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Use of minipiles to reduce ground subsidence due to tunnel excavation

Wai-Man Yan and I-Man Ho
Department of Civil and Environmental Engineering, University of Macau, Macau, China

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ABSTRACT

The use of tunnels in enhancing the dimensions in transportation network is very popular especially in highly developed urban areas. Nonetheless, historical buildings with shallow foundation can be seriously damaged due to the construction. The use of minipiles that installed between the building to be protected and the tunnel may be a feasible way to reduce the ground subsidence around the building owing to tunnelling. However, its effectiveness is not well understood yet. In this study, the tunnel-pile interactions were studied numerically by a series of preliminary three-dimensional fully-coupled finite element analyses. A tunnel construction was simulated in a hypothetic soft ground with minipiles installed wish-in-place prior to the excavation. Ground movements were investigated under various minipile densities. The results showed that even a pile wall with low pile density is able to reduce the ground movements noticeably.

1 INTRODUCTION

Macau, located in the estuary of the Pearl River in the southeast China, is well-known of its west-meet-east historical background. The Historic Centre of Macau clearly demonstrates the culture mixing and was listed as a World Heritage Site by UNESCO in July 2005. Besides, the city is experiencing its fastest development since the handover in 1999. The city is recently named as the 4th most congested city in the world by Forbes. Like many other major cities, underground development is being recognized as a common solution to alleviate the congestion in urban areas. However, any construction closed to the heritages should be highly caution and remains a great challenge to engineers, especially in Macau where the city is developed on a thick layer of soft marine clay. The use of minipiles to reduce ground movements owing to a nearby construction may offer a feasible solution to protect nearby buildings. However, its effectiveness remains uncertain.

Bilotta et al. (2006) performed a series of centrifuge tests at 160g to investigate the effectiveness of using minipiles to reduce ground movements induced by adjacent tunnelling. Their studies focused on the effect of pile spacing (s) on ground movements and provided useful insight on the problem. The piles were placed at a distance of 1.5D (D=diameter of the tunnel) from the tunnel-axis and the pile toe was located just below the tunnel invert level. Tunnel support pressure was reduced to simulate the excavation process until undrained failure. Based on their test results, an s/d (d=diameter of the minipile) ratio of 3.1 reduced the lateral movements around the piles by around 50% as compared to the no-pile case.

In the present study, preliminary numerical analyses were performed on a hypothetical soft ground to investigate the short term effect of minipiles on ground movements nearby a tunnel excavation.

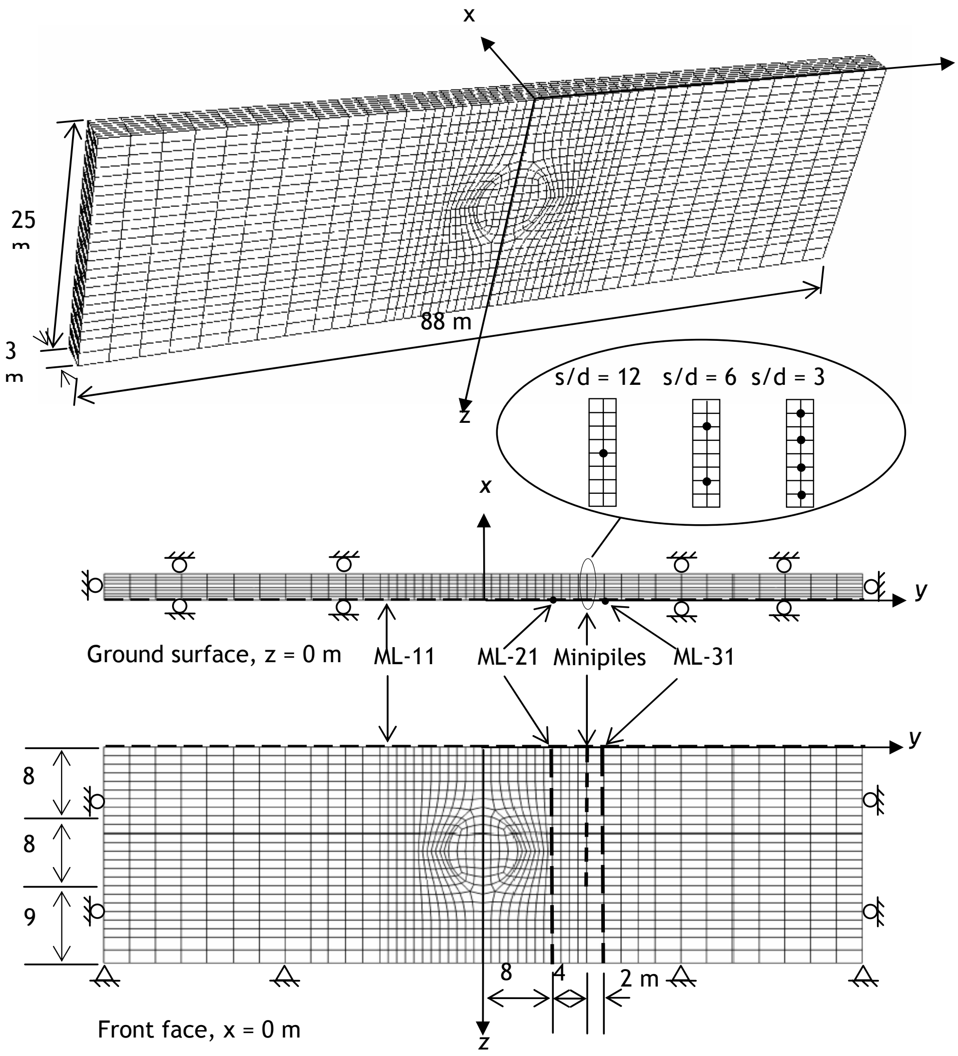

Figure 1: Finite element mesh adopted in the analyses

2 NUMERICAL MODELLING

2.1 Mesh, boundary and initial conditions

Tunnel excavation was simulated to be carried out in a hypothetical soft ground with minipiles pre-installed. Three-dimensional finite element program ABAQUS ver. 6.4 (Hibbitt, Karlsson and Sorensen, Inc. 2003) was adopted to perform fully-coupled analyses. The finite element mesh is shown in

Figure 1. A tunnel of 8 m diameter (D) was simulated to be constructed. The tunnel axis was located 12 m below the ground surface (i.e. a tunnel cover of 1D). A roll of 19 m long minipiles (pile diameter d = 0.25 m) was installed 1.5D away from the tunnel axis. Various minipile densities were simulated in the analyses. The mesh was 3 m (0.75D) long, 88 m (11.0D) wide and 25m (3.125D) high. Plane of symmetry in the x-direction was employed to reduce the size of the mesh. Geometry of the model was selected based on the aforementioned centrifuge tests (Bilotta et al. 2006). Roller boundaries were used along the vertical faces so that movement normal to the face was not allowed. Movements in all directions were fully restricted at the bottom of the mesh. The mesh consisted of 9,728 elements and 11,601 nodes. An earth pressure coefficient at rest (K_o) of 0.7 was adopted to simulate a slightly overconsolidated condition prior to tunnel excavation.

2.2 Finite elements and soil constitutive model

The soil was modelled by the 8-node isoparametric solid element with pore-pressure while the pile was modelled by the 2-node linear beam element. The soil was modelled by the modified Camclay (MCC) model and the pile was modelled as a linear elastic material. It should be noted that the conventional MCC model cannot truly represent the anisotropic yield surface of the soil in the field situation. However, as a preliminary study, the model was considered to be adequate. No soil-pile interface was modelled in the analyses. Model parameters are shown in Table 1.

Table 1: Input model parameters

Soil	
Void ratio (e) [i]	1.54
Poisson's ratio (υ)	0.2
Saturated density (ρ_{sat})	1.63 Mg/m^3
Earth pressure at rest (Ko)	0.7
MCC parameter: λ [ii]	0.122
MCC parameter: κ [ii]	0.022
MCC parameter: M [iii]	0.90
MCC parameter: p_o [iv]	200 kPa
Coefficient of permeability (k) [v]	1 x 10^{-4} m/day
Steel Pile	
Young's Modulus	200 x 10^6 kPa
Poisson's ratio (υ)	0.15
Density (ρ_{steel})	7.8 Mg/m^3

[i] Based on the 1D consolidation data reported by Parry and Nadarajah (1973) on kaolin at a maximum overburden pressure of 200 kPa

[ii] Based on the experimental data reported by Prashant and Penumadu (2004)

[iii] Evaluated from ϕ'_{cs} = 23° (Bilotta et al. 2006)

[iv] Assumed a preconsolidation pressure of σ'_{vo} = 200 kPa and K_o = 0.6. Note the value was smaller than the pressure adopted in Bilotta et al. (2006) (σ'_{vo} = 350 kPa) such that the simulated ground was softer

[v] Based on the experimental data reported by Al-Tabbaa and Wood (1987)

2.3 Modelling sequences

An initial equilibrium was achieved by establishing the initial stresses of the ground with minipiles installed wished-in-place (s/d = 3, 6, and 12). The soil elements inside the tunnel was then removed at once while a normal pressure (u_T) of 190 kPa was then applied on the inner surface along the tunnel. The pressure was then reduced to 80 kPa incrementally which was similar to the centrifuge tests reported by Bilotta et al. (2006).

3 RESULTS

Three monitoring lines are defined as shown in Figure 1. ML-11 lies on the ground surface on the front face where ML-21 and ML-31 are vertical monitoring lines 1.0D and 1.75D away from the tunnel axis. It is found that the volume loss at u_T = 80 kPa ranges from 3.5% (s/d=3) to 3.7% (no pile). The ground settlement profiles along ML-11 with different pile densities are shown in Figure 2. The settlement profile is skewed due to the presence of minpiles. It can be seen that an s/d = 12 reduces the surface settlement noticeably. More importantly, differential settlement is much reduced towards the right of the piles. Therefore, tilting of buildings built on shallow foundations is expected to be reduced with the aid of minipiles. Further increases in pile density have relatively minor effect. The result is different from the centrifuge tests by Bilotta et al. (2006) in which s/d = 12 gave almost no effect on ground movement reduction.

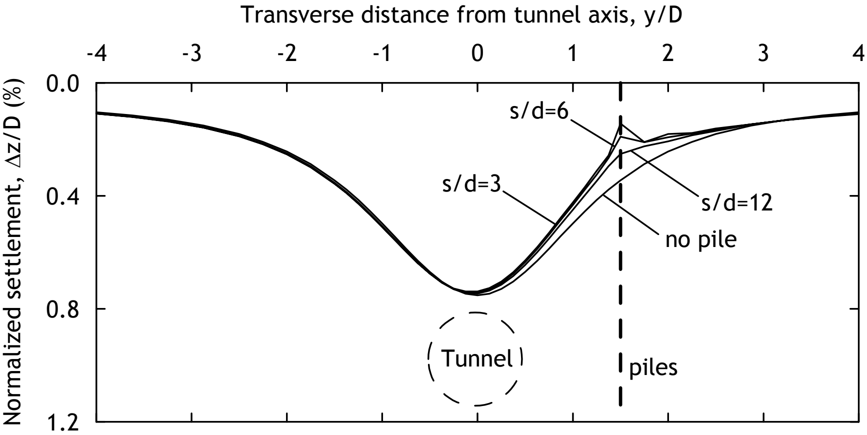

Figure 2: Ground settlement profiles along ML-11 with different s/d ratios (u_T = 80 kPa)

Subsurface lateral deformations along ML-21 and ML-31 are shown in Figure 3. It is noted that the use of minipiles reduces the subsurface lateral deformation significantly for s/d = 12 or lower. Because of the rigidity of the minipile, subsurface deformation between the tunnel and the minipile (ML-21) is reduced noticeably, especially at the tunnel level, even at a s/d = 12. Further increases in pile density only give relatively minor effect. As shown in Figure 3(b), the reduction in lateral movement behind the pile (ML-31) is minimal. It may be due to the fact that the monitoring line is located far enough from the tunnel such that any tunnel-induced movements are insignificant. The front face subsurface settlement profiles of different pile densities are shown in Figure 4. It clearly demonstrates the effectiveness of minipiles in reducing soil movements, especially in the region close to the pile.

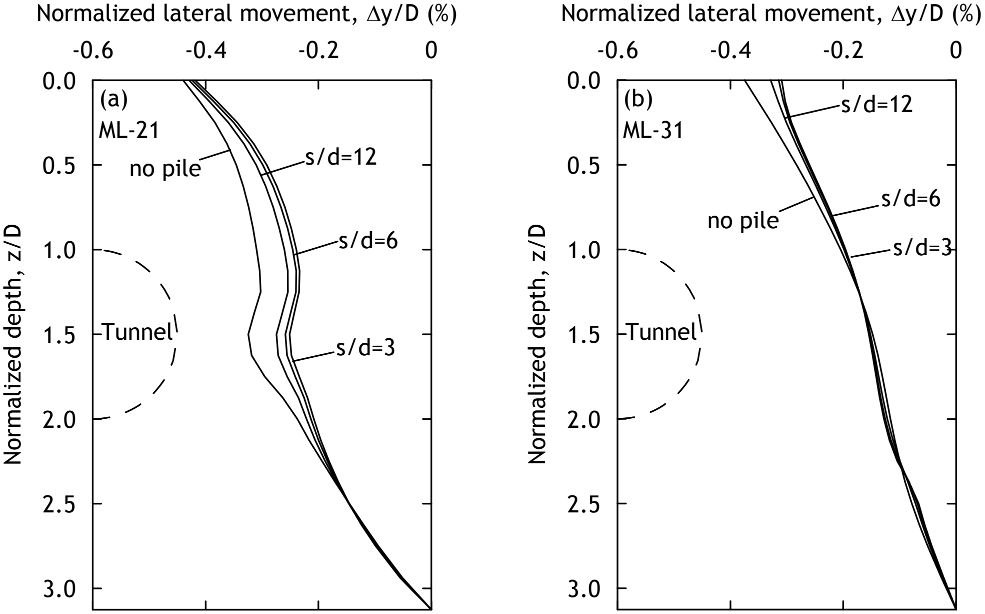

Figure 3: Subsurface lateral movements with different s/d ratios at u_T = 80 kPa along (a) ML-21 and (b) ML-31

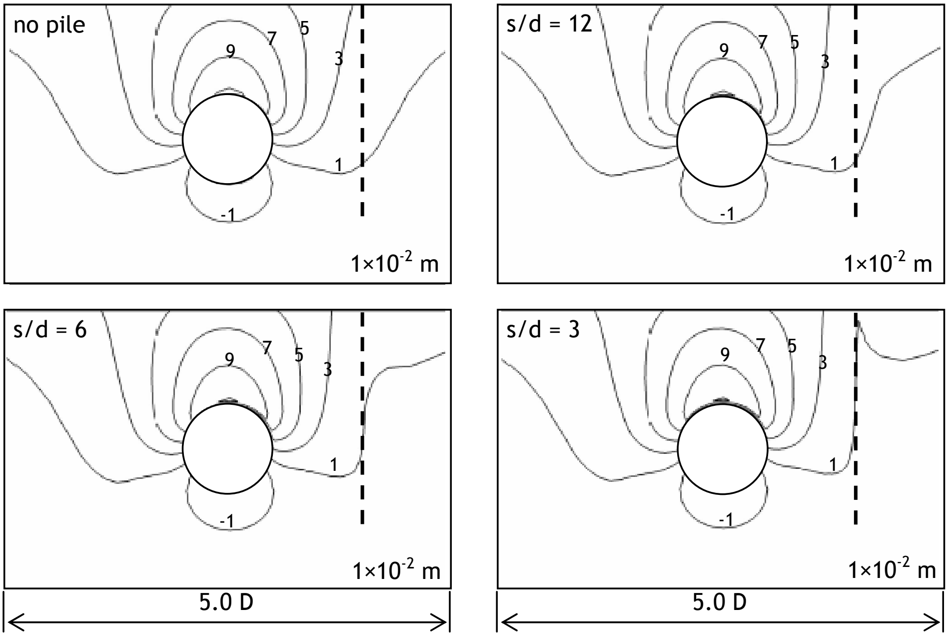

Figure 4: Subsurface settlement contour with different s/d ratios at u_T = 80 kPa

4 CONCLUSIONS

A series of preliminary numerical simulations were carried out to investigate the effect of using minipiles on ground movement reduction during a tunnel excavation in soft ground. Various minipile densities as represented by different s/d ratios were studied. The analyses showed promising results in which the ground movements were noticeably reduced even at a low pile density with s/d = 12.

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