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Response of the ground and adjacent buildings due to tunnelling in completely weathered granitic soil

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ABSTRACT

The excavation induced ground movements and their impact on adjacent buildings is one of the major concerns for tunnelling in urban areas. This paper presents a case study on the response of the ground and a group of buildings to the construction of a sprayed concrete lining (SCL) subway twin tunnel through completely weathered granitic residual soil in Shenzhen, China. Ground and nearby structures displacements were monitored through extensive field instrumentation. The observed maximum surface settlements exceeded 400 mm, which caused considerable damage to certain buildings. Potential risks of large ground deformation for tunnelling in similar ground condition, with structures nearby, are highlighted. Encouraging effectiveness of the permeable grouting on this ground condition was demonstrated by the distinct Greenfield behaviour at the two monitoring sections. Different responses between Greenfield ground and adjacent structures show an evident soil structure interaction. Piled reinforced concrete frame buildings were found to behave rigidly in response to the tunnelling induced ground movement and to be without visible crack in contrast to masonry wall structures.

1. Introduction

Tunnel construction induces ground movements which consequently may impact buildings or services in the vicinity. In recent years, the estimation of such building response became important in both the phase of design and construction of tunnels in urban areas. Other important considerations along with such estimations are the ground behaviour, structure distortion as well as the soil-structure interaction. Reliable direct prediction and assessment is difficult as it is affected by a variety of factors; e.g. geology, geometry and the construction method as well as the complexity of the nearby structures.

Excavation induced ground movements usually result from stress relief and changes in water pore pressure in the ground. These deformations can propagate to the ground surface thereby forming the surface settlement trough. Empirical method is widely used in the estimation of Greenfield ground movements to fulfil the design requirements. Here Greenfield refers to undeveloped land surface without any buildings or structures. Such method enables the Greenfield ground movement to be relatively well understood and calibrated based on case histories (Peck, 1969; O'Reilly and New, 1982; Attewell et al., 1986; Mair et al., 1993). The surface settlement trough above a tunnel usually can be represented by an invert Gaussian distribution curve of the form shown in Eq. (1).

$$S_x = V_s/(i\sqrt{2\pi})\exp\left(-x^2/(2i^2)\right) \quad (1)$$

where S_x is the vertical components of ground movements at the transverse distance x from the tunnel centre line; $S_{(\max,z)}$ is the maximum surface settlement at $x = 0$; V_s is the settlement volume expressed as a percentage of the tunnel volume excavated per unit advance in terms of ground loss; and i is the distance from the tunnel centre line to the point of inflexion related to the ground condition. The parameter i has a strong linear correlation with the tunnel depth (O'Reilly and New, 1982), and can be simplified to the form

$$i = kz_0 \quad (2)$$

The horizontal displacement can be approximated by assuming a direct relationship to the vertical settlement, in the form of

$$H_x = S_x(x/z_0) \quad (3)$$

where z_0 is the depth of tunnel axis.

For twin tunnels constructed close together, however, many authors reported an increase in volume loss for the second tunnel comparing with the first tunnel (Peck, 1969; Mair et al., 1996; Addenbrooke and Potts, 2001; Chapman et al., 2004). Peck (1969)

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pointed out this increase but also argued that if the twin tunnels are sufficiently close, the settlement profile over twin tunnels is likely to be a single symmetric settlement trough and the Gaussian curve could still be applicable for describing the settlement trough. Mair et al. (1996) indicated that for twin tunnels in close proximity, simply summation of the profiles calculated separately using the empirical method might be conservative. A method of incorporating these considerations was proposed by Chapman et al. (2004) given as

$$S_x^{\text{mod}} = \left(1 + \left(M\left(1 - \frac{|d' + x|}{aKz_0}\right)\right)\right)S_x \tag{4}$$

where M is a modification factor (typically 0.6); a is a multiple of i to make a half trough width (typically 2.5–3); k is the trough width parameter for the first tunnel and d' is the spacing between the tunnels axes (a negative value for distance on the left hand side of the second tunnel). The superposition of the separately calculated ground movements above the first and second tunnel can be applicable (Mair et al., 1996; Chapman et al., 2004). Moreover, for tunnelling in completely weathered granitic residual soil in Shenzhen area, local case record reported by Zhang and Huang (2004) shows that the trough width parameter k is about 0.47, and the transverse spread of the settlement trough is approximately 8i, which is larger than the empirical value (about6i) given by Rankin (1988).

Ground movements propagate to the adjacent building foundation leading to the effect of tunnelling on buildings to be an interactive problem. Many cases have been studied with field observations to correlate tunnelling induced ground movements with its associated building response (Breth and Chambosse, 1974; Frischmann et al., 1994; Forth and Thorley, 1995; Mair and Taylor, 2001; Dimmock and Mair, 2008; Farrell et al., 2011). Generally, the settlement induced building damage can be evaluated from the deformation parameters such as deflection ratio and horizontal strain (Burland and Wroth, 1974). These parameters can be calculated from tunnelling induced Greenfield ground movements via modification factors. Such modification factors were defined to account for the effects of soil–structure interaction on building settlement and axis response (Potts and Addenbrooke, 1997; Franzius et al., 2006). The deflection ratio should be separately modified from sagging and hogging part of the settlement profile, while the horizontal strain should be modified in compression or tension mode. This existing tool can predict building deformation in good agreement with field observations (Mair and Taylor, 2001; Dimmock and Mair, 2008; Farrell et al., 2011), but most of these studies were undertaken for masonry structures.

However, the mechanism of tunnel–soil–building interaction is still not fully understood. The effects of building foundation such as piles and strip footing on the soil deformation were not resolved. There is always a great need for valuable field measurement, particularly for cases where tunnels have to be constructed close to structures being constructed with reinforced concrete (RC) and being piled.

This paper presents the characteristics of ground movements due to tunnelling in completely weathered granitic residual soil and the investigation of behaviour of adjacent buildings in response to large ground settlement. Extensive field measurements were taken from the construction of a selected twin tunnel episode of the Shenzhen Metro Line 5 project in China (Shenzhen-Standard, 2010). The construction consists of twin tunnels excavated under congested area with a nearby group of reinforced concrete buildings. The two tunnels are oval shaped and have an equivalent diameter of 6.4 m each. The axis of each tunnel is 15.6 m below the ground surface level, with a centre line separation of 13.2 m between them. Six reinforced concrete frame buildings are situated on the southern side of the twin tunnels. Their eccentricities vary in the transverse direction with respect to the southern tunnel centre line. Relative positions and specific information of the buildings are shown in Fig. 1 and Table 1.

2. Ground conditions

Field exploration was undertaken prior to the construction. The twin tunnels are located in Shenzhen area where a typical type of weathered granitic residual soil is widely distributed. The twin tunnels were excavated in weathered granitic residual soil (gravelly clay) which is overlain by sandy silty clay followed by plain fill up to the ground surface. Completely weathered granite (clayey sand with gravel) lies beneath the tunnel invert (deeper than 20 m), and the degree of weathering decreases with depth. The ground profiles of the two instrumented transverse sections are shown in Fig. 2. Site investigation shows that the weathered granite residual soil is dark reddish brown and has proven to be very easily disintegrated by loading or by immersion in water.

The weathered granite residual soil, where the twin tunnel is excavated, contains 25–30% quartz gravels coarser than 2 mm and 50–60% fines. Unweathered boulders (diameter 0.3–0.6 m) were also found in this soil layer. Approximate average value of water content w_c = 28.6%, specific gravity G_s = 2.66 and saturation ratio S_r = 84.7% led to void ratio of e = 0.9. The ground water table was found approximately 4.5–5.5 m below ground level for the studied area. Drainage in the underlying weathered granite indicates that the underground conditions are not hydrostatic. Results from in-situ pumping tests indicate that the permeability of the completely weathered residual soil formation lies between 10^{-5} and 10^{-6} due to relatively higher coarse contents, while sandy silty clay results in low permeability between 10^{-7} and 10^{-8} due to higher fine contents (greater than 70%).

Results from SPT test (N_{60}) indicate that for I_P = 19% the undrained shear strength (c_u) at the tunnel axis (z_0) is around 165 kPa using the correlation proposed by Stroud (1989) in Powrie (1997). The undrained soil stiffness (E_u) is estimated from undrained shear strength following the correlations given by Duncan and Buchignani (1976), E_u = 800c_u for I_P < 30%. This gives E_u at the top of the weathered granitic residual soil (approximately $z_0/2$) to be about 96 MPa. The E_u of the sandy–silty clay and plain fill was estimated to be about 66 MPa and 44 MPa, respectively. The estimation of ground conditions is made similar to Farrell et al. (2011).

3. Construction techniques

Due to the mixed ground conditions and the presence of un-weathered boulders, the two tunnels were designed and constructed using the New Austrian Tunnelling Method (NATM). The cross section and the support system of the two tunnels and the excavation sequences are shown in Fig. 3. Each tunnel face was excavated in four steps and was sequentially supported with reinforced shotcrete. The first step is the excavation of the top heading (portion 1) leaving behind the central core (portion 2) for supporting the tunnel face. The top heading was excavated with a round length of 0.5 m and was then supported with reinforced shotcrete. After removing the top central portion, the upper part (portion 1 and 2) was closed as a loop with temporary shotcrete which was approximately 1–1.5 m behind the face. Then the lower part (portion 3 and 4) was excavated and supported sequentially with a round length of 2 m.

During the construction, the top heading of each tunnel face was advancing 10 m ahead of the invert bench, while the face of the northern tunnel (NT) was being excavated 25 m in advance to the southern tunnel (ST) face. In order to increase the speed of