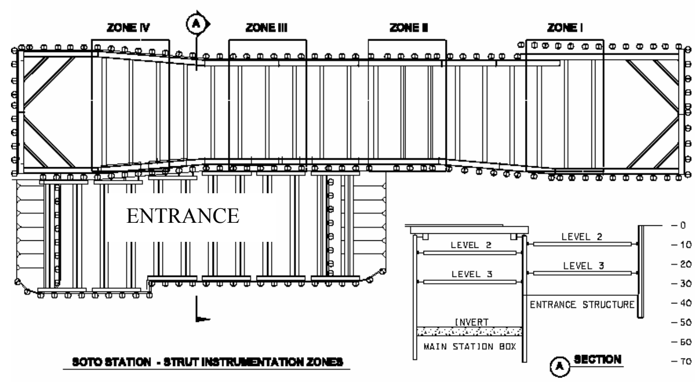

Fig. 24. Soto Station bracing layout and section through mezzanine/entrance excavation

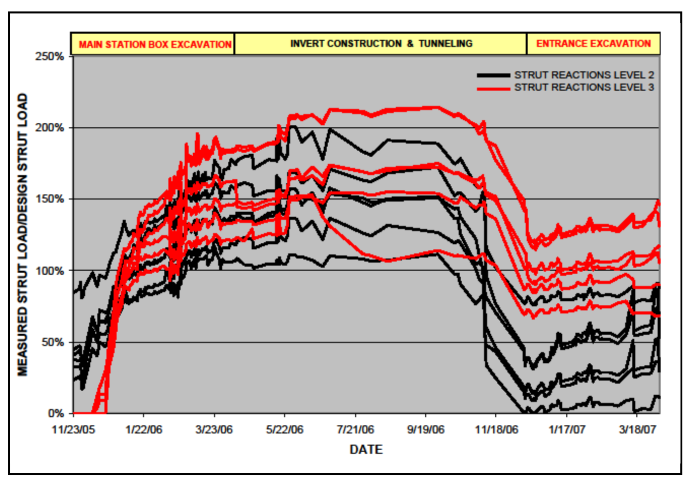

Fig. 25. Variation in Soto Station bracing loads with construction stages

CONCLUSIONS

The tunnel segment with two underground stations of the Gold Line East LA Extension project is located within a geologic/tectonic region with high horizontal in-situ stresses. Based on the results of the investigation described herein, we concluded that the high bracing loads were caused by high in-situ stresses, because the stiff shoring design didn't allow sufficient wall movement to relieve these stresses. In essence, the requirement for minimizing shoring deflections, aimed at avoiding settlement damage of adjacent buildings, was found to be incompatible with the specified shoring-pressure diagram which failed to account for the high horizontal in-situ stresses of the region.

Notwithstanding the above, it should be pointed that high bracing loads in the tectonically stressed regions of the Los Angeles Basin may occur more frequently than is commonly assumed. These loads simply remain undetected, because strut loads are seldom monitored in much detail, if at all. Signs of localized distress in strut-waler connections can easily be overlooked, or are sometimes ignored. An argument could be made that wall movement resulting from localized buckling of strut-waler connections instantly reduces shoring pressures and, by implication, strut loads. However blindly relying on this "self healing" mechanism could jeopardize overall shoring stability as uncontrolled localized yielding may twist or otherwise adversely affect walers. Conversely, if connections are too stiff/strong, struts could even begin to buckle.

For soil conditions with high in-situ stresses, shoring-design pressures must either account for excess stresses, or the shoring must be allowed to undergo sufficient movement for these stresses to be relieved in a controlled manner. Neither option was provided for in the contract specifications of the Gold Line East LA Extension project. Given that the shoring-performance requirements were incompatible with the wall-pressure diagram specified in the contract drawings, the responsibility for dealing with strut-overloading firmly rested with the owner/designer.

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