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Interaction between tunnelling and bridge foundation—3D numerical investigation

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ABSTRACT: This paper presents the results of three-dimensional numerical investigation on the interaction between conventional tunnelling and a pile supported bridge. A hypothetical tunnelling condition under an existing pile supported bridge was first developed with due consideration of urban tunnelling situation. Various components of the bridge including piers, piles, and pile caps are realistically modeled. Also included in the model is the pile-ground interface to simulate possible slip between the piles and the ground during tunnelling. The results of the analysis indicate that during tunnel driving, piles directly above the tunnel experience significant loss of their supporting capacity due to downward settlements of piles relative to surrounding soil. Piles further away from the tunnel however tend to experience increases in the pile load. Practical implications of the findings are discussed.

1 INSTRUCTIONS

Due to continued urban population growth, there has been a pressing need for expansion of infrastructures for transportation. Going underground has become a viable option for expansion of transportation due largely to environmental consideration. During urban tunnelling, there are many cases where a tunnel is constructed under existing pile-supported buildings or a bridge. As typical urban tunnelling situations involve unfavorable ground conditions, the effect of tunnelling on any existing structures is considered of prime design and construction issues.

There have been a number of studies concerning tunnelling under an existing pile(s) (Vermeer and Bonier 1991, Chen et al. 1999, Lee and Ng 2005, Lee and Jacobsz 2006, Lee and Yoo 2006, Cheng et al. 2007). Although these previous studies have identified important governing mechanism relevant for the effect of tunnelling on an existing pile(s), most of the studies are based on idealized tunnelling situations or simplified plane strain approximations.

In this paper, the results of a three-dimensional numerical investigation into the conventional tunnelling under an existing pile supported bridge are presented, aiming at identifying the fundamental governing mechanism of the effect of tunnelling on the stability of the bridge, in terms of settlements and load carrying capacity of piles. A hypothetical tunnelling situation was developed and a three-dimensional finite element model was constructed in order to attain meaningful results that can be extended to similar tunnelling works in urban environment. A particular attention was paid to the modelling of the pile-ground interface so as to allow for realistic simulation of the soil-structure interaction. The following sections present the tunnelling and site conditions, the 3D finite-element model, and finally, practical implications of the findings.

2 TUNNELLING CONDITION AND FINITE ELEMENT MODELING

2.1 *Tunnelling condition*

A hypothetical tunnelling condition in which the tunnel is excavated under a four lane roadway bridge is considered as shown in Figure 1. For simplicity, it was assumed that the direction of tunnel driving is perpendicular to the axis of the bridge. A typical tunnel cross section in urban tunnelling was considered in this investigation. The tunnel has a maximum height and width (D) of 8.0 m and 11.0 m, respectively, giving the net excavation area of approximately 87 m^2.

It was assumed that the tunnelling is performed in a multi-layered ground consisting of a 14 m thick decomposed granitic soil with a thickness ranging 8.0~12.5 m below which a solid granitic rock layer is followed. No groundwater table is assumed to exist. In terms of the primary support pattern, the tunnel was assumed to be supported by a 200 mm thick shotcrete layer with a typical bench-cut excavation method. No rock bolts are considered in this study to simplify the model.

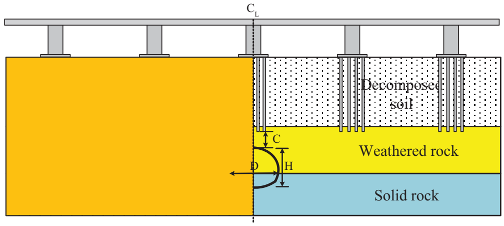

Figure 1. Schematic view of tunnelling condition.

The bridge is supported by piers having 20 m center-to-center spacing, each of which has a 1.5 m × 3.0 m cross section with eight, 15 m long, 0.5 m diameter steel piles, installed at 1.5 m centre-to-centre spacing. The clearance between the tunnel crown and the pile tip (C) is 1.5 m.

2.2 *Finite element modeling*

A three-dimensional (3D) finite element model was adopted in this study with due consideration of the three-dimensional nature of the tunnel-bridge geometry and the excavation condition. The analysis was carried out using a commercial finite element package Abaqus (Abaqus, Inc. 2007).

On account of the symmetry about the tunnel centerline, only 1/2 of the entire domain was included in the model. Figure 2 shows the finite element model, consisting of nearly 141,000 three-dimensional elements with over 218,000 nodes. In the analysis, the components of bridge structure, i.e., pier, pile cap, and piles, were explicitly modelled including the pile-soil interface. The bridge deck, however, was not included in the model but replaced with an equivalent surcharge corresponding to the body weight of the bridge deck.

The eight-node linear displacement elements with reduced integration (C3D8R) were used to discretize the ground and the piles while the linear quadrilateral shell elements (S4R) were used for the shotcrete lining. The pile-soil interface behavior was modeled using the contact pairs with appropriate frictional property. In terms of displacement boundary condition, the degree of freedom perpendicular to the vertical boundaries was restrained while pinned support was assumed at the bottom boundary.

The ground was assumed to be an elastic-plastic material obeying the Mohr-Coulomb failure criterion together with the non-associated flow rule by Davis (1968). The structural members of the bridge as well as the shotcrete lining were assumed to be an elastic material having Young's moduli of 23 GPa and 10 GPa, respectively, with a Poisson's ratio of 0.25. Table 1 summarizes the geotechnical properties of the ground.

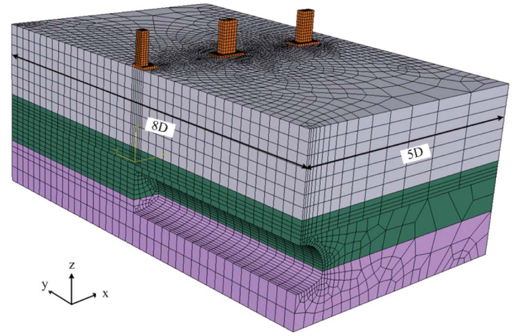

Figure 2. 3D finite element model.

Table 1. Material properties for soil and rock layers.

	Decomposed granitic soil	Weathered granite rock	Solid granite rock
γ^a (kN/m^3)	21	25	25
c'^b (kPa)	20	50	450
ϕ'^c (deg)	33	35	45
E^d (MPa)	60	200	1000
K_o^e	0.5	0.5	1.0
ν^f	0.30	0.25	0.25

[a]γ = total unit weight; [b]c' = cohesion; [c]ϕ' = internal friction angle; [d]E = deformation modulus; [e]K_o = lateral earth pressure coefficient; [f]ν = Poisson's ratio

3 BRIDGE RESPONSE TO TUNNELLING

3.1 *General*

The bridge response to tunnelling was examined using the results from the 3D FE analysis such as progressive changes of pile settlement and load. Figure 3 depicts the symbols used for the piles.

3.2 *Pile tip settlement and load*

The progressive development of pile tip settlements with the tunnel advancement for piles CP1, CP4, and CP6 are shown in Figure 4. As seen in Figure 4, the pile tip settlement S_v for CP1 starts to develop when the tunnel heading arrives at 2.0D away from the pile location. The pile tip settlement then increases approximately to $0.06\%D$ when the tunnel heading arrives immediately below the pile. Note that the pile settlement of $0.06\%D$ amounts to 50% of its final value, suggesting that any unprotected pile can experience 50% of its final settlement before the passage of tunnel heading. Further advancement of the tunnel heading rapidly increases the pile tip settlement until the tunnel heading reaches approximately 1.0D beyond the pile CP1. Due to remoteness of the piles CP4

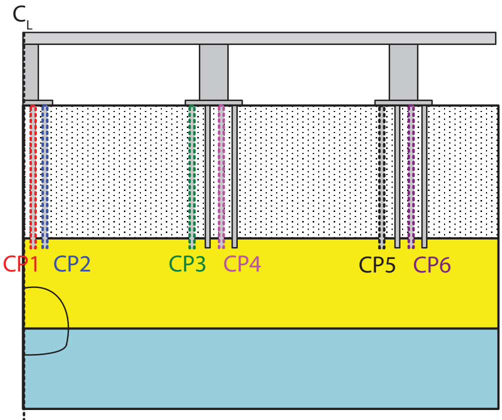

Figure 3. Notations used for piles.

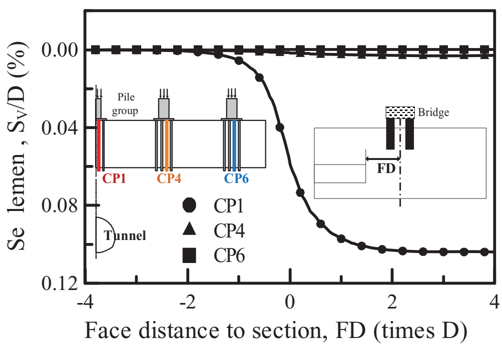

Figure 4. Progress development of pile tip settlements.

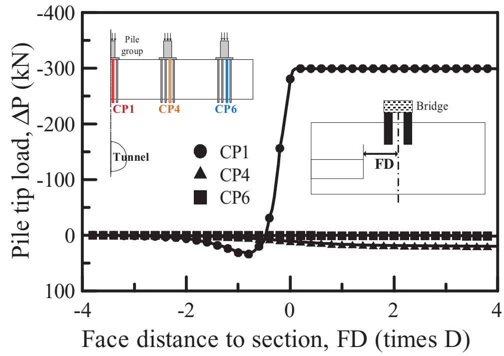

Figure 5. Progress development of pile tip load.

and CP6 from the tunnel, the pile tip settlements are negligible, i.e., less than $0.002\% D$.

Progressive changes in the pile tip load (ΔP_{tip}) with the tunnel advancement are shown in Figure 5. In this figure, the positive sign of ΔP_{tip} indicates an increase in ΔP_{tip} whereas the negative sign indicates a decrease in ΔP_{tip}. As expected, pile CP1 experiences significant changes during the tunnel advancement. For example, it is seen that the pile tip load gradually increases by 50 kN, or 24.5% from its initial load of 204 kN, until the tunnel heading reaches approximately –1.0D away from CP1. A sudden decrease in pile load then follows as the tunnel advancement is continued until the tunnel heading reaches immediately below the pile tip, resulting in a maximum decrease of 300 kN, or 147% of the initial value. No significant variation in ΔP_{tip} is seen after the passage of the tunnel heading beyond the pile CP1. The decrease in the pile load is in essence an indication that the pile loses its load supporting capacity during the tunnel advancement caused by the pile settlement as observed in Figure 4. Of interest trend is that most of the pile tip load reduction is completed before the tunnel heading passes the pile, implying the most critical stage being just before the tunnel passage in view of the bridge stability.

Piles CP4 and CP6, located further from the tunnel laterally, however show increases in ΔP_{tip}, although the magnitudes are not as significant, i.e., less than 50 kN. The increases in the pile load for CP4 and CP6 are likely caused by the downdrag of the surrounding soil as will be further discussed later in the section. The trends shown here are in good agreement with those reported by Yoo and Kim (2008) in which the performance of multi-faced tunnelling under a pile-supported building in water bearing soft ground is investigated.

3.3 *Pile axial load and relative settlement*

Figure 6 illustrates the changes in the axial pile load (ΔP) at various stages of tunnel excavation for piles CP1, CP4, and CP6. As shown for CP1, the axial load tends to decrease during the tunnel advancement, resulting in a maximum decrease as great as 500 kN, or 125% from the initial value, when the tunnel heading arrives 2.0D away from the pile. For CP4 and CP6, the axial loads along the pile shaft tend to increase somewhat, although the magnitudes of the increase are only minimal, i.e., less than 50 kN. As noted by Yoo and Kim (2008), for similar tunnelling situations considered in this study, whether or not pile load increases or decreases fully depends on the lateral location of a pile relative to the tunnel being considered. For example, a decrease in pile load is expected for piles located directly above the tunnel while a slight increase in the pile load should be expected for piles located laterally some distance away from the tunnel.

Normalized relative settlements (S_v/D) of the piles with respect to surround soil are shown in

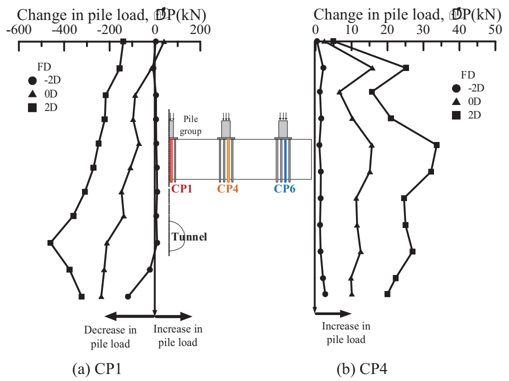

Figure 6. Change in pile axial load during tunnel advancement.

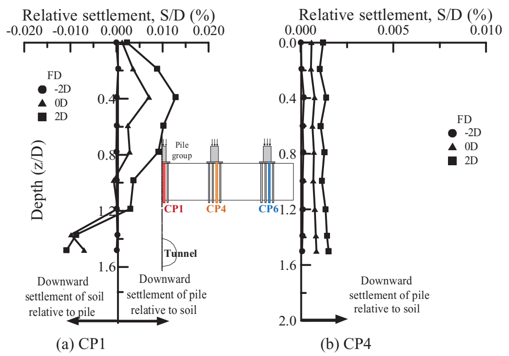

Figure 7. Relative settlement between piles and soil during tunnel advancement.

Figure 7 for various tunnelling stages. Note that a downward settlement of surround soil relative to pile is denoted by a negative S_v/D whereas the opposite sign i.e., positive, indicates that a pile settles more than surrounding soil. In terms of the pile load development, a negative S_v/D induces a negative skin friction (NSF) along the pile shaft while a positive S_v/D results in a positive skin friction (PSF) as indicated by Lee and Ng (2005). As shown in Figure 7(a) for pile CP1, negative as well as positive relative settlements are appeared to develop along the pile with a neutral point at the lower 1/4 of the pile length. For example, positive relative settlements, as great as $S_v/D = 0.013\%$, are developed in the upper 3/4 portion while negative relative settlements, as great as $S_v/D = 0.013\%$, are developed in the lower 1/4 portion of the shaft. In pile CP4, only positive relative settlements are developed but with 1/10 order of the magnitudes compared to CP1.

4 CONCLUSIONS

The results of a three-dimensional numerical investigation into the conventional tunnelling under an existing pile supported bridge are presented in this paper, aiming at identifying the fundamental governing mechanism of the effect of tunnelling on the stability of the bridge, in terms of settlements and load carrying capacity of piles. A hypothetical tunnelling situation was developed and a three-dimensional finite element analysis was carried out.

The results of the analysis indicate that during tunnel driving, piles directly above the tunnel experience significant loss of load due to downward settlements of piles relative to surrounding soil. Piles further away from the tunnel however tend to experience increases in the pile load. Also shown is that the most critical stage is just before the tunnel passage in view of the bridge stability as most of the pile tip load reduction is completed before the tunnel heading passes the pile.

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