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Physical Modelling in Geotechnics

Bearing behavior of pile resting on soft rock with NATM type tunnel

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ABSTRACT: Vertical loading tests of single pile resting on soft rock with NATM type tunnel were carried out in 50g and 1g environments. In the model soft rock, two semi-circular tunnels with diameters of 100mm, 140mm were made, and three aluminum-made solid piles with 20mm diameter (Φ) were loaded, two piles above the tunnel crowns and one at the portion without tunnel underneath. The piles were embedded in a 100mm thick sand layer above the soft rock, and the distance of the pile end to the tunnel crown was fixed to 80mm (4Φ). Two conditions of soft rocks made by clay-sand-cement mixture were tested in the unlined condition in 50g, one well compacted and the other poorly compacted with relatively large voids. For the well compacted one, unreinforced concrete lining tunnels were modelled in 1g. The three piles showed similar bearing behavior over 10%Φ settlement. However, as the settlement increased, the piles showed different behavior depending on tunnel diameter, ground condition, and lining condition, attributed to compressibility and the failure mechanisms of soft rock beneath the pile.

Keywords: NATM tunnel, soft rock, pile, vertical loading, failure mechanism.

1 INTRODUCTION

The deep underground for the tunnel construction could be defined as the depth where the tunnel does not affect the foundations of supper structures and vice versa (MLIT, 2001). The use of deep underground space is becoming common in tunnel construction projects in highly populated urban areas, since tunnelling underneath private land is inevitably needed. Although, the critical condition affecting the interaction between the tunnel and piles is the mutual distance. In addition, the tunnel diameter, lining, and bearing layer could also affect the mutual interaction.

In this study choosing NATM type tunnel in a soft rock as a common combination in urban tunnelling project, a series of preliminary physical model tests on the vertically loaded single pile was carried out under 50g centrifugal acceleration and 1g environment. From the tests results, discussed are the effects of the tunnel on pile bearing behavior and the effects of the pile on the tunnel deformation, and failure mechanism of soft rock and tunnel.

2 PHYSICAL MODELLING

3.1 Test setup and procedures and conditions

The test setup used in this study is shown in Fig.1. On the bottom of the model container, stacks of 20mm thick acrylic plates were fixed to reduce the height to 440 mm on the right side and 420 mm on the left. Two semi-circular tunnels with diameters (D) of 100mm, 140mm were made in the soft rock layer. Three aluminum-made solid piles with 20mm diameter (Φ) were placed on the rock surface, two piles above the tunnel crowns and one at the center without tunnel underneath.

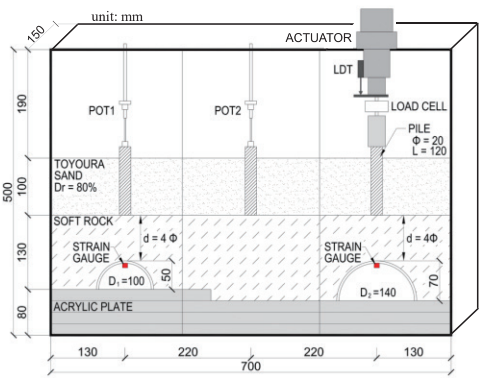

Fig. 1 General Test Setup (model scale).

The piles were embedded in a 100mm thick sand layer of Toyoura sand (Dr=80%). With the different container heights and tunnel diameters, the distances of pile base to the tunnel crown (d) were kept constant, 80mm, for two tunnels, which was 4 times Φ. The model soft rock was made by a clay-sand-cement mixture. Two conditions of soft rocks were tested in unlined conditions,

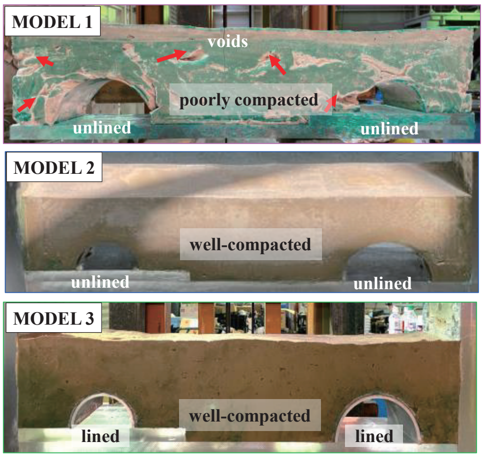

Fig. 2 Model soft rock grounds with tunnels.

Table 1. Test conditions.

Model No.	Soft rock model			Tunnel model		
	Mixture	q_u (kPa)	ρ (g/cm^3)	D_1	D_2	Lining
Model 1	C-S-CH	600	1.57	100	140	N
Model 2	C-S-CL	570	1.97	100	140	N
Model 3	C-S-CL	1200	2.01	100	140	Y

one well compacted in casting the mixture and the other poorly compacted with relatively large voids. For the well compacted one, unreinforced concrete lining tunnels were also modelled. Three model grounds with tunnels are shown in Fig.2. Table 1 summarizes the test conditions of the three models.

Two tunnels were set up on top of the acrylic plate base: D_1 (100mm) at the left and D_2 (140mm) at the right, referred to as T100 and T140 in this paper. T100 and T140 are unlined in Models 1 and 2 and lined in Model 3. To observe the tunnel behavior, strain gauges were attached to the inner surface of each tunnel. An electric actuator with laser transducer and load cell was set up above a pile and the vertical load was applied cyclically up to 5mm pile settlement and then monotonically increased until the clear failure was observed in load-settlement relation. After loading the centrifuge was stopped and reset the jack for the loading to the other pile. Originally, the vertical loadings were planned to conduct in 50g for all the models. However, due to an unavailability of the centrifuge test machine, the loadings of Model 3 were done in 1g condition. Shafi et al. (2021) investigated the behavior of laterally loaded pile in the soft lock in 1g and 50g conditions and found the mobilized pile resistances were almost the same for 1g and 50 g models until surface tension crack initiated at the rock surface in 1 g model. Considering compressive stress dominant condition, this is also the case for vertical loading.

2.2 Tunnel preparation

Soil-cement mixture for model soft rocks

Soft rock ground was modelled using two different mixtures: sand-cement-bentonite(CH) for Model 1 and sand- cement-clay(CL) for Models 2 and 3. Unconfined compression tests were conducted for the mold samples and sample trimmed from the soft rock ground on the day of experiments, about 14days after casting the mixture. There were variations of the UCT results in the batch for the specific model and also between the model. The average of measured UC strength (q_u) and density are given in Table 1.

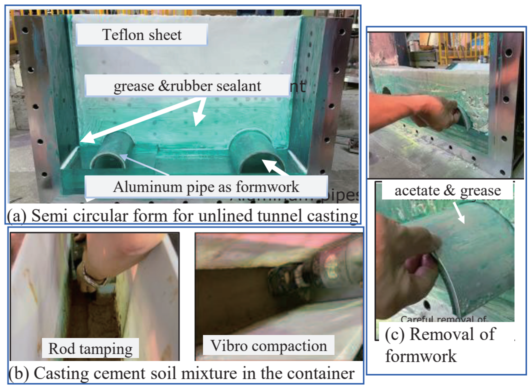

Fig. 3 Unlined tunnel preparation.

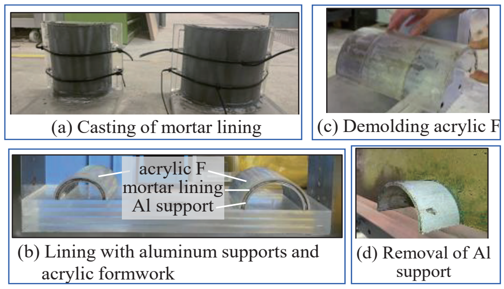

Fig. 4 Lined tunnel preparation.

Unlined tunnels, Model 1 and Model 2 (Fig.3)

In the case of the unlined tunnels, two half-cut 5mm thick aluminum (Al) pipes as formwork were fixed to the grooves on the acrylic base to prevent movement during casting. For smooth removal of the Al pipes, grease was used to lubricate the top surface of the pipes, and the lubricated surface was covered with acetate film. Teflon sheets were attached to the front and back sides of the container. The cement soil mixture was subsequently cast by gentle rod tamping and compaction by vibration for Model 1 and Model 2, respectively, and allowed to cure for fourteen (14) days. Finally, the Al pipe formworks were carefully removed. These casting processes result in poorly compacted and well compacted soft rock conditions, as shown in Fig.2.

Lined tunnels, Model 3 (Fig.4)

In Model 3, the mortar linings were casted using molds made of semicircular acrylic and aluminum pipes for tunnel external and internal surfaces with 5mm thickness. The Al pile is the same one used for unlined tunnels. On both internal surfaces of the molds, acetate films were attached using grease to keep the mortar from sticking with the mold surface. Next, a fresh sand cement mortar with high fluidity was poured into the mold and compacted by vibration. On 7th day of curing, the external acrylic pipes were removed, leaving the casted lining and the internal aluminum pipe, which served as support for the lining during compaction of the cement - soils mixture. Once the setup was completed, soft rock ground was prepared using the same way of Model 2. After 15 days curing, the front and back container walls were detached, the aluminum support was removed, and strain gauges were attached to the inner tunnel crown part. The walls were then attached to the container, model piles were placed, and a sand layer (Dr=80%) was made. The q_u of the sand cement mortar measured after 3week curing was about 14MPa.

3 RESULTS AND DISCUSSIONS

3.1 Influence of Tunnel on Pile Foundation

Pile load-displacement curves observed for three piles (NT, T100, T140) in three models are depicted in normalized values by the unconfined compression strength (q_u) and pile diameter (Φ) respectively in Fig.5. Though weird behavior was measured in the displacement at the unloading and reloading portion due to the poor performance of the loading jack, the load-settlement curves were obtained from the envelope. The bearing resistances of all NT piles in three models showed continuous increase without showing the peak, attributed to the hardening of soft rock. While for the piles above tunnels also showed similar increases of the resistance over 10% Φ settlement, which is commonly used as the ultimate limit of pile design (AIJ, 2019). However, as the settlement increases over 10% Φ, the bearing resistances of piles above the unlined tunnel in well compacted soft rock (Model 2) become smaller than the NT pile. Clear diversion from NT pile can be seen from about 20% and 40%Φ, and the resistances reached the peaks at about 45% and 60% Φ for T140 and T100, respectively. In the poorly compacted soft rock model (Model 1), the pile resistances of T100 and T140 increased till 80% Φ without showing clear differences.

In Model 3 with the lined tunnel in well compacted soft rock, pile bearing behavior was different from those of unlined tunnel cases. T140 and T100 showed a slightly larger resistance than NT, which could be attributed to the high stiffness of concrete lining. T100 shows a larger resistance than T140 till about 25% Φ settlement, but over 30% Φ, it became smaller than T140. T100 showed an abrupt decrease of the resistance immediately after the peak resistance. In contrast, gradual decrease in the resistance was observed for T140 before the abrupt resistance drop, resulting in higher peak pile resistance. The ratio of the peak resistance to that at s/Φ=10% in Model 3 is about 2, which is smaller than those of Models 1 and 2 (about 3). This could be

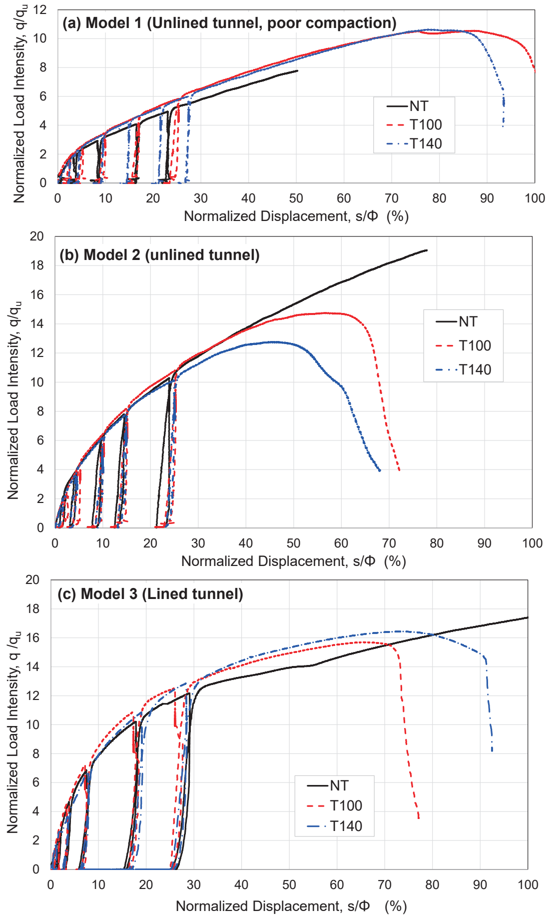

Fig. 5 Observed load – displacement curves.

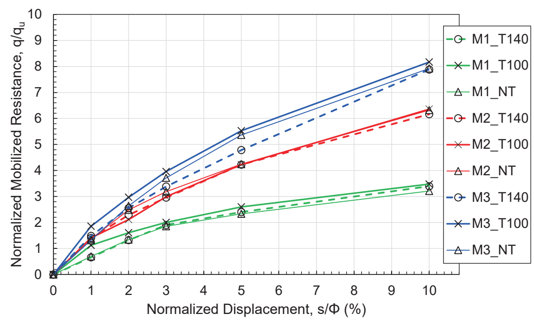

Fig. 6 Mobilized pile resistance and displacement relationship.

the effect of confining stress on the compressibility of rock; higher in 50g than 1g environment.

To scrutinize the pile bearing resistance of pile for relatively small settlement, the normalized pile resistances are plotted to s/Φ up 10% in Fig. 6. For unlined tunnel models, the mobilized resistances of Model 2 are higher than those of Model 1, proving that the ground resistance did not develop as much in the highly porous ground with high compressibility of the bearing layer. Furthermore, comparing the results based on the tunnel lining condition, it may be observed that the mobilized resistances in Model 3 (lined) are higher than those of Model 2 (unlined). In Model 3 the resistance of T100 is larger than T140. The stiffer lining

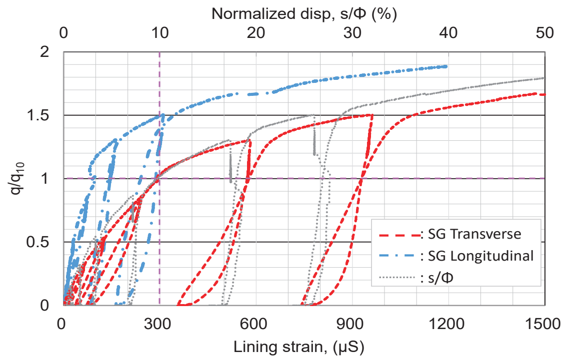

Fig. 7 Relationships between normalized load intensity and strains at the crown of T100 lining in Model 3.

than the soft rock could decrease the compressive zone beneath the pile and cause the higher resistance mobilization than NT pile and piles underneath the unlined tunnels.

3.2 Influence of Pile on Tunnel

To assess the tunnel behavior subjected to the pile loading, the strains of lining at the tunnel crown were measured. Figure 7 shows the variation of strains in the transverse and longitudinal direction with load intensity normalized by that at s=10% Φ (q_{10}) for T100 tunnel of Model 3. The yielding points of the load strain curves are about q/q_{10}=1.2 and 1.1 in the longitudinal and transverse directions respectively. For the T140 tunnel, the yield point was observed at q/q_{10}=0.9 in the transverse direction. It may be concluded that tunnel lining could remain undamaged till the pile load is near the ultimate design limit.

3.3 Failure mechanism of tunnel and soft rock under pile loading

After the loading test, the rock mass was vertically cut into three blocks, including the pile loading point at the center. Red ink was injected into the hole made by the pile loading, and the cracks appeared in the tunnel surface to visualize the failure mechanism of the soft rock. After the injection, the blocks were split vertically at the center of the pile loading portion. Figs. 8a show photos of the cut sections of Model 2, and Figs.8b show the damaged linings and the cut section above the tunnels of Model 3. For the pile without tunnel underneath, neither crack nor heaving at the rock surface was observed. This implies that the pile penetration volume was absorbed by the compression of soft rock, resulting in a continuous increase of bearing capacity with pile settlement. While for the piles with the unlined tunnels, a truncated cone shape block with a steep angle of about 70° was formed beneath the pile. The angle decreased downward, resulting in a wide failure block at the tunnel surface. The failure mechanisms of the unlined tunnel were almost the same for the two piles with a little wider failure zone for large tunnel (T140). In lined tunnel cases, the failure mechanisms were very different for T100 and

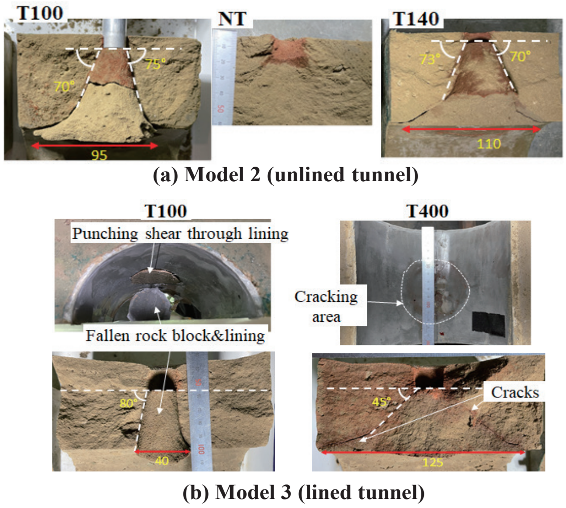

Fig. 8 Observed failures of tunnel and soft rock layer.

T140. In T100, a steeper angle truncated cone block was formed to the tunnel, which caused punching shear failure at the tunnel crown. In T140, a large truncated cone shape deformation area was observed with cracks of smaller angle of about 45°. This rock deformation caused cracking in a wide area at the tunnel crown. These deformation and failure mechanisms well agree with the observed bearing behavior of the piles for the specific conditions.

4 CONCLUSIONS

In this study choosing NATM type tunnel in a soft rock as a common combination in tunneling construction, a series of preliminary 50g and 1g physical model tests on vertically loaded single pile were carried out. Based on the test results at given conditions, such as pile-tunnel relative distance, d=4Φ, the followings are concluded:

- The compressibility of soft rock is a critical factor for the bearing capacity of the pile on soft rock.
- Though the failure mechanism of the tunnel depends on various conditions, such as rock compressibility, tunnel diameter, and lining condition, up to the pile settlement of 10% pile diameter, no negative effect of the tunnel on pile bearing capacity was observed. The deformation of the tunnel could be also minor till the 10% settlement.

REFERENCES

AIJ.2019. Architectural Institute of Japan: Recommendations for Design of Building Foundation, 3rd edition.

MLIT (Ministry of Land, Infrastructure, Transport and Tourism, Japan. 2001. *Act on Special Measures Law Concerning Public Use of Deep Underground,https://web.archive.org/web/2008 1225220641/http://www.mlit.go.jp/crd/daisindo/index.html.*

Shafi, SM, Takemura, J. and Kunasegaram, V. 2021. Physical modelling of laterally loaded large diameter steel tubular pile socked in soft rock, *Proc. 3rd Asiafuge November 2021*. Singapore.