Semi-Empirical Method for Excavation-Induced Surface Displacements—Los Angeles Metro K Line Crenshaw/LAX Transit Project

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ABSTRACT

Estimating excavation-induced ground surface displacements in urban areas is needed to assess potential structure damage. Empirical settlement distribution models have been widely used to estimate the zone of influence and ground response behind braced excavation walls. Three underground station excavations, part of the Los Angeles Metro's K Line Crenshaw/LAX Transit Project, offer a unique opportunity to collect field instrumentation data to improve estimates of ground deformations. One excavation employed cross-lot braces and soldier piles and wood lagging while the other two were supported by cross-lot braces and stiffer Cutter-Soil-Mixing (CSM) walls. For the excavations with stiff support systems and relatively small wall

movements, upward surface displacement or heave governed the ground surface response, while surface settlement was measured at the excavation with the more flexible wall system. This heave behavior is often masked by settlement caused by relatively large wall movements, and is thus commonly disregarded. By idealizing the excavation unloading as an upward strip load at the ground surface, the Boussinesq solution for elastic upward movement can be used in combination with a settlement component resulting from lateral wall movements to estimate the magnitude and distribution of excavation-induced surface displacements.

INTRODUCTION

Deep excavations induce ground movement in urban areas. Estimating these displacements is necessary to quantify potential damage to nearby structures (Boscardin and Cording 1989). Many studies propose models for estimating the magnitudes and distributions of the surface displacements in homogeneous soil profiles (Peck 1969; Clough et al. 1989; Clough and O'Rourke 1990; Hashash & Whittle 1996; Kung et al. 2007). Leung and Ng (2007) then carried out studies in mixed ground profiles. With good workmanship, these ground displacements are mainly a function of soil properties, excavation geometry, and support stiffness.

Twenty-eight Metro projects are scheduled for potential completion by the 2028 Summer Olympics in Los Angeles as part of the Los Angeles (LA) County Metropolitan Transportation Authority's "Twenty-Eight by '28 Initiative." One of these new projects is the K (Crenshaw/LAX) Line which includes three underground stations Exposition (Expo), Martin Luther King (MLK), and Vernon connected by twin tunnels running along Crenshaw Boulevard (Figure 1). The excavation sites were extensively instrumented with building and surface settlement monitoring points, shape accelerometer arrays, strain gauges, tiltmeters, piezometers, and observation wells. The data collected by these instruments during construction are presented in a case history reported by Beaino et al. (2022).

Figure 1. Station footprints and instrumentation layout

For the temporary retaining systems for Expo and MLK Stations, 30-in (72.6-cm)-thick Cutter-Soil-Mixing (CSM) walls were used. These walls were chosen to prevent water infiltration into the stations, given that the groundwater table was above the excavation invert. As for Vernon Station, the groundwater table was below the excavation invert, and a more flexible support system consisting of soldier piles and wood lagging was used. The system stiffness of MLK and Expo Stations is 5 times larger than that of Vernon Station, quantified using Clough and O'Rourke (1990). All excavations were braced by steel struts and walers, which were installed after excavating to a depth of about 4 to 5 ft (1.2 to 1.5 m) below each intended support elevation level and preloaded up to 25% of their design load.

The data collected from the shape accelerometer arrays at the excavation walls show relatively small deflections for the Expo and MLK Stations, with a maximum horizontal movement on the order of 0.25 to 0.5 in (6.3 to 12.7 mm) by the end of excavation. Maximum wall displacements reached 1.0 in (25.4 mm) at Vernon Station. Building and surface monitoring points (BMP and SMP) showed ground surface settlement with a maximum value of around 0.47 in (11.9 mm) by the end of excavation at the Vernon Station. On the other hand, the ground surface heaved around the Expo and MLK Stations by 0.36 and 0.42 in (9.1 and 10.7 mm) respectively.

ANALYTICAL SOLUTION FOR SURFACE HEAVE

The Boussinesq (1885) solution can be used to estimate the surface displacement magnitude and distribution by idealizing the excavation as an upward strip load on the surface as illustrated in Figure 2. Representing excavation unloading as an upward strip load was used by Bjerrum and Eide (1956) to derive a safety factor associated with excavation depth for flexible walls. The excavation unloading actually occurs at the bottom of the excavation. The upward strip load, however, is simplified in this case as being at the ground surface. This unloading condition is relatively straightforward to apply. As will be shown in forthcoming sections of this paper, a simplified strip load at the surface can account for the patterns of observed surface displacement. Other than simplifying the excavation into a two-dimensional plane strain problem, the solution also assumes that the soil is homogeneous, isotropic, and exhibits linear elastic behavior. Three-dimensional effects caused by the relatively high stiffness at the corners of an excavation cause smaller ground movements near the corners than at the middle of the excavation wall (Finno and Roboski 2005).

The stress change throughout the domain is given by the following equations:

$$\Delta\sigma_z = \frac{p}{\pi}(\alpha + \sin\alpha\cos(\alpha + 2\beta)) \tag{1}$$

$$\beta = \tan^{-1}\left(\frac{x}{z}\right) \tag{2}$$

$$\alpha = \tan^{-1}\left(\frac{x+B}{z}\right) - \beta \tag{3}$$

where x, z, and B are defined in Figure 2.

The vertical strain can then be calculated by:

$$\varepsilon_z = \frac{\Delta\sigma_z - \nu\Delta\sigma_x}{E} = \frac{\Delta\sigma_z(1-\nu^2)}{E} \tag{4}$$

where E is the soil's modulus, and ν is Poisson's ratio assumed equal to 0.3 for soil.

This assumes $\varepsilon_x = \frac{\Delta\sigma_x - \nu\Delta\sigma_z}{E} = 0$, hence $\Delta\sigma_x = \nu\Delta\sigma_z$. The implication of this assumption is discussed in the next sections.

Finally, the vertical surface displacement at distance x can be obtained:

$$\delta_z = \sum \varepsilon_z \Delta z \tag{5}$$

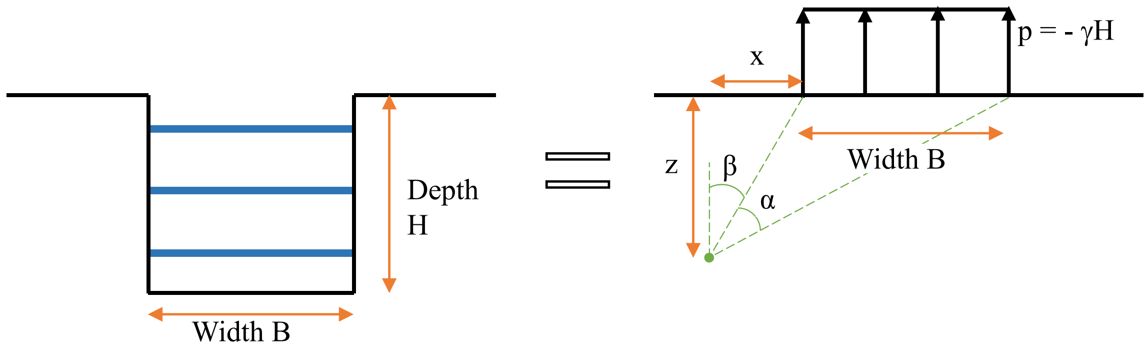

Figure 2. Heave component resulting from excavation unloading

EMPIRICAL METHOD FOR SURFACE SETTLEMENT

The above analytical solution estimates the heave component of excavation-induced ground surface displacements. A settlement component is also required to represent the effect of the volume of the soil displaced laterally as the excavation walls deflect inwards. This volume can then be reflected as surface displacement of equal quantity V assuming a parabolic distribution. The surface settlement at distance x from the excavation face is represented as:

$$\delta_z = \frac{3V}{D} \times \left(\frac{D-x}{D}\right)^2 \tag{6}$$

where D is the influence zone defined in Figure 3. A value of 2H to 3H is reported by Clough and O'Rourke (1990). For the data collected from the three excavations, an influence zone of 3H captures the behavior better. Furthermore, due to the shape of the parabola, the magnitude of settlement at 2H would only be around 11% of the maximum settlement value at the excavation face.

EVALUATION OF THE PROPOSED METHOD

For the three station excavations, the average soil unit weight γ is 125 pcf (19.6 kN/m^3). The average shear wave velocities Vs for Expo, MLK, and Vernon Stations are 1090, 1230, and 1190 ft/s (332, 375, and 363 m/s) respectively. Hence, their average maximum soil modulus $E_{max} = 2\rho Vs^2(1+\nu)$ = 12000, 15300, and 14300 ksf (575, 733, and 685 MPa) respectively. Realistically, some modulus reduction is expected as strains develop, but they are assumed sufficiently small to cause a significant difference in estimates (maximum computed shear strain for the K Line excavations < 0.017%).

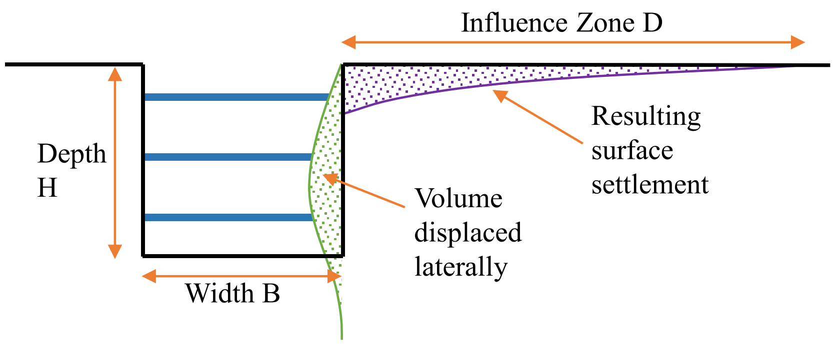

Figure 3. Settlement component resulting from lateral wall movements

Using Eq. 1 through 4, vertical strains are calculated in the domain extending 6.5B below the surface. The displacements are then summed at small increments (Eq. 5) to obtain the total surface heave at the ground surface, represented as "Boussinesq" in Figures 6, 7, and 8. For Expo and MLK Stations, the predominant behavior around the excavations was upward movement throughout the excavation stages. The computed elastic solution shows good agreement during early excavation stages where lateral wall displacements were minimal but overestimated the magnitude of surface heave for final excavation stages.

Selected measured lateral wall deflection profiles for each station at the end of the excavation are illustrated in Figure 4. The remaining data collected at other locations is presented in Beaino et al. (2022). The soil volumes displaced laterally (Figure 5) are calculated by numerically integrating the wall deflection measurements. The resulting envelope can be used to determine the maximum volume displaced as a function of the system stiffness for excavations in similar stratigraphy. It can be expressed as:

$$\frac{V}{H^2}\,(\%) = -0.05\ln\left(\frac{EI}{\gamma_w h_{avg}^4}\right) + 0.26 \tag{7}$$

where $EI/\gamma_w h_{avg}^4$ is the system stiffness proposed by Clough and O'Rourke (1990).

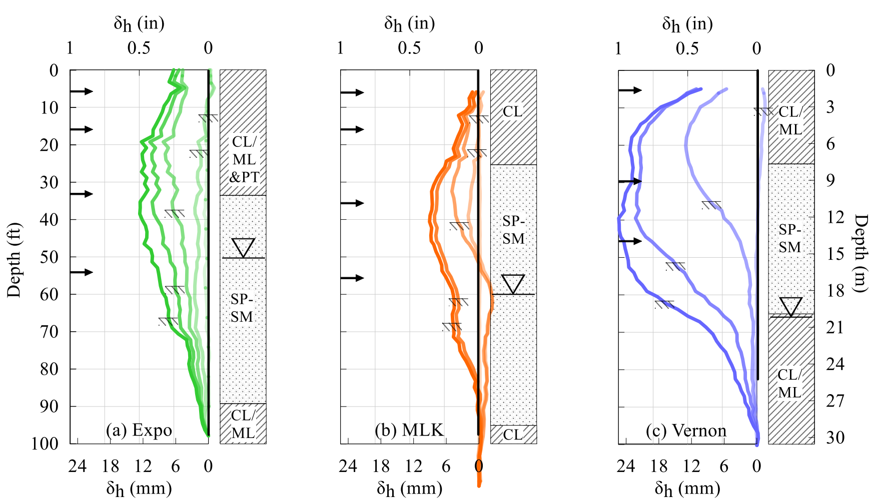

Figure 4. Lateral wall deflections at final excavation stage

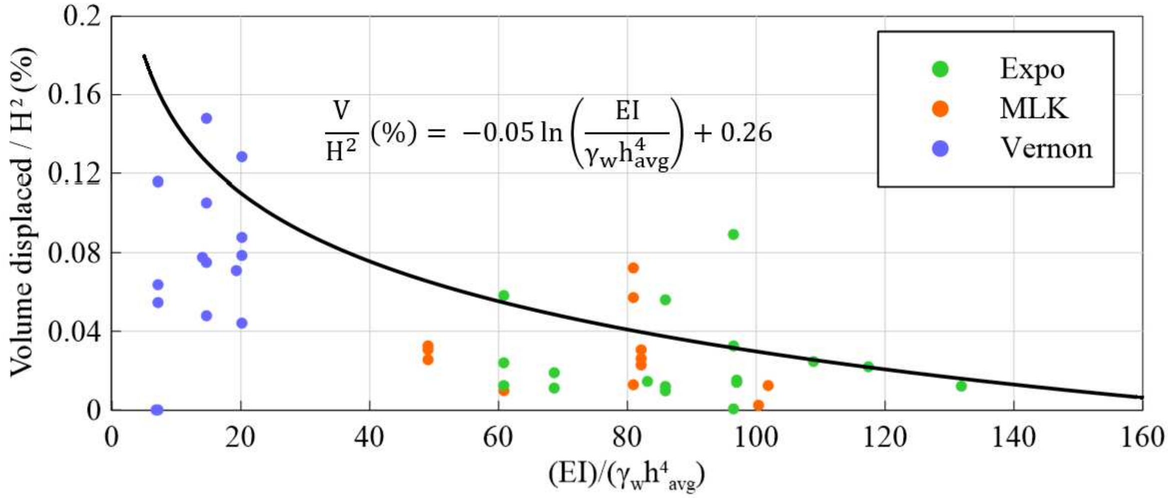

Figure 5. Lateral volume displaced as a function of system stiffness

The volume estimated by the curve is used to compute the settlement component presented as "Volume displaced laterally" in Figures 6, 7, and 8 using Eq. 6 and 7. Finally, the two solutions are summed to obtain the superposition of the two mechanisms.

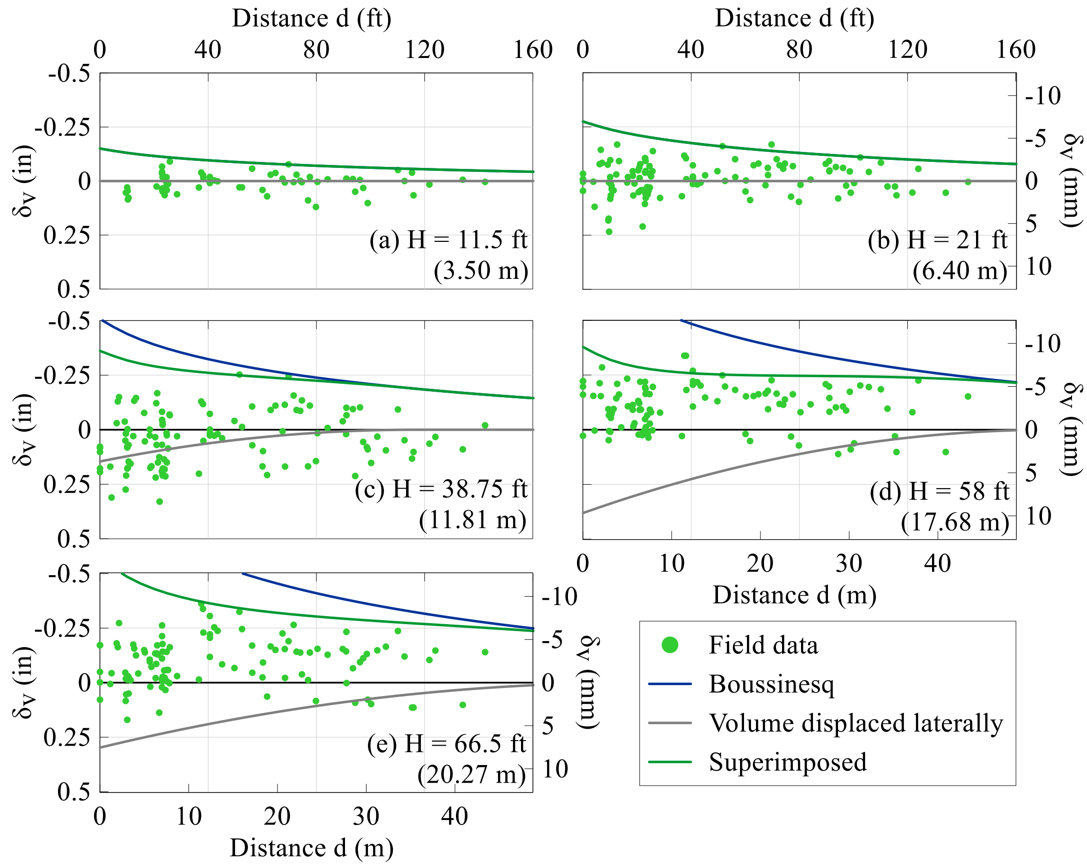

Figure 6. Evaluation of the proposed methods with measured data at Expo Station

During early excavation stages with relatively shallow depths, the surveyed data show some scatter at a small displacement scale, mainly attributable to the survey's accuracy, resulting in a general mismatch with the proposed methods. However, as the excavation deepens, clear displacement trends emerge and have good agreement with the outlined method.

Figures 6 (b) and (c) show significant surface heave and settlement around the excavation. By analyzing time histories of the data, this settlement is likely a surveying error corresponding to a sudden dip in the movement data. Settlement is on the order of 0.3 in (7.6 mm) with no corresponding major construction activities or changes in lateral wall deflections. Such movements reflect unrealistic excavation behavior, i.e., ground settlement followed by significant heave throughout the excavation sequence. The actual behavior should result in surface heave when the excavation is shallow and lateral displacements are low, followed by settlements as the excavation deepens and more soil is displaced laterally towards the excavation.

The "Superimposed" solution, which is the sum of the two curves "Boussinesq" and "Volume displaced laterally", envelopes the measured surface heave for all excavation stages, most notably in Figures 6 (d and e) and 7 (b, c, and e).

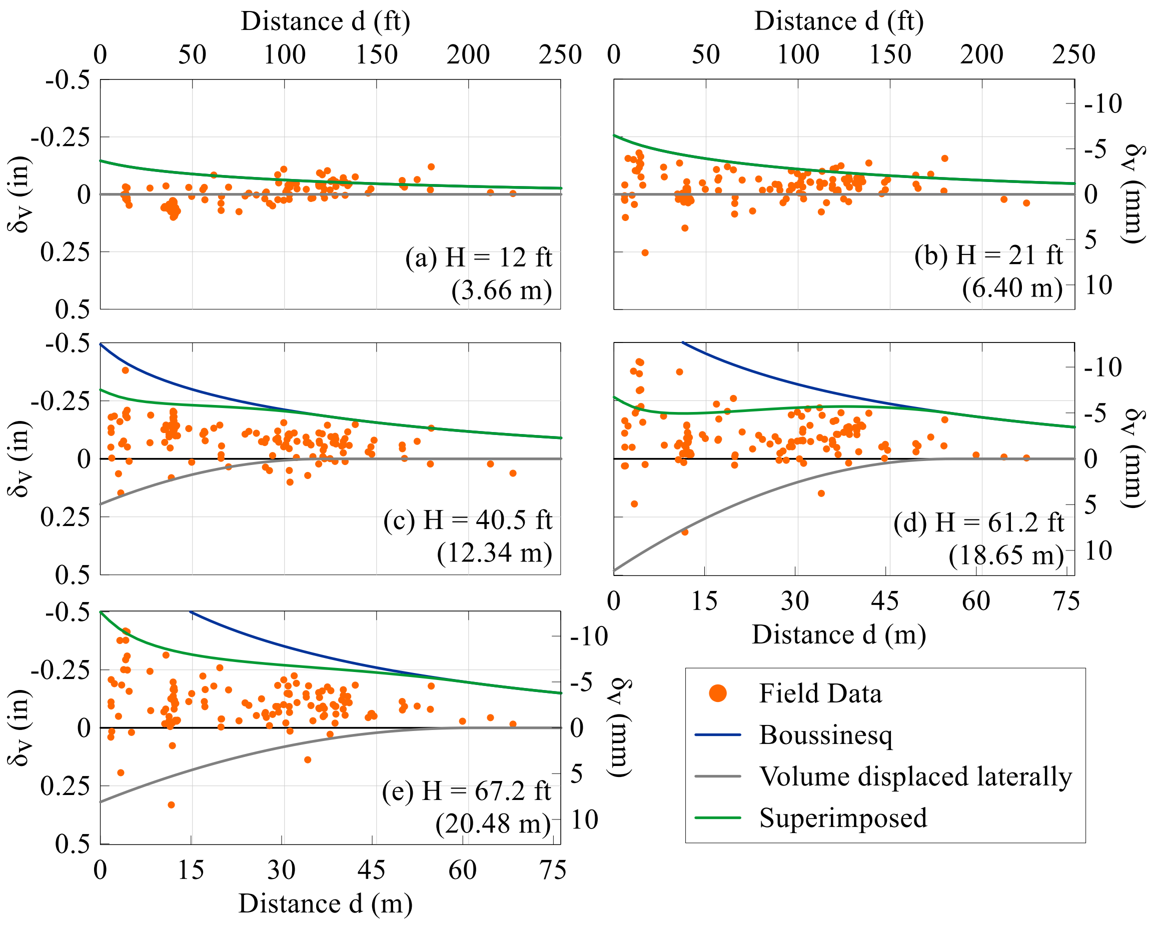

Figure 7. Evaluation of the proposed methods with measured data at MLK Station

The excavation at Vernon Station induced surface settlements due to the relatively large lateral wall displacements (Beaino et al. 2022). The "Superimposed" solution was still able to envelop most of the heave data points away from the excavation face. However, the "Volume displaced laterally" curve showed good agreement with the settlement data presented in Figure 8 (c and d). Early excavation stages had relatively small displacements, influenced by the accuracy of the survey. Furthermore, the volume displaced laterally overestimated settlement in Figure 8 (b) due to the logarithmic shape of the proposed curve in Eq. 7.

Some data points have relatively smaller displacements for the three station excavations compared to the proposed curves. At the station corners, the excavation walls deform less due to the high stiffness at the corners relative to that at the center. This generally cause smaller ground movements near the corners which cannot be captured in an idealized plane strain problem.

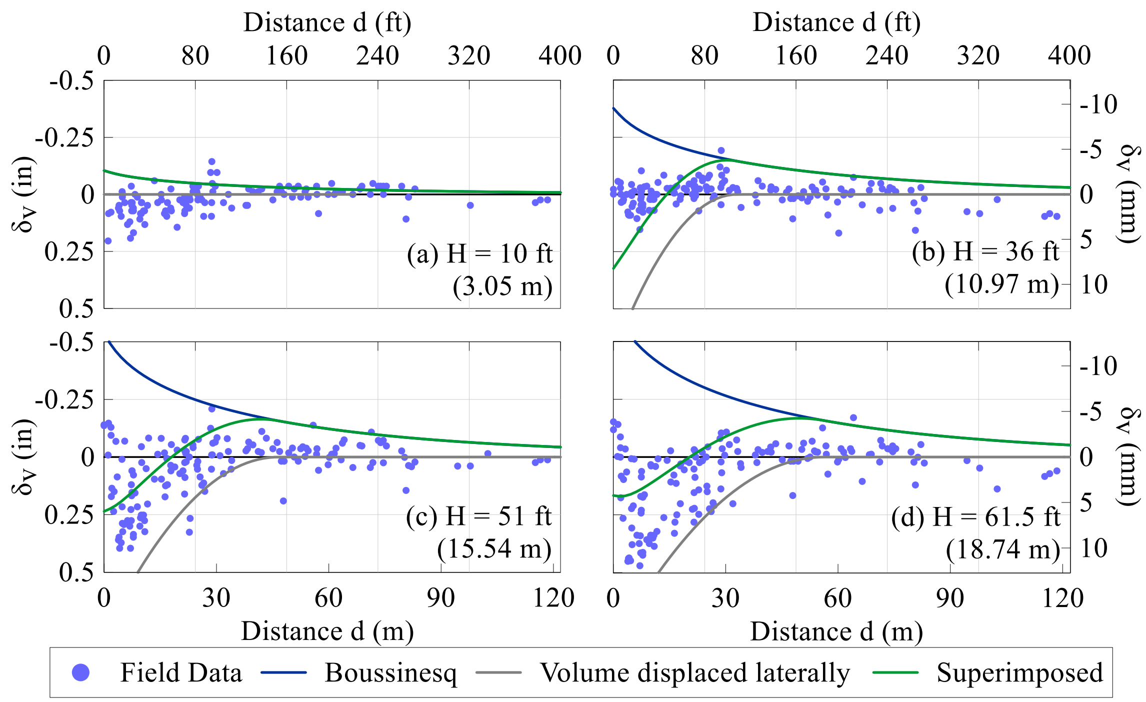

Figure 8. Evaluation of the proposed methods with measured data at Vernon Station

SUMMARY AND CONCLUSION

Data collected from station excavations at the K Line Crenshaw/LAX Transit Project shows that stiff support systems in braced excavations result in relatively small lateral wall deflections, allowing elastic heave to govern the ground surface response. This heave can be estimated using the Boussinesq solution when the excavation unloading is idealized as an upward strip load at the ground surface. However, as the excavation walls deflect inwards, some volume of soil is also displaced laterally to occupy the volume created. This is reflected as downward surface displacements that can envelop settlement data measured from the K Line braced excavations. The superposition of those mechanisms can envelop the excavation-induced elastic surface heave component measured from the K Line excavations.

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