Evaluation of Empirical Methods for Estimating Tunneling-Induced Ground Movements—Los Angeles Metro K Line Crenshaw/LAX Transit Project

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ABSTRACT

Empirical methods for estimating tunneling-induced ground movements have been widely adopted in the tunneling industry. The transverse surface settlement profile can be described by a Gaussian curve or a modified Gaussian curve whose maximum value and trough width are related to volume loss. Volume loss in turn is related to soil type, tunnel geometry, and construction techniques. Several empirical equations have been developed based on the Gaussian curve and the assumptions of (1) trough width dependency on tunnel depth and ground condition; and (2) volume loss dependency on the ground type and construction techniques. For Earth Pressure Balance Machine (EPBM) tunneling, a volume loss of 0.5% in granular soils and

1%–2% the soft clay has been assumed in the past as an initial estimate. However, with complete filling and pressurization of both the shield (overcut) gap and the grouted tail gap around the lining, volume losses below 0.1% to 0.2% are being achieved in the alluvial granular and clay soils on current Los Angeles Metro tunneling projects. The LA Metro K Line Crenshaw/LAX transit project, tunneled from 2016 to 2018, has provided an opportunity to acquire and organize data on compatible data management systems, and evaluate the extensive field monitoring data for ground conditions specific to predominately granular soils in Old Alluvium. These data allow for the improvement of current empirical methods and correlations for predicting surface settlement induced by EPBM tunnels. The approximately 1-mi (1.6-km)-long, 20.6-ft (6.5-m)-diameter twin tunnels were excavated by an EPBM in a dense sand layer overlain by a silt/clay layer. The cover-to-diameter ratio was consistently about 2. The settlements and volume losses are observed to be heavily dependent on the face/shield pressures. In general, maintaining continuous pressures can significantly reduce settlements. An equation for estimating the volume loss based on the measured EPBM shield pressures is proposed. This equation can be used with the existing empirical methods to estimate the surface settlement profile transverse to the longitudinal axis of the tunnel.

INTRODUCTION

The magnitude of tunneling-induced ground movement is related to multiple factors including soil conditions encountered along tunnel alignment, tunnel geometry, construction techniques, and workmanship. Peck (1969) observed that the settlements above a tunnel display a trough-like shape resembling the error function, working with Schmidt (1969) who proposed a Gaussian distribution equation to represent the transverse surface settlement trough. Several modified Gaussian curves have also been proposed to better estimate the shape of the settlement trough consistent with the observation in the field (Celestino et al. 2000; Vorster et al. 2005). Empirical methods are developed to estimate the parameters of the curves based on sparse ground movement data with considerations of only soil type and tunnel depth. In addition, the implementation of empirical methods has also relied on assuming volume losses based on previous tunneling experience, that may not be applicable to current tunneling projects with the Earth Pressure Balance Machines (EPBMs) that are operated with complete filling and pressurization of the shield overcut gap and the grouted tail gap around the installed lining. The EPBM is being adopted in most tunneling projects in urban areas due to its better control of ground movement and construction safety improvement in comparison to old tunnel excavation systems. It is necessary to evaluate the applicability of existing methods to more recent EPBM tunneling projects, as well as to evaluate the impacts of EPBM operations on ground movements.

The Los Angeles Metro K (Crenshaw/LAX) Line Tunnel is a twin-bored tunnel constructed with an EPBM. This highly instrumented machine recorded operational data approximately every ten seconds. An extensive field monitoring program was also conducted to monitor tunneling-induced ground movements, which consisted of both surface settlement markers above the tunnel centerline and transverse to the tunnel axis, as well as the multi-point extensometers (MPBX) with deep anchor located 5 ft (1.5 m) above the tunnel crown to monitor displacements around the advancing EPBM. The field monitoring data are used to evaluate the existing empirical methods. In addition, EPBM operational parameters are correlated to ground movement data to evaluate the impacts of tunneling in the Alluvial granular soils.

EMPIRICAL METHODS OF ESTIMATING TUNNELING-INDUCED GROUND MOVEMENTS

Transverse surface settlement

Schmidt (1969) proposed a Gaussian distribution to estimate surface settlement, $S(x)$, for the transverse tunnel profile:

$$S(x) = S_{max} e^{\frac{-x^2}{2i^2}} \tag{1}$$

where S_{max} is the maximum surface settlement over the tunnel centerline, x the horizontal distance to the tunnel centerline, and i the width parameter, representing the horizontal distance from the inflection point to the center point of the Gaussian curve. The adoption of the Gaussian curve requires a width parameter, i, and volume loss, V_l. Schmidt (1969) proposed an equation for calculating the width parameter as related to soil type, tunnel diameter, and tunnel depth:

$$\frac{i}{r} = k\left(\frac{z_0}{2r}\right)^n \tag{2}$$

where i is the width parameter, r $(=\frac{D}{2})$ the tunnel excavation radius, z_0 the tunnel depth from the surface to the tunnel axis, and k and n are empirical parameters developed from previous case histories. Modified forms of both the equation and empirical parameters were proposed by many researchers (Cording and Hansmire 1975; Clough and Schmidt 1981; O'Reilly and New 1982; Attewell et al. 1986; Mair et al. 1993; Moh et al. 1996; Mair and Taylor 1997; Marshall et al. 2012)

Modified Gaussian curve

It was found that the Gaussian curve could be modified to improve the fit with field data measured in the sand (Celestino et al. 2000; Vorster et al. 2005). Vorster et al. (2005) proposed a modified Gaussian curve with an additional degree of freedom by introducing a new parameter n (or α) to control the position of the inflection point, i, as a function of the horizontal distance, x, as:

$$S(x) = \frac{n}{(n-1)+\exp[\alpha(\frac{x}{i})^2]} S_{max} \tag{3}$$

where the definition of parameters remains the same as the Gaussian curve except for the inclusion of a new parameter $n = e^{\alpha \frac{2\alpha-1}{2\alpha+1}}$, which controls the vertical location of the inflection point. The parameter, n (or α), however, does not have direct physical meanings.

Marshall et al. (2012) performed centrifuge tests in sand and proposed relations for estimating parameters for the Modified Gaussian curve. They also consider the cover ratio and volume loss when determining the shape of the settlement trough.

EPBM tunneling-induced volume loss, V_l

Volume loss is defined as the percentage of the area of the surface settlement profile to the excavated areas of the tunnel. Areas of surface settlement troughs can be calculated by integrating surface settlements along the transverse settlement profile, which can be described by either the Gaussian or the modified Gaussian curve. Mair and Taylor (1997) reported that, for EPBM tunneling in the sand, volume losses were often as low as 0.5%. In soft clays, volume losses (excluding consolidation settlement) were reported as 1% to 2%. However, recent case histories have shown that volume losses can be as low as 0.2-0.3% (Farrokh et al. 2021; Netzel 2009). Cording (2018) shows that the large-diameter Seattle SR-99 tunnel has volume losses of less than 0.1% for settlements immediately above the advancing tunnels.

PROJECT OVERVIEW

The K (Crenshaw/LAX) Line is an extension of Los Angeles' Light Rail Transit between the LA Metro Green Line and Expo Line in Los Angeles, California. The tunnel portion, K (Crenshaw/LAX) Tunnel, is located at the northern end of the extension. As shown in Figure 1, these twin tunnels (southbound and northbound) connect the Expo Station, at the intersection of Crenshaw and Exposition (Expo) Boulevard, through the Martin Luther King (MLK) Station, along MLK Boulevard, to Vernon Station, near West 48th Street in the Leimert Park. The total length of the K (Crenshaw/LAX) Line Tunnel is approximately 5,328 ft (1,624 m), consisting of a 3,484-foot (1,062-m)-long segment between Expo and MLK Stations as well as a 1,844-foot (562-m)-long segment between MLK and Vernon Station. The southbound (SB) and northbound (NB) tunnel segments are parallel with a centerline separation of 39.1 ft (11.9 m). The SB tunnel was constructed first followed by the NB tunnel. The excavated tunnel diameter was 20.6 ft (6.3 m). The excavation depth of the tunnel between Expo and MLK Stations was about 52 ft (15.8 m) below the ground surface. The tunnel depth gradually decreases from 60 ft (18.2 m) to 40 ft (12.1 m) below the ground surface from MLK through Vernon Station. Construction started in April 2016 and concluded in April 2018 using an EPBM, manufactured by Herrenknecht AG. The EPBM shield has a length of 29.7 ft (9 m) from cutterhead to tail. When the EPBM reached Vernon Station, it was returned to the Expo Station, where it excavated the NB tunnel.

GEOLOGICAL CONDITIONS

This project is located in the northern part of the Los Angeles Basin. The K (Crenshaw/LAX) Line Tunnel was constructed in sandy sediments which are unconsolidated Holocene age sediments (Young Alluvium), underlain by late-Pleistocene materials (Old Alluvium). The soil profile along the tunnel alignment is presented in Figure 2. Based on engineering parameter properties, the subsurface soil is classified as Fill, Type 1 Soil, and Type 2 Soil (Hatch Mott MacDonald 2012b). Fill consists of granular soil plus asphalt, concrete, and aggregate base. Type 1 Soil consists of fine-grained silt, clay, and organic soil. Type 2 Soil consists predominantly of a mixture of fine- to coarse-grained sands and gravels and includes cobbles and boulders. The groundwater table elevation is subject to seasonal variation.

The groundwater is about 47 ft (14 m) below the ground surface along the Expo - MLK Station route and about 85 ft (26 m) below the ground surface along MLK-Vernon Station route. Tunnel drives along the Expo-MLK route were constructed in SP-SW dense sands and cobbles beneath the water table, whereas tunneling along the MLK-Vernon Station route was constructed above the water table and in a layer of SP dense sand. During construction, extensive clay deposits were not encountered.

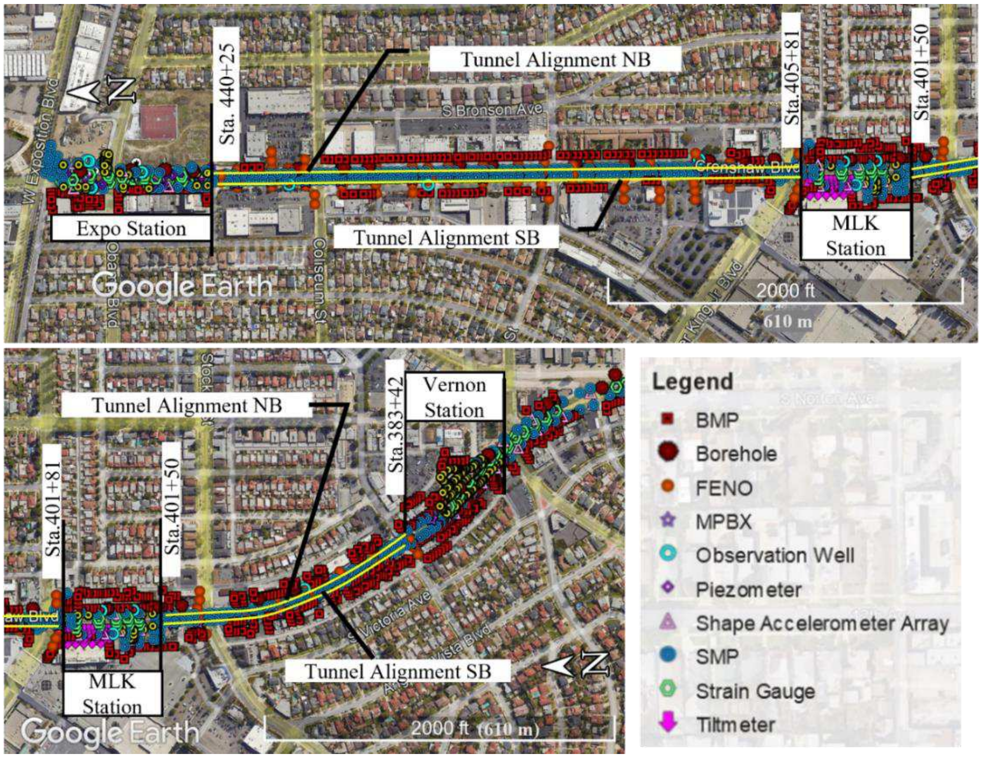


Figure 1. K (Crenshaw/LAX) Line Tunnel alignment and layout of the installed instrumentations

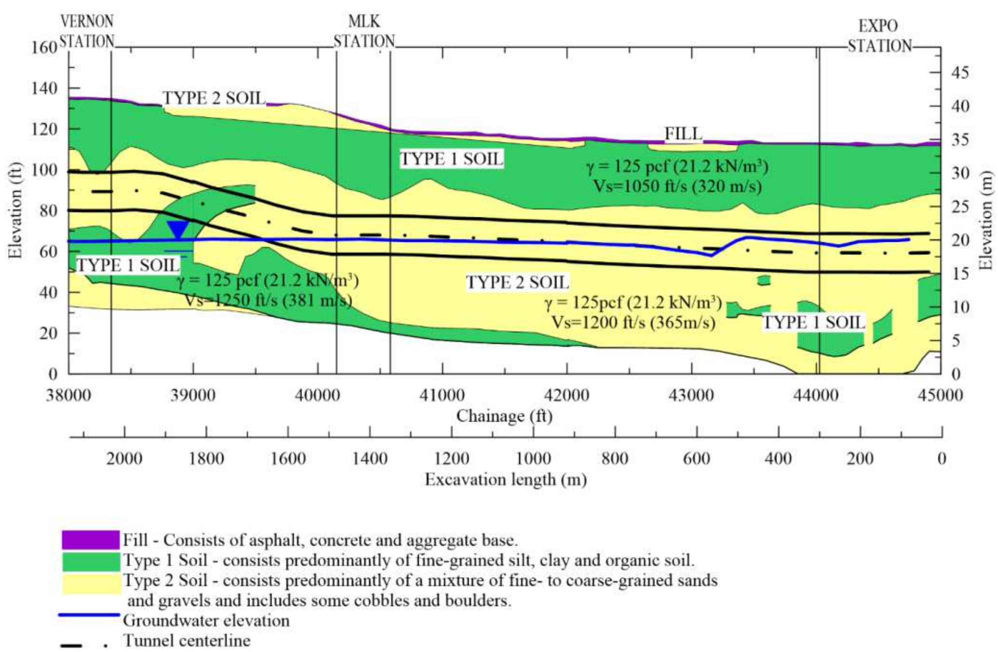


Figure 2. Soil Profile (adapted from Hatch Mott MacDonald 2012a)

GROUND MONITORING INSTRUMENTATION & EPBM OPERATION MONITORING

An extensive field monitoring program was initiated to monitor ground movements during tunneling construction. Instrumentation was installed along the tunnel alignment, including Surface Monitoring Points (SMPs), Feno-type Anchors (FENOs), Multi-Point Borehole Extensometers (MPBXs), and Building Monitoring Points (BMPs) (Figure 1).

SMPs were installed at a horizontal spacing of 40 ft (12 m) along the tunnel centerline. FENO anchors were installed to measure surface movements at various distances from the tunnel axis. BMPs were installed on adjacent structures. The measurements were collected by manual surveys which have a 0.1-in (2.5 mm) precision. The measuring frequency was as high as once a day when the EPBM approached and passed through the monitoring point. After the EPBM was beyond the zone of influence, the measuring frequency was reduced. Final measurements were also taken when construction concluded. A total of 23 settlement arrays, consisting of SMPs, FENO anchors, and BMPs, are constructed transverse to the centerlines of the tunnels.

MPBXs were installed every 200 ft (61 m) above the tunnel axis, which measured subsurface differential movements between fixed anchors and the MPBX rim (benchmark). An individual MPBX consists of three fixed anchors at different elevations with fiberglass rods and an electrical head assembly. The three fixed anchors were installed at 5ft (1.5 m) below the ground surface, 5 ft (1.5 m) above the tunnel crown, and halfway between the shallow and deep anchors. The MPBX anchors were measured at 5-min intervals when the EPBM approached and passed through the monitoring point. The EPBM was equipped with eight earth pressure gauges in the upper, middle, and lower cutterhead chamber and six pressure gauges on the perimeter of the shield. EPBM sensor data were recorded in real-time, and millions of data points were collected each day and stored in an Integrated Risk and Information System (IRIS) database.

EVALUATION OF EXISTING EMPIRICAL METHODS AGAINST FIELD MEASUREMENTS

Field-measured maximum settlements above the tunnel centerline at both the surface and 5ft (1.5 m) above the tunnel crown are presented in Figure 3. Measurements vary along the tunnel drive and more settlements were measured at a deeper depth compared to that at the surface. Assuming 0.3% volume loss, maximum settlements can be calculated from the existing empirical methods (Cording and Hansmire, 1975; O'Reilly and New 1982; Attewell et al. 1986; Mair et al. 1993; Moh et al. 1996; Marshall et al. 2012). Results are compared to the field measurements. It is found that an assumed volume loss does not capture the settlements throughout the tunnel drive, regardless of the empirical method used for approximating the settlement profile.

The Gaussian curve (Eq. 1) is adopted by Cording and Hansmire (1975), O'Reilly and New (1982), Attewell et al. (1986), Mair et al. (1993), and Moh et al. (1996) to construct the surface and subsurface settlement profile, while Marshall et al. (2012) adopts the modified Gaussian curve (Eq. 3) by Vorster et al. (2005).

The fitting capability of each empirical method for estimating the shape of the surface settlement trough can be evaluated by matching the maximum surface settlements above the tunnel centerline to the field measurements. The coefficient of determination, r^2, is adopted as the measure of goodness of fit. Figure 4 shows that, Cording and Hansmire (1975), O'Reilly and New (1982), Attewell et al. (1986), and Mair et al. (1993) match well with the field data (relatively high r^2). Specifically, with the increase of the maximum settlement at the surface from 0.1 in (2.5 mm) to 0.5 in (13 mm), the fitting capability of these empirical methods become better. For example, the r^2 of Cording and Hansmire (1975) increases from 0.66 to 0.96. Note that the low values near the outside of the curve are in the ± 0.1 in (2.5 mm) error band.

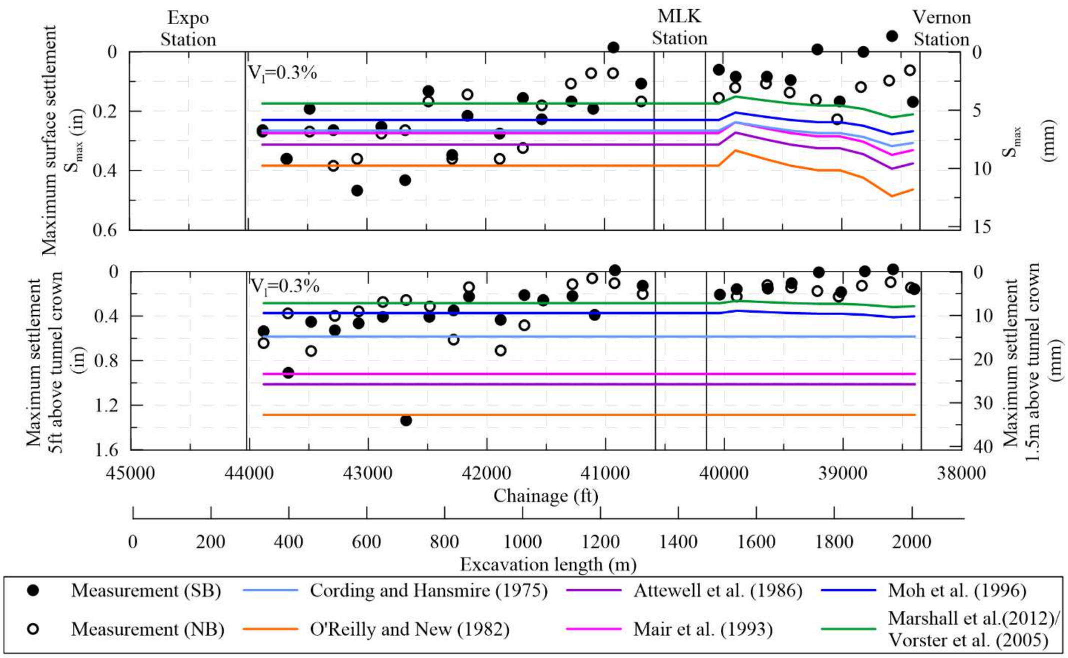


Figure 3. Evaluation of empirical methods for estimating tunneling-induced maximum settlements above tunnel centerline at both surface and 5ft (1.5 m) above tunnel crown

IMPACTS OF EPBM FACE AND SHIELD PRESSURES ON GROUND MOVEMENTS

The operation of the EPBM and pressures applied to the face and body of the shield play an essential role in limiting ground movements (Cording 2018). A total of 8 sensors were installed from the top to the bottom of the EPBM face to measure face pressures. The pressures in the face increased from top to bottom following the gradient of gravity. A total of 6 shield sensors were installed to measure pressure on the top of the EPBM shield. At the K(Crenshaw/LAX) Line, bentonite was injected around the shield to form a pressurized envelope. If the measured shield pressures are close to or higher than the face pressure in crowns, the overcut gap is filled, otherwise it is not.

Figure 5 shows sample time series plots from two sections, Section A (Sta. 42+680) (Figure 5 (a)) and Section B (Sta. 42+878) (Figure 5 (b)) when constructing the second tunnel NB. The tunneling-induced settlements are plotted separately as the surface settlement and the differential settlement between the surface and anchor 5ft (1.5m) above the tunnel crown, due to the difference in measuring frequencies of settlement markers and MPBXs. Settlements presented for NB are incremental settlements, in other words, settlements shown are only those induced by the excavation of the NB tunnel excluding the effect of the first SB tunnel. The upper face pressure (one sensor) and average shield pressure (average of 6 sensors) are selected for correlation analysis.

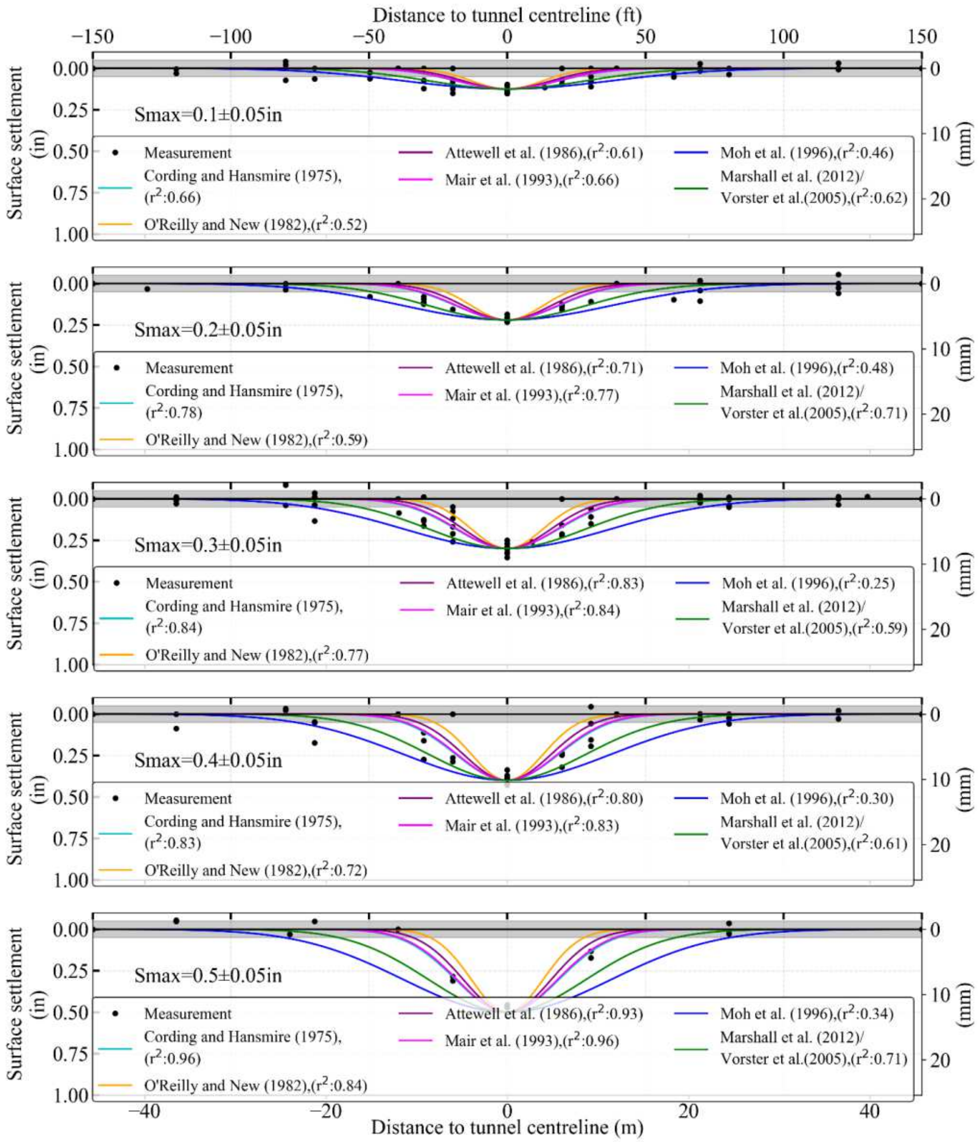
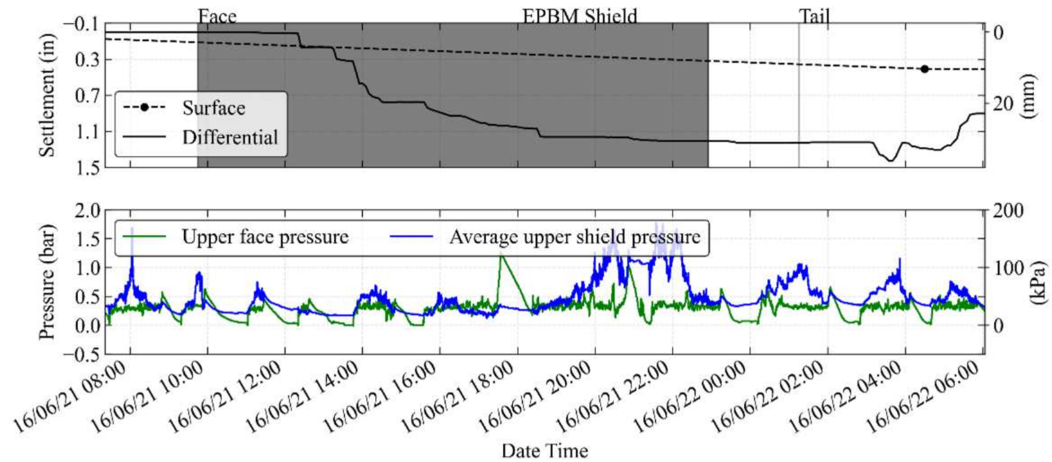
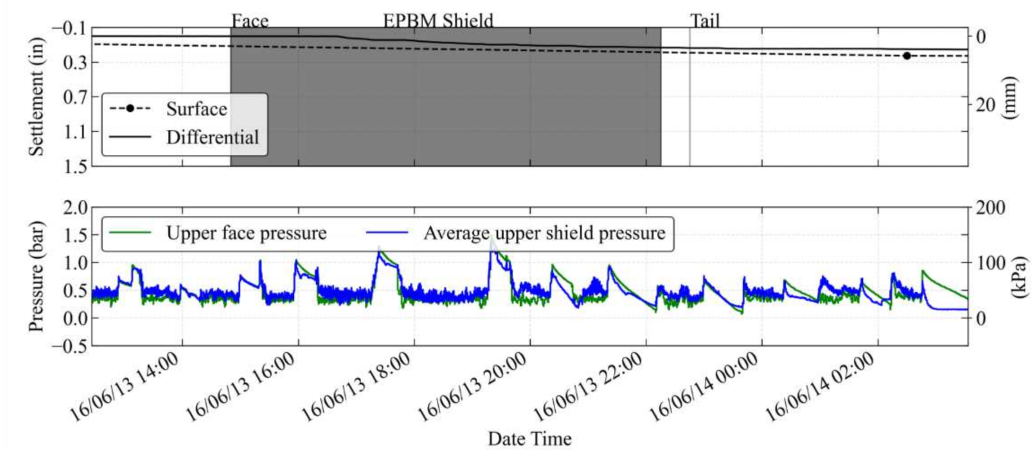


Figure 4. Evaluation of empirical methods for estimating the shape of surface settlement trough

Approximately 0.3-in (7.6-mm) surface settlement and 1.1-in (27.9-mm) differential settlement from the ground surface to the deep anchor occur at Section A (Figure 5 (a)). The measured upper face/shield pressures are as low as 0.25 bar (25 kPa) when the EPBM is passing under the section and the deep anchor, 5 ft (1.5 m) above the EPBM shield settles a total of 1.4 in (35.6 mm) all over the shield. The shield pressures increase as the rear of the shield passes the extensometer, which prevents further soil settlement. In section B (Figure 5(b)), in contrast, barely any movements happen, and it is observed that measured upper face pressure/shield pressures are consistently held at 0.5 bar (50 kPa). It should be mentioned that, for the K (Crenshaw/LAX) Line Tunnel, face/shield pressures were intentionally increased high at the end of the EPBM shove (advance) and left to drop during ring-build or downtime. It is assumed that no ground movement occurs when EPBM stops.



(a) Section A (Sta. 42+680)



(b) Section B (Sta. 42+878)

Figure 5. Settlements above tunnel centerline and EPBM pressures

Figure 6 compares the maximum surface settlements from all monitoring sections to their corresponding shield pressures. The impact of tunnel depth, i.e., the overburden pressures are also considered. To integrate the dual impacts, the differential shield pressures, $\sigma_{v0} - p_i$, is normalized by the overburdne pressure, σ_{v0}. p_i is the minimum shield pressure measured when the EPBM shield is passing under the monitoring section (excluding measurements when EPBM stops). Since the tunnel depth of the K (Crenshaw/LAX) tunnel is mostly consistent along the alignment, the shield pressure is the controlling factor. Larger settlements are observed (1) when the EPBM operates at a very low (closer to zero) shield and face pressures in the crown, and (2) in a couple of cases when the bentonite injection is not functioning and the overcut gap is not filled. For the K (Crenshaw/LAX) Tunnel, the impact of low pressure is greater due to the short stand-up time for tunneling in the sand.

The modified Gaussian curve (Vorster et al., 2005) (Eq.3) is used to fit the data points of individual settlement arrays. Volume losses are calculated based on the best-fitted Modified Gaussian curve (Vorster et al., 2005). The volume loss, V_l (%) is compared to differential shield pressure normalized by the overburden pressure. Figure 7 shows that the volume loss is also dependent on the shield pressures.

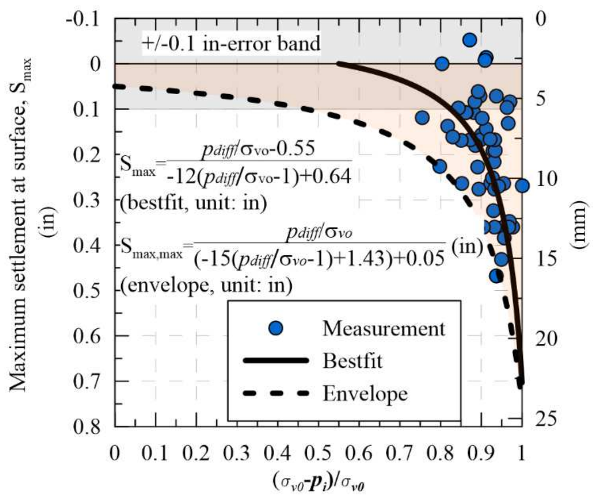


Figure 6. The impact of the shield pressure on maximum surface settlements

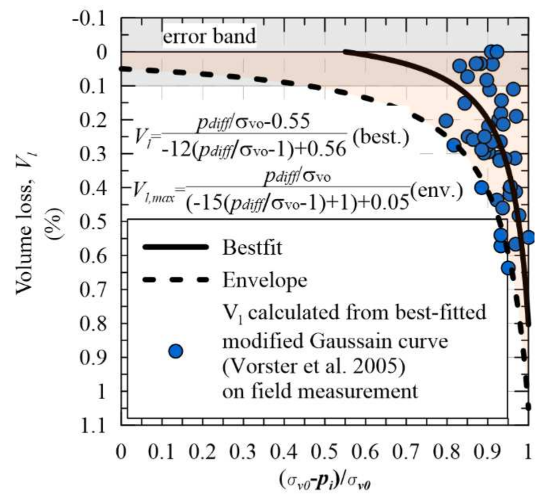


Figure 7. The impact of the shield pressure on volume losses

EMPIRICAL METHOD DEVELOPMENT

An asymptotic curve is used to best fit the data of maximum surface settlement (Figure 6) and volume losses (Figure 7), separately. Constraints are imposed at the end of the curves with physical considerations. The best-fitted curve as well as the boundary envelopes are developed to correlate the shield pressure to the maximum surface settlement or the volume loss. Due to the prevalent use of volume losses in existing empirical methods, an equation is proposed to estimate the volume loss with a given shield pressure and overburden pressure based on the best-fitted curve developed upon the data of K (Crenshaw/LAX) Tunnel as shown in Figure 7,

$$V_l(\%) = \frac{\frac{p_{diff}}{\sigma_{v0}} - 0.55}{-12\left(\frac{p_{diff}}{\sigma_{v0}} - 1\right) + 0.56} \tag{4}$$

where p_{diff} is the difference between the overburden pressure σ_{v0} and the minimum shield pressure p_i.

Another equation based on the envelope curve in Figure 7 is also proposed that can estimate the maximum volume losses to be expected at a given condition,

$$V_{l,max}(\%) = \frac{\frac{p_{diff}}{\sigma_{v0}}}{\left(-15\left(\frac{p_{diff}}{\sigma_{v0}} - 1\right) + 1\right) + 0.05} \tag{5}$$

EVALUATION OF PROPOSED EMPIRICAL METHODS

Volume losses can be calculated using Eq. 4 or Eq. 5 with the measured minimum shield pressure when EPBM is passing under monitoring sections for K (Crenshaw/LAX) tunnel. The existing empirical methods are re-evaluated with the estimated volume losses. The Root Mean Square Root (RMSE) is adopted to measure the fit, i.e., the lower value means a better fit. Figure 8 compares the field-measured maximum surface settlements above the tunnel centerline to the settlements estimated by existing empirical methods with volume losses V_l calculated using Eq. 4. Cording and Hansmire (1975), Mair et al. (1993), Moh et al. (1996), and Marshall et al. (2012) can estimate settlements the closest to the field measurements, though Marshall et al. (2012) tends to underestimate the relatively large settlements. O'Reilly and New (1982) and Attewell et al. (1986) slightly overestimate the settlement. Eq. 5 can be used to estimate the maximum volume losses $V_{l,max}$ to be expected at a given condition. The comparison between the estimated settlements with $V_{l,max}$ and the field-measured settlements is presented in Figure 9. Among all methods, Marshall et al. (2012) can estimate the closest to the field measurements. The lower boundary of the estimated settlements of Cording and Hansmire (1975), Mair et al. (1993) and Moh et al. (1996) match with the field-measured settlements. This is because the intent of Eq. 5 is to estimate the maximum volume loss to be expected. With the estimated volume losses, O'Reilly and New (1982) and Attewell et al. (1986) largely overestimate the settlement.

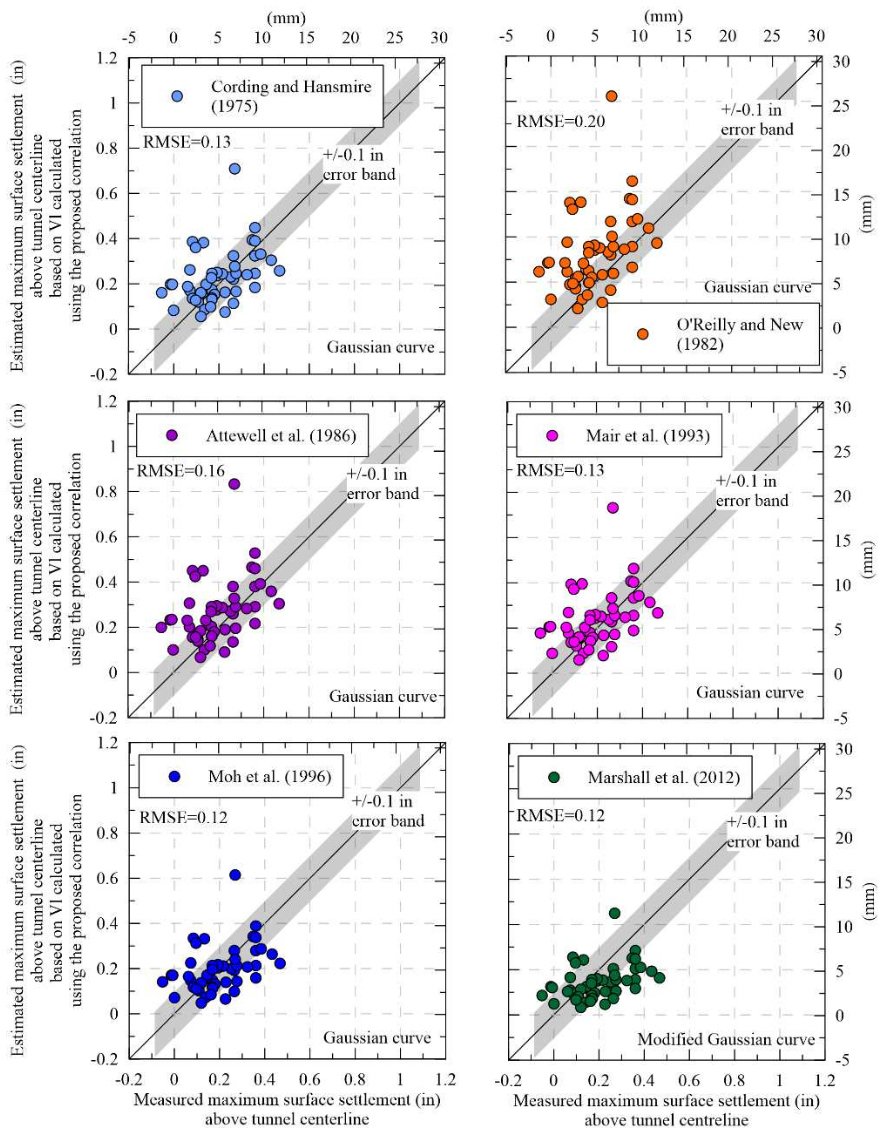


Figure 8. Evaluation of existing methods for estimating S_{max} above tunnel centerline with volume loss calculated using the proposed relation (Eq. 4)

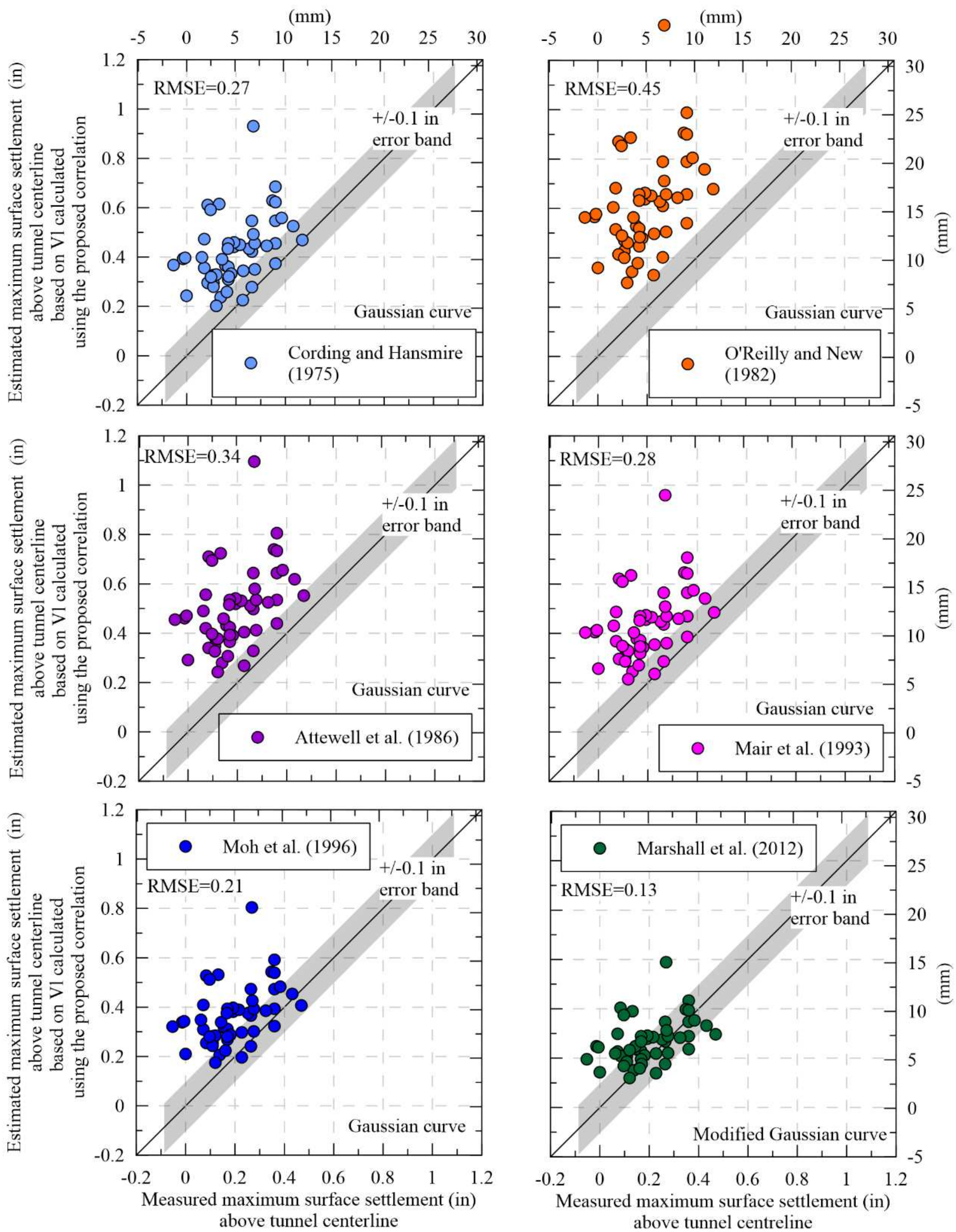


Figure 9. Evaluation of existing methods for estimating S_{max} above tunnel centerline with volume loss calculated using the proposed relation (Eq. 5)

CONCLUSION

From data of the K (Crenshaw/LAX) Tunnel, it is observed that volume losses and settlements are heavily dependent on the shield pressures of the EPBM. In general, maintaining continuous pressure can significantly reduce settlements and volume losses. Relations are developed to correlate the shield pressures to volume losses, which can be used with existing empirical methods to estimate settlements and transverse settlement profiles. It is noted that the relations are developed specifically to the geology of the K (Crenshaw/LAX) Line. The relations will be extended to more geologies by incorporating the stiffness of the ground.

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