Investigation of subsurface settlement profiles above tunnels using transparent soil models

Mahmoud Ahmed, Ph.D., P.E.[1] & Magued Iskander, Ph.D., P.E., F.ASCE[2]
[1] *Project Engineer, New York State Department of Transportation, New York, New York, USA*
[2] *Professor, Polytechnic Institute of New York University, Dept of Civil Engineering, Brooklyn, New York, USA*

ABSTRACT
Ground movements continue to be the primary concern of tunneling in urban areas. The study presented in this paper focused on the subsurface settlement profiles above tunnels in granular material simulated by transparent soil. Analysis of the displacement field inside the transparent soil models indicated that subsurface settlement trough at different depths can be approximated by Gaussian curve. However the value of the trough parameter *K* is not constant but increases with depth, giving wider settlement profiles closer to the tunnel crown. The measured data also indicated that subsurface ground movements can be in excess of the observed surface settlement, which can adversely affect underground utilities. In general, results of the study were in agreement with current knowledge of full-scale situations.

RÉSUMÉ
Mouvements de terrain continuent d'être la principale préoccupation des tunnels dans les zones urbaines. L'étude présentée dans le présent document se concentre sur les profils de tassement du sous-sol au-dessus des tunnels dans un matériau granulaire simulé par le sol transparent. Analyse du champ de déplacement à l'intérieur des modèles de sols transparents indique ce creux de règlement du sous-sol à différentes profondeurs peut être approchée par la courbe de Gauss. Cependant, la valeur du paramètre *K* creux n'est pas constante, mais augmente avec la profondeur, en donnant les profils de tassement proportionnellement plus proche de la calotte du tunnel. Les données mesurées ont également indiqué que les mouvements du sol sous-sol peut être au-delà du tassement de la surface observée, ce qui peut affecter les installations souterraines. En général, les résultats de l'étude sont en accord avec les connaissances actuelles des situations de grande envergure.

1 INTRODUCTION

Tunnel construction in soft soil usually affects existing ground stress and hydro-geological conditions. Modification of ground natural stress conditions is typically associated with ground movements such as surface settlement, subsurface settlement and horizontal movements. Ground movements induced by shallow tunnels affect the safety of nearby underground and aboveground structures. Therefore prediction of ground movements and assessment of their potential impact on infrastructure is crucial to planning, design and construction of tunnels in urban environment. To date, these tasks continuing to be challenging for tunneling community. The theoretical determination of displacement field around tunnel opening remains difficult, particularly when it comes to achieving a mathematical representation of the complex phenomena observed during tunneling. This is due to the large number of parameters to be taken into account and to the three-dimensional pattern of ground movement around the opening (Leca and New, 2007). The relationship between magnitude of ground movement, tunnel size and depth is complex.

Current available principal methods for predicting ground movement induced by tunneling includes empirically derived relationships, numerical and analytical models. The major objective of these methods is to offer a reasonable estimate of surface and subsurface settlement profiles. Empirically derived relationships are in the form of formulae which have been established from observed surface settlement behavior. Peck (1969) assumed a particular geometric form of the surface settlement profile. He suggested that the settlement trough above a tunnel can be reasonably represented by Gaussian curve (normal distribution curve). This concept is well established and has been accepted as the basic form of the settlement profile by many researchers such as Attewell (1978); Atkinson et al. (1975); O'Reilly and New (1982) and Cording (1991). These researchers have studied tunneling in different soil conditions and concentrated on evaluating the volume of ground loss due to tunneling and the shape of the surface settlement trough in two dimensional form.

Analytical methods for evaluation of ground movements have been developed based on the fundamental equations of elastic and continuum theories (*e.g.*, Clough and Schmidt, 1981; Rowe and Lee, 1983; and Sagaseta, 1987). These methods apply simplified assumptions in terms of tunnel geometry, geotechnical properties and definition of boundary and initial conditions. Although the simplified model can predict the general tendency of ground movement, it has yet to reach the stage where it can describe more complicated soil behavior such as high shear strain and consolidation. Also, most of these methods focused on defining the new stress field induced by tunneling. So far, limited work has been devoted to the distribution of underground movements around the opening and time effects, due to the complexity of such analyses.

Numerical methods have been widely used in recent years due to powerful and advance computing tools. Numerical methods were applied not only to ground settlement prediction but also to the entire tunnel design procedures, including simulation of the excavation sequence, placing of linings, soil–tunnel–linings interaction, effects on nearby tunnels, seepage, and consolidation. One of the more refined numerical methods is the Finite Element Methods (FEM) which are capable of simulating initial and boundary conditions similar to the actual field conditions with time dependent effects. However, three dimensional analyses still remain complex (Leca & New, 2007) and often involve parameters that are difficult to estimate. There are also many cases where data such as locations and material properties of underground utilities and foundations were not available. Therefore, full soil-structure interaction analysis is not possible.

In this study an attempt is made for the first time to study subsurface settlement with transparent soil models. Because the models are transparent, they allow measurement and visualization of ground movement distribution at location near and away from the tunnel face. A tunnel is pre-placed inside a saturated transparent soil, which represents saturated sand. Tunnel face support is simulated using an internal pressure (σ_T) applied inside the tunnel. Tests are conducted by reducing the tunnel pressure σ_T in stages until collapse of the soil occurs. Because the model is transparent, it can be sliced using a laser light sheet, at the location of the tunnel face. Images of the soil at the tunnel face illuminated by the laser light were captured after each decrement of σ_T reduction and used to obtain corresponding 2D deformation fields. While this technique might not precisely model tunnel construction in the field, nevertheless it is capable of revealing patterns of behavior relevant to the mechanics of internal soil deformations induced by tunneling.

1.1 Surface settlement

In practice, surface settlement is usually estimated using Peck (1969) empirical method which was based on the available data from many tunnel projects. He observed that the settlement trough over a single tunnel could usually be represented within reasonable limits by the error function or normal probability curve also known as Gaussian curve. Peck’s (1969) solution provides an estimate of settlements to be expected at varying distance laterally from the centerline of tunnel. The properties of the normal probability function and its relationships to the dimensions of the tunnel are shown in Fig 1.

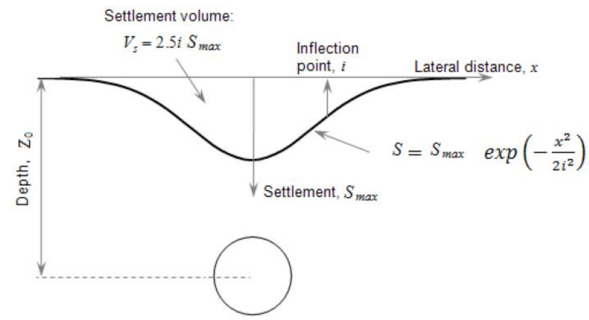

Figure 1: Properties of the normal probability function.

Peck (1969) assumed that the volume of surface settlement (V_s) is equal to the volume of ground loss at the tunnel (V_L). In shield tunneling ground loss can occur due to insufficient pressure (face loss) or over excavation. Peck also observed that most of the tunnel in clays develops surface settlement volumes approximately equal to volume of ground loss into tunnels. Therefore volume of settlement trough, per unit length, can be estimated using the property of the Gaussian probability curve as.

$$V_S = 2.5\, i\, S_{\max} \qquad \text{[Eq. 1]}$$

According to Mair and Taylor (1997), ground loss (V_L) depends on number of factors such as ground type, groundwater conditions, tunneling method, and length of time in providing positive support, and the quality of workmanship. In practice, volume loss is usually estimated (1-2% of the theoretical tunnel volume) based on experience in a given area employing a particular tunneling method
Values for settlement trough parameter *i* have been reported by Peck (1969) for tunnels where reasonably reliable settlement data are available. Using his data, Peck (1969) estimated the value of *i* as:

$$\frac{i}{R} = \left(\frac{Z_0}{2R}\right)^n \qquad \text{[Eq. 2]}$$

where R is the tunnel radius, Z_0 is the depth to tunnel axis and n is a dimensionless factor (0.8 - 1.0).

O'Reilly and New (1982) proposed that ground movements above tunnels can be estimated using empirical methods similar to Peck's (1969) which based on available case history data. They further proposed that the relationship between the trough parameter *i* and depth to tunnel axis Z_0 is approximately linear function:

$$i = k\,Z_0 \qquad \text{[Eq. 3]}$$

where k is an empirical constant of proportionality. Values for parameter k range 0.2 to 0.7 depending on soil type and tunnel construction method. These values were found to be in good agreement with Fujita (1981) filed data from several projects in Japan excavated by various types of shields including compressed air, slurry shield (SS), and earth pressure balance shield (EPB).

1.2 Subsurface settlement

In practice, it's usually assumed that the shapes of subsurface settlement profiles developed during tunnel construction also approximate to a Gaussian curve as shown in Fig. 1. Mair et al. (1993) showed that the subsurface settlement profiles in clay can be approximated by the Gaussian curve in some way similar to surface settlement profiles. These authors indicated that the parameter K does not remain constant but increases with depth, giving relatively wider settlement profiles closer to the tunnel crown. Similar observations have been reported by Lee (2009) for model tunnels in sand, Moh et al. (1996) for tunnels in silty sands below the water table and Dyer et al. (1996) for tunnel in loose sands overlain by a firm to stiff clay layer. Mair et al. (1993) further proposed relation between K and the dimensionless subsurface below ground level (z/Z_0):

$$k = \frac{0.175 + 0.325\left(1 - z/Z_0\right)}{1 - z/Z_0} \qquad \text{[Eq. 4]}$$

where z is the depth of subsurface settlement trough below ground surface.

2 TRANSPARENT SOIL TUNNEL MODELS

A Plexiglas model (Fig. 2) 30.48 cm long, 25.4 cm wide and 20.32 cm high was used to contain the transparent soil. The dimensions of the model have been chosen in such a way, that the influence of the boundaries was minimized. The tunnel is modeled by a PVC tube of 2.54 cm diameter preinstalled inside the model at a depth of 12.7 cm. A latex membrane (0.3 mm thick) of negligible strength was attached to the end of the tube to represent the tunnel face. The membrane was left slack to prevent mechanical influence on the displacement of the face. The tube (tunnel) was then filled with air under pressure to simulate the tunnel support pressure (σ_T) which can be read and controlled by the pressure board. In reality, such a support can be achieved by use of compressed air, bentonite slurry or earth pressure balance (EPB). In this study, σ_T is assumed to be constant over the tunnel face, which best models the case of compressed air support, but also provides valuable information for slurry or EPB shields. For application of surcharge or surface pressure σ_S, the Plexiglas model container was placed between two identical metal plates (Fig. 2) connected by four threaded rods. A rubber tire with internal pressure σ_S was placed on top of the transparent soil, and connected to the pressure board. The tunnel support pressure σ_T was increased such that $\sigma_T = \sigma_S = 69$ kPa at the beginning of the test. The tire was placed on to top of the transparent soil which was well leveled to assure uniform pressure distribution.

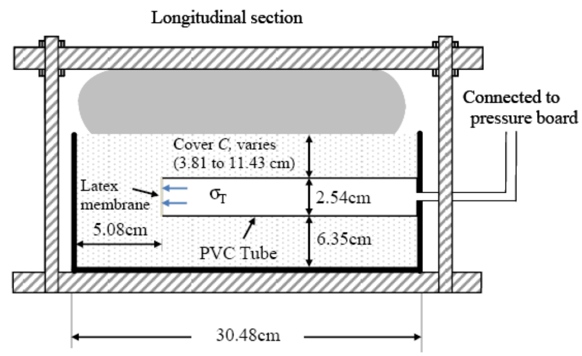

Figure 2: Transparent soil tunnel model.

Transparent sand used in this study is classified as SP (poorly graded sand) per the United Soil Classification System. The coefficient of uniformity, $C_u = 2$ and coefficient of curvature, $C_c = 0.96$. It has a unit weight of 8.53 kN/m^3, friction angle of 36°, particles size of 0.5 - 1.5 mm, specific gravity of 2.2, zero cohesion and 32 MPa modulus of elasticity (Iskander, 2010). The same transparent material has been used previously to study pile penetration (Liu and Iskander, 2010) and shallow foundations (Iskander and Liu, 2010).

In addition to the tunnel container, the set up also included a Cohu 2622 black & white CCD camera, 35mW Melles Griot laser light source, a line generator lens, a loading frame, a test table, and a PC for image processing (Fig.3). The camera has a resolution of 640x480 pixels and controlled by the PC through a Matrox Meteor 2/4 frame grabber. A macro-zoom lens with a variable focus length from 18-108 mm was mounted on the CCD camera.

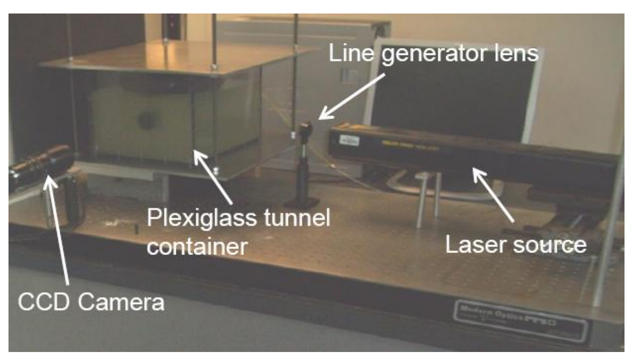

Figure 3: Test setup.

The tests were conducted by reducing the tunnel pressure σ_T in stages until collapse occurred. After each decrement of tunnel pressure, the model was sliced optically using laser light sheet to illuminate the plane of measurements inside the model and an image was taken by CDD camera. Later, these images were processed to obtain corresponding deformations relative to pressure drop and volume loss in the soil mass induced by the tunnel. Complete strain and deformations fields were obtained from the set of images taken during each tests.

3 DISPLACEMENT MEASUREMENT BY DIGITAL IMAGE CORRELATION

The interaction between laser light and transparent soils produces a distinctive speckle pattern. This speckle pattern manifests the interaction between the transparent soil matrix, impurities, entrapped air, and the laser. Small particle movement will result in change in the speckle distribution in the plane of measurement. If the deformation is small, the contrast distribution resulting from the speckle effect will follow the particle movement.
Displacement measurement from a sequence of images, also referred as optical flow estimation, is performed by treating the two dimensional image as a continuous mathematical function, f(x,y), in which f(x,y) equals to the light intensity at the position (x,y). One of the most recent techniques that provide enhanced capabilities for displacements and flow measurement is digital image correlation (DIC). This technique is based on using correlation function to locate the best matching position of two images and thus predicting particles movements. The cross-correlation function of two image functions, f(x,y) and g(x,y) = f(x+Δx,y+Δy) and is given by:

$$c(u,v) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(x,y)\, g(x+u, y+v)\, dx\, dy \quad \text{[Eq.5]}$$

The peak of the cross-correlation function (Eq. 5) is located at $(u,v)|c_{max}$, which will coincide with (Δx,Δy). Locating the position of the peak indicates both, the magnitude and direction of the displacement. An advanced form of DIC that employs window shifting and window sizing called adaptive cross correlation (ACC) has been used (Liu and Iskander, 2004). ACC is implemented in Flow Manager software, which is the software used in this research.

4 ANALYSIS OF THE RESULTS

The observed subsurface settlement profiles at various depths (z) were normalized by the tunnel diameter and presented in Fig. 4 for a tunnel with cover to diameter (C/D) ratio equal 1.5 and volume loss, V_L = 2.5%. The measurements indicated that subsurface settlement profiles can be approximated by Gaussian curve. However the value of the trough parameter K is not constant but increases with depth, giving relatively wider settlement profiles closer to the tunnel crown. Similar results have been obtained by Mair et al. (1993), Moh et al. (1996) and Dyer et al. (1996) for tunnels in variety of soils.

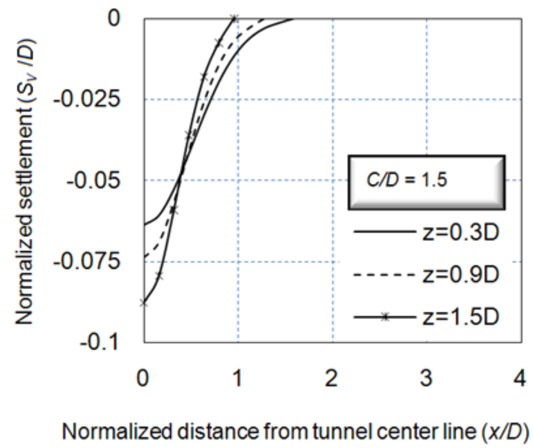

Figure 4: Observed subsurface settlement profiles.

Typical displacement vectors observed in transparent soil models is shown in Fig. 5 for a tunnel with C/D equal 1.5 and volume loss, V_L = 2.5%. Soil movements in and around tunnel face tend to manifests itself at the surface in a sinkhole extending from tunnel axis. Vertical soil movements below tunnel invert were found be minimal. The entire movement was confined above the tunnel level.

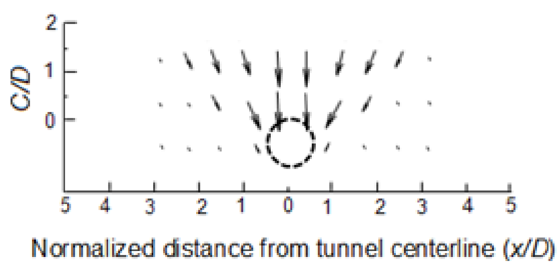

Figure 5: Displacement vectors observed in transparent soil models.

This fact is illustrated by the contour of vertical displacements shown in Fig.6 for tunnel with C/D equal 1.5 and volume loss, V_L = 2.5%.

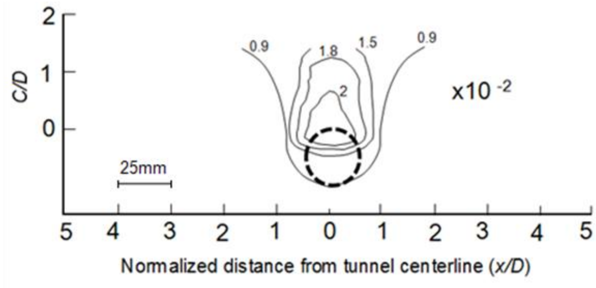

Figure 6: Contour of vertical displacements.

Values of k obtained from measurements of i for subsurface profiles shown in Fig.4 are plotted along in Fig.7 with data from Moh et al. (1996), Dyer et al. (1996) and calculated k values from Eq. 4 for the test condition. The transparent soil modeling results were found to be in a good agreement with the data reported by Dyer et al. (1996) in sand. However, the k observed by Moh et al. (1996) in silty sand and calculated per Mair et al. (1993) using Eq. 4 were somewhat different. This is mainly because Eq. 4 is based on data of subsurface settlement profiles for tunnels in clay (Mair and Taylor 1997).

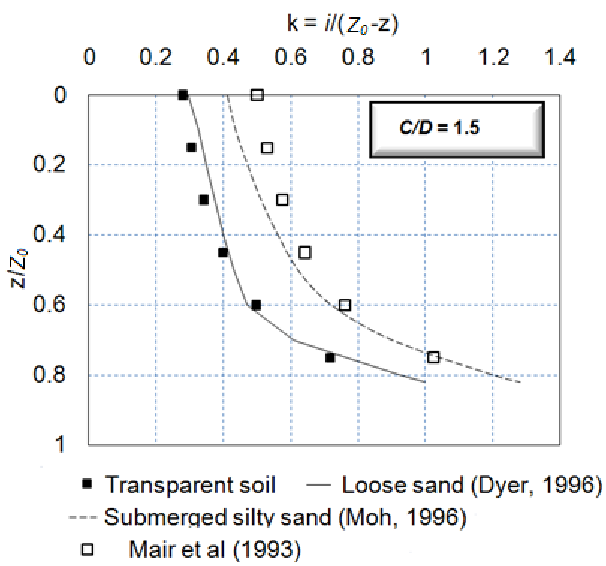

Figure 7: Variation of k with depth for subsurface settlement.

Strain calculated using MATLAB function originally developed by Eberl et al. (2006) and modified by the writers is presented in Fig. 8 for tunnel model with C/D equal 1.5 and volume loss, V_L = 2.5%. The calculated vertical strains ranged between 2.2% at tunnel level to 1.3% at the surface. This result emphasizes the importance of predicting subsurface movements because they tend to be of greater magnitude than surface displacement.

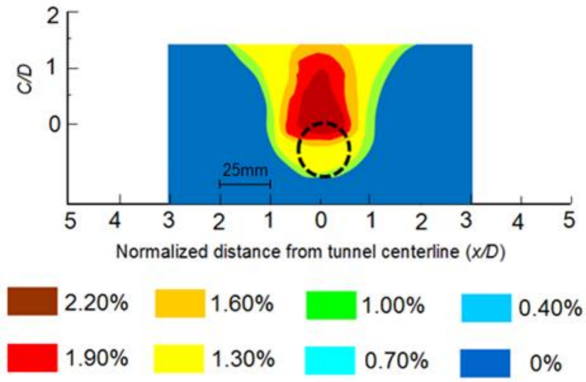

Figure 8: Strain inside the transparent soil model.

5 CONCLUSIONS

Experimental technique and procedures were developed to analyze subsurface settlement induced by tunneling in saturated sand. A transparent soil model, which represents sand was sliced using a laser light sheet perpendicular to the tunnel axis at the tunnel face. Images of the soil illuminated by a laser light sheet, perpendicular to the tunnel axis, were captured after each decrement of σ_T and used to obtain corresponding two dimensional deformation fields. Later, these images were processed using Flow Manager to obtain corresponding deformations relative to pressure drop and volume loss in the soil mass induced by the tunnel.

The use of a transparent soil allowed for comprehensive investigation of surface and subsurface ground movements in relation to volume loss. Analysis of the displacement field inside the transparent soil models indicated that: subsurface settlement trough at different depths can be approximated by normal probability curve. However the value of the trough parameter K is not constant but increases with depth, giving relatively wider settlement profiles closer to the tunnel crown. The measured data also indicated that subsurface ground movements can be in excess of the observed surface settlement, which can adversely affect underground utilities. The equations proposed by Mair et al. (1993) for predicting subsurface settlement in clay yields acceptable results in sand. In general, results of the study were in agreement with current knowledge of full-scale situations.

6 REFERENCES

Atkinson, J.H., Orr, T.L.L., and Potts, D.M. 1975. Research studies into the behavior of tunnels and tunnel linings in soft ground. Technical Report 176 UC, Transport and Road Research Laboratory, Crowthorne, UK.

Attewell, P. B. 1978. Ground movements caused by tunneling in soil. *Proc. Int. Conf. on Large Movements and*

Structures (ed. J. D. Geddes), Pentech Press, London, pp. 812-948.
Clough, G. W. and Schmidt, B. 1981. Design and performance of excavations and tunnels in soft clay. *Soft Clay Engineering,* Elsevier, pp. 569-634.
Cording, E. J. 1991. Control of ground movements around tunnels in soil. *General Report, 9th Pan-American Conference on Soil Mechanics and Foundation,* Engineering, Chile.
Dyer, M. R., Hutchinson, M. T. and Evans, N. 1996. Sudden Valley Sewer: a case history. *Proceedings, Int. Symp. Geotech. Aspects of Underground Construction in Soft Ground*, R. J. Mair and R. N. Taylor, eds., London, Balkema, pp. 671-676.
Eberl, C., Thompson, R., Gianola, D., Sharpe, W., Jr., and Hemker, K. 2006. Digital image correlation and tracking." ⟨http://www.mathworks.com/matlabcentral/fileexchange/12413⟩ (June 29, 2011).
Flow Manager (Computer software). Dantec Dynamics, Tonsbakken, Denmark.
Fujita, K. 1981. On the surface settlement caused by various methods of shield tunneling. *Proc 11th Conf. on Soil Mechanics and Foundation Engineering.* Vol. 4, pp. 609-610
Iskander, M. & J. Liu. 2010. Spatial deformation measurement using transparent soil *ASTM Geotechnical Testing Journal*, Vol. 33, No. 4, doi: 10.1520/GTJ102745.
Iskander, M. 2010. Modeling with transparent soils, visualizing soil structure interaction and multi phase flow, non-intrusively. Springer ISBN: 978-3-642-02500-6.
Leca, E. and New, B. 2007. Settlements induced by tunneling in soft ground. *Tunnelling and Underground Space Technology*, 22, pp. 119–149.
Lee, Yong-Joo. 2009. Investigation of subsurface deformations associated with model tunnels in a granular mass, *Tunnelling and Underground Space Technology*, 24, pp. 654–664
Liu, J., and Iskander, M. 2004. Adaptive cross correlation for imaging displacements in soil. *J. Comput. Civ. Eng*., 17(2), 88–96.
Liu, J.and Iskander, M. 2010. Laboratory investigation of the modeling capacity of synthetic transparent soils. *Canadian Geotechnical Journal*, Vol. 47, No. 4, pp. 451-460, DOI: 10.1139/T09-116.
Mair, R. J., and Taylor, R. N. 1997. Theme lecture: Bored tunneling in the urban environment. *Proceedings, 14th Int. Conf. Soil Mechanics & Foundation Engineering*, Hamburg, 4, pp. 2352-2385.
Mair, R. J., Taylor, R. N. and Bracegirdle, A. 1993. Surface settlement profiles above tunnels in clays. *Geotechnique*, Vo1.43, No.2, pp.3 15-320.
Moh, Z., Ju, D. H. and Hwang, R. N. 1996. Ground movements around tunnels in soft ground. *Proceedings, Int. Symp. Geotech. Aspects of Underground Construction in Soft Ground,* R. J. Mair and R. N. Taylor, eds., London, pp. 725 -730..
O'Reilly, M. P. and New, B. M. 1982. Settlements above tunnels in the UK- Their magnitude and prediction. *Proceedings, Tunnelling'82*, IMM, London, pp. 173-181.
Peck, R. B. 1969. Deep Excavations and Tunneling in Soft Ground. *Proceedings, 7th International Conference on Soil Mechanics and Foundation Engineering*, Mexico City, State-of-the-art Volume, pp. 225-290.
Rowe, R. K., Lee, K. and Lo, K. J. 1983. A method of estimating surface settlement above tunnels constructed in soft ground.*Canadian Geotechnical Journal*. Vol. 20, No 8: pp. 11-22.
Sagaseta, C. 1987. Analysis of undrained soil deformations due to ground loss. *Geotechnique,* Vol. 37, No. 3, pp. 301-320.