Analysis of Shield’s Mechanism Inducing Ground Deformations

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1. Introduction
Presently, many tunneling projects have been built in congested urban environments which often involve tunneling in soft ground. Additionally, in many cases, the new tunnels are excavated close to the surface and adjacent to existing structures. One therefore needs to be able to cope with ground deformation caused by the tunnel construction in order to avoid any damage. The important issue of tunneling in urban areas is to estimate components of ground movements such as stresses, strains, and displacements in the surrounding ground.

Currently, analytical solutions become popular since they can be used to describe both vertical and horizontal ground movements within a single step calculation. The specific technique proposed by the analytical solution depends on its assumption. The closed-form equation can determine the displacement in any coordinates on its plain strain. Therefore, simple solution and single step calculation are the advantages of analytical solutions.

The research was proposed by Chaiwonglek & Suwansawat (2009) that studied and evaluated existing analytical solutions used for predicting ground deformations induced by tunneling. New approach namely “Shield’s 3-Zones Mechanism Analysis” incorporating shield’s influencing parameters measured at each shield position/zone (i.e. shield face, shield body, and shield tail) into analysis processes. As a result one could describe ground deformations well. Compared with Shield’s 3-Zones Mechanism Analysis using the extensive instrumentation records obtained from the Bangkok MRTA Subway Project [11] and MWA Water Supply Transmission Tunnel Project, It was found that the new approach successfully gave good agreements with both field data.

2. Using shield’s 3 zones mechanism with exiting analytical solutions
Several attempts have been made to develop simple closed-form analytical solutions for tunneling-induced ground deformations in clays. [10] presented an approximate solution for a tunnel in a homogeneous elastic half-space by extending a method suggested by [9] for the case of ground loss in an incompressible soil. The solution given in this technical is a generalization of Sagaseta’s solution in that it gives the solution for the case of ground loss not only for the incompressible case (with Poisson’s ratio equal to 0.5), but for arbitrary values of Poisson’s ratio, and it includes the effect of ovalization (Fig. 1.(b)) of the tunnel opening. They considered the uniform radial ground movement around the tunnel for the short-term undrained condition (Fig. 1.(a)). In order to take into account the oval-shaped ground deformation pattern in the short-term undrained condition (Fig. 1.(c)), [4] presented a modified solution from [10] by suggesting the use of an equivalent undrained ground loss parameter, which can be estimated using the gap parameter proposed by [3]. Then the nonlinear ground movement due to the deformation of an oval-shaped gap is modeled by adapting an exponential function to the equivalent undrained ground loss with some boundary conditions.

[9] refer to his techniques ([8]), that presented closed form solutions for obtaining the strain field in an initially isotropic and homogeneous incompressible soil due to near – surface ground loss. Controlled strain and obtained strains by using only the incompressibility condition are
considered. The presence of the top free surface was considered by means of a virtual image technique, and some results were obtained for the elastic half space. [9] extended his research for soil deformation around tunnels which based on solutions for incompressible irrotational fluid flow or existing technique namely “Virtual image technique”, for which elastic solutions for the half space are used including anisotropic in-situ stress behavior ($K_0$ is not equal to 1) and described further for plastic strains or soil compressibility were applied. The radial movement (Fig. 1.(a)) induced by average radial convergence and ovalization (Fig. 1.(b)) can be analyzed that significant vertical and horizontal movements. The movement also attenuates with the distance to the tunnel.

![Fig. 1. Ground deformation patterns around the tunnel section.](image)

[1] applied these analytical solutions to compare with field measurement obtained from the Bangkok MRTA project where high accuracy of monitoring data were recorded. It was found that existing analytical solutions have some different and limitations in all cases. Using [9] to predict ground deformations indicated that geological parameter, geometry parameter and operational parameter were significant parameters in the calculation procedure. The results were in agreement with field measurement especially in case of lateral deformations that had inward and outward movements, which can be proved that the stress occurs by overburden or shield operational pressure (such as face pressure or grouting pressure) was the significant factor contributing to the ground deformations. However, one could not input important operational parameters more than one value in these normal calculations. Additionally, only face pressure value was inputted into the calculation. Therefore, “Shield’s 3-Zones Mechanism Analysis” can simulate the realistic ground movement behavior due to EPB shield tunneling by using operational parameters such as face pressure and grouting pressure. Nevertheless, it was proved that some existing analytical solutions were not appropriate for applying in 3-Zones mechanism. Results obtained from the solution proposed by [9] and [10] were different from those of field measurement. Further the solutions were not based on the mechanism of EPB shield tunneling. However, it was still adequate to be adopted for the adjusting solution, namely 3 zones analysis because it included stress-strain function corresponding to the EPB shield mechanism.

Most soft ground tunneling projects have adopted the Earth Pressure Balance shield technique. The EPB shield is usually considered particularly suitable for cohesive or silty ground that does not contain cobble or boulder obstructions and in which the water head at the face is not high such as in the Bangkok subsoil. In other words, the more homogeneous and consistent the soil, the more successful the technique is.

An EPB shield is operated by controlling the amount of excavated soil that is transported from the shield face by a screw conveyor. As a result, the tunnel face can be supported by soil held in the front chamber at a controlled pressure. In practice, face pressure is usually the primary control
parameter during excavation. Based on this fundamental aspect of EPB shield tunneling, face pressure is one of the most significant factors that have a direct effect on the magnitude of ground movement. The quality of tail void grouting also contributes to the ground deformation. As the shield is jacked forward, a tail void around the outside of the lining is created by the difference between the excavated periphery and the outer liner interface. Tail void grouting is necessary in order to prevent ground moving toward the void. Grouting pressure should be high enough to guarantee the flow of grout material and to resist the ground moving into the void. Tunneling operations with high grouting pressure can considerably reduce settlements and lateral deformation developed after shield passing.

Fig. 2. Three zones of consideration point to estimating ground deformation.

Based on the fundamental framework as described above, ground movements induced by the EPB shield tunneling can be separated by shield tunneling behavior or construction phases into three distinct zones as shown in Fig. 2., during shield passing the consideration plane (the inclinometer or surface settlement measurement point) that occurs in a short period of time but not absolute immediately. The ground movements occurred after the shield passed, installed lining and finished backfill grouting are considered as long term behavior that excludes in this research.

3. Improved analytical solutions
Ground deformation behavior induced by shield tunneling can be separated into 3 zones as following:

Zone 1: at shield face; face pressure is a significant factor affecting the surrounding ground. The pressure at shield face can cause inward or outward ground movement which depends on surrounding earth pressure.

Zone 2: after shield passing (at tail gap); during shield passing, face pressures might still has effect but at tail gap it could be assumed as non support pressure or zero. However in real situation, magnitude of ground movements due to closure of the soil into the gap depend on time interval between after shield’s tail skin passed and before grouting, and mainly influenced by ground conditions.

Zone 3: during tail void grouting; grouting with high pressure is applied. The pressure occurs by grouting can cause outward movement around the surrounding ground based up on earth pressure. In this zone, the grouting pressure is assumed to be uniform radial pressure around a tunnel circumferential.

Mechanisms of EPB Shield clarify that every stages have a relationship with pressure. Hence, an appropriate analytical solution should analyze with stress that would be a major factor for estimating ground deformations. Additionally, surrounding pressure both vertical and horizontal pressure should be used an in-situ pressure or average pressure at a short interval distance of
shield driving. Typically, face pressure and grouting pressure obtained from shield operational collection system. The vertical and horizontal pressure can be estimated by a simple calculation as noted in Fig. 3.

![Fig. 3. Vertical and horizontal pressure calculation and notation](image)

As described in the previous section, it was clarified that radial contractions and ovalization were proposed by [9] based on stress-strain function appropriate to incorporate with shield’s 3-zones mechanism analysis. The ground deformations are estimated by this new approach can calculate simply by using two main factors that are ground loss and ovalization. The ovalization should be calculated only one time because it was not related with operational parameters. Therefore, the expression for calculating ovalization was not necessary to change. On the other hand, ground loss or radial contraction will be calculated into three times with three difference operational parameters in each zone. The new expressions for calculating the radial contractions are:

\[
\varepsilon_{\lambda} = \frac{\sigma (1 + K_0) - 2\lambda}{4G}
\]

(1)

\[
\varepsilon_{\sigma} = \frac{\sigma (1 + K_0)}{4G}
\]

(2)

\[
\varepsilon_{\beta} = \frac{\sigma (1 + K_0) - 2\beta}{4G}
\]

(3)

The ovalization expression is:

\[
\delta = \frac{\sigma}{2G} \frac{1 - K_0}{2} (3 - 4\mu)
\]

(4)

Where,

- \(\varepsilon_{\lambda}\) = Radial contraction induced by face pressure
- \(\varepsilon_{\sigma}\) = Radial contraction at non support pressure
- \(\varepsilon_{\beta}\) = Radial contraction induced by grouting pressure
- \(\delta\) = Ovalization
- \(\lambda\) = Face pressure
- \(\beta\) = Grouting pressure
- \(\sigma\) = Total earth pressure
- \(K_0\) = initial lateral stress coefficient in total stress
- \(\mu\) = Poisson’s ratio
- \(G\) = Shear’s Modulus
  \[G = \frac{E}{2(1+\mu)}\]
- \(E\) = Ground’s Modulus
By observation from field measurement and behavior of ground movement induced by EPB shield tunneling represent that the inward ground movements occurred above tunnel crown level but moved outward at the tunnel springline level. Therefore, it can be assumed that the sink source point locates at a gap around the upper part of a tunnel or at the tunnel crown. As a result, the maximum inward ground movement would occur above the tunnel crown level. To simulate this phenomenon into zone 2, the sink source point (normally is located at tunnel center) was shifted to the tunnel crown corresponding to the model test conducted by [2].

The final displacement field due to radial contractions and ovalization for estimating ground deformation in each direction of ground movement can be expressed as:

1) Improved [10] (Method 1)

\[ u_z = -\varepsilon_R R \left( \frac{x}{r_c^2} \right) + 2 \varepsilon_R R \left( \frac{(m+1)z}{r_c^2} \right) \]

\[ u_x = -\varepsilon_R R \left( \frac{x}{r_c^2} \right) + 2 \varepsilon_R R \left( \frac{1}{r_c^2} \right) \]

2) Improved Sagaseta (1998) (Method 2)

\[ S_z = -\varepsilon_s a^s \left[ \frac{1}{r_1^2} + \frac{1}{r_2^2} \right] - 4 x^2 z \frac{1}{r_2^2} + \delta a^s \left[ \frac{x^2 - z^2}{r_1^4} + \frac{x^2 - z^2}{r_2^4} \right] \]

\[ S_x = -\varepsilon_s a^s \left[ \frac{1}{r_1^2} + \frac{1}{r_2^2} \right] - 4 x z \frac{1}{r_2^2} + \delta a^s \left[ \frac{x^2 - z^2}{r_1^4} + \frac{x^2 - z^2}{r_2^4} \right] \]

Where \( z_1 = (z - h) \), \( z_2 = (z + h) \), and \( r_1 \) and \( r_2 \) are the distances to the sink and its image, respectively. The prime (‘’) denotes that the level of tunnel depth \( h' = h - a \), \( a = \) tunnel radius) is decreased to the tunnel crown level for simulate the sink source point in zone 2. Additionally, the expressions can be estimated ground movement separately for investigation in each distinct zone.
4. Case study and result

The application of this research was compared with field measurement obtained from MRTA Blue Line Project and MWA Water Supply Transmission Tunnel Project. The field data are obtained from geotechnical instrumentation and shield operational collection system. In Fig. 4.(a) and Fig. 4.(b), the tunnels are located within different soil conditions, the surface settlements were compared with shield’s 3-zones mechanism analysis by using Eq. (5) and Eq. (7). Estimated surface settlements trough match the field measurements well. The magnitude of surface settlement depended on operational parameters which are face pressure and grouting pressure as explained earlier.

In Fig. 5.(a) and Fig. 5.(b), lateral deformations measured at the field were compared with that determined by shield’s 3-zones mechanism analysis using Eq. (6) and Eq. (8). The measured data were obtained from the movement of the inclinometer in each level. The characteristic of lateral ground movement indicates that ground movement at upper tunnel crown zone moved toward the tunnel and ground movement at lower tunnel crown zone moved outward the tunnel. The measured data and estimated data are in a good agreement with each other as they have similar shapes. It was also proved that the characteristic and magnitude of ground movement depended on operational parameters.

![Fig. 4](image-url)

**Fig. 4. Measured surface settlements compared with 3 zones analysis**

Furthermore, this research studied the ground deformation in each zone separately as shown in Fig. 6 (only MRTA Blue Line Project’s field data compare with method 2 are shown) which investigation section of surface settlement and lateral deformation are located at the same place and can be compared together with each operational parameter in three distinct zones. In Fig. 6., section IN-T7-04 (lateral deformation data) and CS-7C (surface settlement) were compared and radial displacement was also investigated to examine the direction of ground movement. In “Zone
1" the surface settlement has a moderate downward movement. The lateral deformation has a little inward movement in all depth but the movement is reduced at the tunnel level, which is observed by radial displacement that has an inward movement in vertical direction and outward movement in horizontal direction. In “Zone 2" the surface settlement has more downward movement than “Zone 1" as the lateral deformation has an inward movement to the tunnel in all depth, which is observed by radial displacement that has an inward movement in all direction. In “Zone 3" the surface settlement has an upward movement due to high grouting pressure. The lateral deformation has an outward movement from the tunnel and maximum outward movement at tunnel springline level and the radial displacement moved outward in all direction. The combinations of 3-zone movements were calculated as shown in the Fig. 6.(c) Zone 3.

Fig. 5. Measured lateral deformations compared with 3 zones analysis

Fig. 6. Ground movements in each zone (a) Zone 1, (b) Zone 2, (c) Zone 3
5. Summary and conclusions
This research indicated that actual ground movements induced by EPB shield tunneling and predicted ground movements by analytical solution should be considered based on stress – strain function on the whole surrounding ground. The solution suggested by Sagaseta (1998) is based on stress – strain function that is the appropriate analytical solution. To make a better solution, it can be improved by shield’s 3-zones mechanism analysis introduced in this paper. The new approach can apply shield operational parameters into the solution. This makes it more realistic and surface settlements can be calculated separately into three distinct zones. The ground movement induced by EPB shield tunneling can affect existing nearby structures. Therefore, all of the measurement data both obtained from geotechnical instrumentation and shield operational collection system are more important to study the behavior of ground movements due to EPB shield tunneling and to provide the appropriate method for predicting ground deformation. The characteristic of ground movements obtained from field measurement corresponding to ground conditions and shield operational parameters were clarified. The new approach namely “shield’s 3-zones mechanism analysis” was obtained and used in this paper can prove that it was the optimum solution for predicting ground deformation induced by EPB shield tunneling with a simple technique, fast using and calculation within only one step.

References