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# Simulation of Surface Settlement Induced by Parallel Mechanised Tunnelling

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**Abstract:** Mechanised tunnelling is extensively utilised for twin tunnel construction, particularly in urban areas. A common challenge encountered during this construction method is the occurrence of surface settlement (SS) induced by tunnelling activities. The integrity of nearby structures can be compromised by SS, making it imperative to accurately quantify and mitigate this phenomenon. Several methods for determining SS exist, including empirical formulas and laboratory studies. However, these methods are often constrained by specific soil types and are time-consuming. Moreover, crucial parameters such as tunnel operational factors and construction stages are often omitted from empirical formulas. Given these limitations, this paper aims to address these challenges by employing 3D numerical analysis to simulate tunnelling-induced SS in twin tunnels. This approach takes into account tunnel geometry, construction sequencing, soil properties, and tunnelling operational factors. By incorporating data from in-situ and laboratory tests conducted on the ground, engineering soil parameters are established as inputs for the numerical analysis. The simulated SS results obtained from the 3D numerical analysis are compared with field measurements of SS taken from available ground surface settlement markers. The transverse SS pattern derived from the numerical analysis closely mirrors the field measurements. Additionally, SS values above the first and second tunnels are compared with field measurements, resulting in coefficient of determination ($R^2$) values of 0.94 and 0.96, respectively. The utilisation of the 3D numerical modelling approach enables the customizable mitigation strategies for managing the SS with project-specific parameters such as tunnel geometry, geotechnical engineering factors, and tunnelling operational variables. This will help plan and construct more sustainable tunnels with minimal effects on the ground and residential areas.

**Keywords:** twin tunnels; 3D numerical analysis; surface settlement; field measurement; geotechnical and geological conditions



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## 1. Introduction

Tunnelling is one of the most significant transport solutions where the overlying population does not need to be displaced. With the advancement of current technologies, mechanised excavations to construct underground spaces such as tunnels have become popular. Although mechanised tunnel excavations have been widely used all around the world, considerable safety considerations during construction need to be ensured. Several problems can be encountered during tunnel excavations, such as tunnel face instability, excessive wear of the cutter head, and excessive surface settlement (SS) [1,2]. Among them, SS induced by mechanised tunnelling is still one of the common issues in tunnel construction [3,4]. The excessive SS during and after tunnelling projects has an adverse impact on the existing structures. Therefore, it is important to estimate the settlements caused by the tunnelling to minimise the effects on the existing structures. Several methods can be used to estimate the SS due to tunnelling, which is empirical or semi-empirical, laboratory-based, and numerical analysis. One of the pioneer empirical formulas to determine the SS due to tunnelling was proposed by Peck [5], which shows that the volume loss is from the radial deformations along the tunnel perimeter directly linked to the SS. Based on the field observations on the site and the simplification of the equation proposed by Litwiniszyn [6], Peck [5] suggested Equation (1) to predict SS induced by tunnelling for soft clay. The settlement in this equation is calculated based on the pattern of SS caused by loss of ground and approximated by a Gaussian probability curve.

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

where $S$ is the surface settlement in the transverse section at a specific distance, $x$ is the distance from the centreline of the tunnel, and $i$ is the point of inflection (settlement through). In this way, the maximum SS can be defined using Equation (2):

$$S_{max} = \frac{V_s}{\sqrt{2\ x\ \pi\ x\ i}} \quad (2)$$

where $V_s$ is the volume loss of the soil ($m^3/m$), and can be expressed by Equation (3):

$$V_s = \frac{Volume\ Loss\ (VL)(\%)}{100}\left(\frac{\pi\ D^2}{4}\right) \quad (3)$$

The main inputs for the calculation of the maximum SS are affected by volume loss of the soil (VL) and settlement trough. These volume losses are affected by the type of ground, tunnel geometry, and ground condition [7,8]. Hence, many researchers have carried out their investigations into different types of ground conditions with various ranges of VL, as summarised in Table 1. In addition, several researchers have also proposed various $i$ equations for different ground conditions, as presented in Table 2.

**Table 1.** Tunnelling methods with various ground conditions of VL.

| Author (s) | Ground Condition | VL (%) | Method of Tunnelling |
|---|---|---|---|
| Attewell and Farmer [9] | London clay | 1.44 | Hand excavation shield tunnelling |
| O'Reilly and New [10] | London clay | 1.0–1.4 | Open face shield-driven tunnels |
| Mair and Taylor [11] | Stiff clay<br>Stiff clay<br>Sand<br>Soft clay | 1.0–2.0<br>0.5–1.5<br>0.5<br>1.0–2.0 | Open face method<br>NATM<br>Closed face Tunnelling Boring Machine<br>Closed face Tunnelling Boring Machine |
| Wan et al. [12] | London clay | 0.8 | Earth Pressure Balance Machine (EPBM) |
| Amir and Mohammad [13] | Graded gravel to silt/clays | 0.2–0.7 | EPBM |
| Le et al. [14] | Sandy | <0.2 to 2.4 | EPBM |

**Table 2.** Summary of empirical formulas for estimation of settlement trough width.

| Authors | Empirical Formula | Variable Definition | Ground Condition | Tunnelling Excavation Method |
|---|---|---|---|---|
| Peck [5] | $i = R\prime\left(\frac{Z}{2R\prime}\right)^n$ | $R'$ is the radius of the tunnel.<br>$Z$ is the tunnel depth below ground level.<br>$n$ is a constant parameter dependent on soil type (0.8–1). | Various types of soils | Open cutting excavation |