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Three-dimensional numerical parametric study of the influence of basement excavation on existing tunnel

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ABSTRACT

For the convenience of shoppers and users, there is an increasing demand for construction of basements in close proximity to existing tunnels. To ensure the safety and serviceability of existing tunnels, many numerical analyses have been conducted to investigate the basement–tunnel interaction. However, most of previous studies have simplified the complex interaction as a plane strain problem and often they have overlooked effects of stress path and strain dependency on soil stiffness. In this study, three-dimensional numerical parametric study is conducted to explore the complex interaction in dry sand by using an advanced hypoplastic soil model. The validity of the soil model and soil parameters is calibrated and verified by centrifuge test results. Parameters considered on tunnel responses by overlying basement excavation include excavation geometry, sand density, tunnel stiffness and joint stiffness. It is found that the basement–tunnel interaction at basement centre reaches a plane strain condition when excavation length along the longitudinal tunnel direction is longer than 9 H_e (final excavation depth). Both heave and transverse tensile strain of tunnel exceed the allowable movement limit and cracking strain when excavation length is longer than 5 H_e and excavation width is wider than 2 H_e. At a given excavation area on plan, the longer side of basement should be perpendicular to the longitudinal tunnel direction to reduce excavation induced adverse effects on existing tunnel. Because a looser soil has smaller stiffness around the tunnel, tunnel heave and tensile strain at basement centre are increased by up to 90% and 80%, respectively, when relative sand density decreases from 90% to 30%. By increasing tunnel stiffness 100 times, induced maximum tunnel heave and tensile strain are reduced by up to 75% and 85%, respectively. This means that stiffening a tunnel can be an effective way to alleviate excavation induced adverse effects on existing tunnel. Induced tunnel heave and tensile strain at basement centre are insensitive to the presence of tunnel joint unless the joint stiffness is less than 30% of the lining stiffness.

1. Introduction

Underground construction can not only meet the demand of usable floor areas but also reduce environmental impacts. For the convenience of shoppers and users, there is a huge demand for construction of deep basements in close proximity to existing tunnels [1–4]. Construction of basement inevitably causes stress changes in the ground leading to soil movements which may cause potential damages to adjacent tunnels. Thus, it is essential for designers and engineers to assess excavation induced movement and tensile strain in existing tunnels.

To ensure the safety and serviceability of existing tunnels, attention was paid to the basement–tunnel interaction via case history [1,5,6] and centrifuge modelling [4,7–9]. Due to time and budget constraints, it is not realistic to conduct extensive field and/or centrifuge tests to investigate the influence of basement excavation on nearby tunnels. Alternatively, many numerical studies have been conducted to investigate tunnel responses by nearby basement excavation [2,3,8,10–15].

Very often, deep excavations impose unsymmetrical stress relief and movement to existing tunnel not only along its transverse but also longitudinal directions. However, the basement–tunnel interaction was often simply assumed as a plane strain problem in previous numerical studies [2,10–14]. Moreover, a linear elastic and perfectly plastic model was normally adopted to simulate soil responses in those studies. Due to corner effects in

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a short and narrow excavation, three-dimensional deformation mechanisms were observed in the ground and retaining wall. Thus, excavation induced tunnel responses at basement centre may not correspond to those of a plane strain condition. It is not uncommon to encounter that excavation length along the longitudinal tunnel direction was less than two times the final excavation depth [3,4,15,16]. If the basement–tunnel interaction at the centre of a short excavation was assumed as a plane strain problem, induced tunnel responses may be significantly overestimated.

Three-dimensional numerical parametric analyses were conducted to investigate the basement–tunnel interaction using the Hardening Soil (HS) model to simulate soil responses [15]. Effects of cover-to-tunnel diameter ratio, excavation geometry and tunnel diameter on the interaction were explored. It is well-known that soil stiffness is not only stress path dependent but also strain dependent [17,18], but the HS model is unable to capture effects of strain and stress path dependency on soil stiffness.

By conducting a preliminary three-dimensional numerical parametric study, the influence of cover-to-tunnel diameter ratio on the tunnel heave by overlying basement excavation was investigated [8]. Sand behaviours were simulated by an advanced hypoplastic sand model, which can capture the effects of strain and stress path dependency on soil stiffness. The tunnel heave induced at basement centre was found to decrease with an increase in cover-to-tunnel diameter ratio, but at a reduced rate.

Despite much attention paid to the basement–tunnel interaction, most of previous studies have simplified the complex interaction as a plane strain problem and often they have overlooked the effects of stress path and strain dependency on soil stiffness. Moreover, tunnel lining was normally assumed as a continuous structure in previous studies. However, a shield tunnel in reality is composed of several concrete pieces bolted together by steel bolts in both circumferential and longitudinal directions. To address those shortcomings, extensive three-dimensional numerical analyses were thus conducted in this study to investigate the complex interaction in dry sand by using an advanced hypoplastic soil model. It started with calibration and verification of the soil model and model parameters by using measured results of a centrifuge test. Three-dimensional numerical parametric study was then conducted to systematically investigate the influence of excavation geometry, sand density, tunnel stiffness and joint stiffness on tunnel responses by overlying basement excavation. Finally, all the computed results were summarised into calculation charts for direct estimation of excavation induced heave and tensile strain in existing tunnel.

2. Three-dimensional centrifuge modelling

Before conducting any numerical parametric analyses, adopted soil model and its parameters were calibrated and verified by results of a published centrifuge test [8]. This test was conducted in dry Toyoura sand at a gravitational acceleration of 60g. By adopting pluvial deposition method, obtained average dry density of sand was 1542 kg/m^3, corresponding to a relative density (D_r) of 68%.

Both model wall and tunnel were assumed to be wished-in-place in the test. A basement with a length (L) of 18 m, a width (B) of 18 m and an excavation depth (H_e) of 9 m in prototype was constructed directly above an existing tunnel in sand. The penetration depth of retaining wall was designed as 0.5 times the final excavation depth. In-flight excavation was simulated by draining away heavy fluid placed inside the basement. Four aluminium sheets with thickness of 12.7 mm in model scale were used to simulate retaining wall. As reported by many researchers in the literature [19–22], the moduli of elasticity of reinforced concrete ranging from 30 to 35 GPa were chosen. By taking the Young's modulus of reinforced concrete as 35 GPa, adopted aluminium sheet was equivalent to 0.96 m thick concrete wall in prototype.

An aluminium alloy tube with a diameter (D) of 6 m and a thickness (T) of 0.18 m in prototype was used to simulate the existing tunnel. Assuming the Young's modulus of concrete as 35 GPa, this aluminium tube had the equivalent longitudinal and transverse stiffness as 420 mm and 230 mm thick slabs of concrete in prototype, respectively. The cover-to-tunnel diameter ratio (C/D) was 2, giving the initial tunnel cover depth (C) of 12 m in prototype. Moreover, the distance between the tunnel crown and the formation level of the basement was designed as 3 m (0.5 D) in the test.

A row of linear variable differential transformers were installed at the crown to measure heave induced in the tunnel along its longitudinal direction. Full-bridge strain gauges were attached to measure the bending moments induced in the tunnel along its transverse and longitudinal directions. Based on the measured bending moment and flexural stiffness of the model tunnel, induced strain in the tunnel could be deduced. More details of the centrifuge test can be found in a previous study [8].

3. Three-dimensional numerical analysis

By using the software package ABAQUS [23], three-dimensional numerical analyses were conducted to investigate the basement–tunnel interaction. Based on a dimensional analysis of the complex interaction [8], governing dimensionless groups affecting the interaction problem were summarised into five groups, i.e., excavation geometry, tunnel location with respect to a basement, stiffness of retaining system, relative tunnel-soil stiffness and soil properties. In this study, the effects of excavation geometry, sand density, tunnel stiffness and joint stiffness on tunnel responses by overlying basement excavation were examined.

3.1. Numerical analysis program

Eighty-four numerical runs in total were performed to investigate the basement–tunnel interaction in dry sand, as summarised in Table 1. In all the analyses, the existing tunnel was located directly underneath basement centreline. When the final excavation depth (H_e) was 9 m, excavation length (L) and excavation width (B) were varied from 18 m (2 H_e) to 90 m (10 H_e) and 9 m (1 H_e) to 54 m (6 H_e), respectively, to explore the influence of excavation geometry on tunnel responses. To study the effects of soil density on tunnel responses by basement excavation, four relative sand densities (i.e., 30%, 51%, 68% and 90%) were considered when the cover-to-tunnel diameter ratios (C/D) were equal to 2.0 and 3.0. Moreover, flexural stiffness of tunnel along its longitudinal direction was varied from 9.76×10^4 to 9.76×10^6 MN m^2 (in prototype) to investigate the influence of tunnel stiffness on the basement–tunnel interaction. By assuming the Young's modulus of reinforced concrete as 35 GPa, adopted flexural stiffness was equivalent to a tunnel with diameter and lining thickness varying from 3.51 m to 11.1 m, and 0.194 m to 0.614 m, respectively. Effects of joint stiffness on tunnel responses by overlying basement excavation were also investigated in this study. The typical range of joint stiffness ratios (i.e., η = joint stiffness/lining stiffness) for subway and highway tunnels constructed in soft ground generally lies between 0.03 and 0.3 [24]. In order to obtain a better understanding of the influence of joint stiffness on the complex basement–tunnel interaction, a wider range of joint stiffness ratios (i.e., 0.01, 0.05, 0.1, 0.3, 0.5, 0.7 and 1.0) was therefore adopted in this study.