Physical Modelling in Geotechnics

Trapdoor tests on ground loosening and collapse by tunnel over excavation in sand

H. Asakura, J. Takemura & S. Seki
Department of Civil & Environmental Engineering, Tokyo Institute of Technology, Japan

K. Yashiro
Structure Technology Division, Railway Technical Research Institute, Japan

ABSTRACT: 2D trapdoor tests were conducted to simulate the deep ground displacement caused by volume loss of shield tunneling in sand layer in 50g centrifugal environment. The trapdoor width (B) and sand depth (H) are 3m and 12m in prototype scales. The tests were conducted in medium dense (Dr=80%) and very dense sand (Dr=95%) assuming the relatively deep bearing layer. Earth pressures and displacement in the ground were measured by small earth pressure cells and Particle Image Velocimetry (PIV). The ground resistances at various locations from the trapdoor center were also measured by cone penetrometer at small and large trapdoor movements. From the tests, affected spatial area in terms of ground displacement and cone resistance were investigated and discussed.

Keywords: trapdoor, sand, displacement, cone resistance, earth pressure.

1 INTRODUCTION

In shield tunnelling, closure of tail void or over-excavation generates the volume loss (*ΔV*) at the depth of tunnel, which causes displacement first near the tunnel, propagating upward as the ground loss ratio (*ΔV/V*) increases. Recently there have been a several sinkhole accidents caused by over-excavation in shield tunnel constructions in Japan (JRTT, 2020; NESCOEJ, 2021). One accident occurred at tunnelling site in deep dense sand/gravel layer. In a tunnelling project, not only subsurface and surface displacements, but also change of the ground bearing capacity should be considered as a potential effect of the over-excavation especially for the relatively deep tunnel passing underneath the private land. The propagation of ground displacement depends on several factors, such as, tunnel cover depth-diameter ratio and soil conditions. To investigate the tunnel induced ground displacement and their effects on the foundation, centrifuge modelling has been used in various perspectives, such as the effects on surround structures (e.g., Mair, 1993, Boonsiri & Takemura, 2015). Trapdoor tests have been used to examine the arching behaviour of geomaterials and arching pressure on the underground structure (e.g., Iglesia et al., 2014).

In this study, 2D trapdoor (TD) tests were conducted to simulate the displacement behaviour in deep sand layer in a centrifuge. On top of ground displacement, earth pressures were measured during the TD movement and the cone penetration tests were conducted at various locations at small and large TD movement, which are equivalent to *ΔV/V*~1.6% and over 30%, respectively, corresponding to tail void closure as a common condition and an over-excavation associated with a tunnel accident, e.g., extra over-excavation accidentally done for long distance. From the tests, the affected area in terms of ground displacement and ground pile resistance were investigated and discussed.

2 CENTRIFUGE MODEL TESTS

2.1 Test setup and model preparation

Test setup shown in Fig. 1 was prepared using a steel made rectangular container with internal dimensions of L700mm, B150mm and H500mm. Fig. 2 is the 2D trapdoor apparatus used in the tests, which mainly made of 20mm thick acrylic plates. The TD width (B) is 60 mm. The TD mechanism is similar to the one by Igresia et al. (2011). Two trapezoidal wedges are smoothly contacted with 1:3 inclination. The upper wedge, which is laterally restrained, is vertically moved by the horizontal movement of lower wedge driven by an electric actuator. With this arrangement, the TD is moved at displacement rate of 0.033mm/sec down to maximum 20mm. Rough surfaces were created on the upper wedge and the top plates of TD apparatus by placing sandpapers (roughness: 80).

Two model grounds with different density were made and tested as shown in Table 1. Dry Toyoura sand (G_s=2·64, d_{50}=0·19mm, e_{max}=0·973, e_{min}= 0·609) was used to make the model ground. The sand samples were made by air pluviation method for Dr=80% sample. For

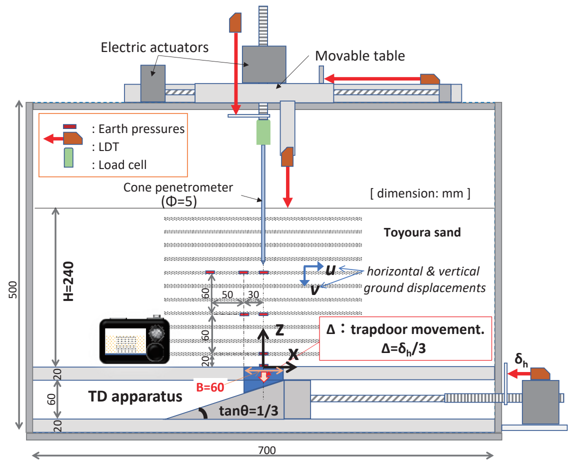

Fig. 1 Test setup.

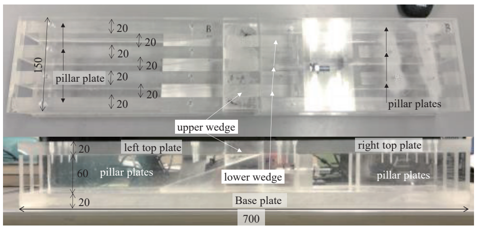

Fig. 2 Acrylic made trapdoor (TD) apparatus.

Table 1. Test conditions (prototype).

Test case	D_r	Sand height: H	T door width: B
Case 3	80 %	240 mm (12m)	60mm (3m)
Case 4	95 %		

D_r=95% sample, after sand pouring, compaction work was added by hand vibrator with an acrylic plate every 20mm depth. To visualize the displacements and slip planes, inked Toyoura sand was poured adjacent to the front window to create 5mm thick black layer every 20mm depth. In the sand sample preparation, small pressure cells were placed at the position shown in Fig. 1. After the sand preparation, on the container fixed was a movable table with a cone penetrometer of diameter Φ=5mm at the breadth center position. A pair of LDTs were also attached on the table to measure the ground surface settlement by scanning the surface. In Fig. 1, definitions of space coordinates (x, z) and displacements (u, v) are shown, which are used in following sections.

2.2 Trapdoor tests and cone penetration tests

The test setup was mounted in Tokyo Tec Mark-III centrifuge and spun up to 50g. To measure the intact ground cone resistance, cone penetration tests were first conducted at two points x=200mm and 230mm. After the first trapdoor movement down to Δ=1mm, the cone penetrations were conducted at three points, x=0, 30 and 60mm. Second trapdoor movement was induced down to Δ~18-19mm, followed by the cone tests at x=15, 45, 75, 105, 135 and 165mm. Assuming TD width, B, as a tunnel diameter, Δ=1mm (~1.6%B) and 18mm (~30%B)

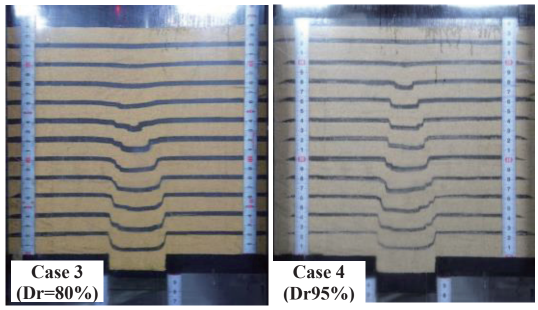

Fig. 3 Ground displacements by large TD movement (Δ~30%B).

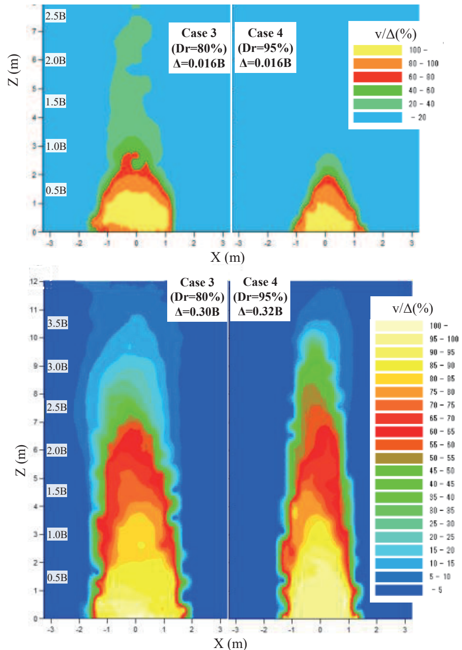

Fig. 4 Contours of ground vertical displacements (v) at small Δ (1.6%B) and large Δ (~30%B).

are equivalent to volume loss ratio *ΔV/V*=1.6% and 30%, respectively. During the trapdoor movements, the vertical earth pressures on TD and in the ground above the TD were measured and photos were taken by digital camera every 1mm movement for PIV analysis.

3 RESULTS AND DISCUSSIONS

In the following section, test results are presented in a prototype scale, unless otherwise stated.

3.1 Ground displacements

The photos taken at the large Δ(~30%B) are shown in Fig. 3. Contours of normalized vertical displacement (v/Δ) in the ground are also depicted for the small and large DT movements (Δ=1.6%B and 30%B) respectively in Fig. 4. Fig. 5 shows the progresses of the vertical displacement with Δ at different distances (z) above the TD centre. For the small Δ, the sand with Dr=95% formed very clear arch in limited area with smaller loosening area in horizontal and vertical directions than the sand with Dr=80%. As Δ increased, the volume loss by the TD movement of the very dense sand mainly

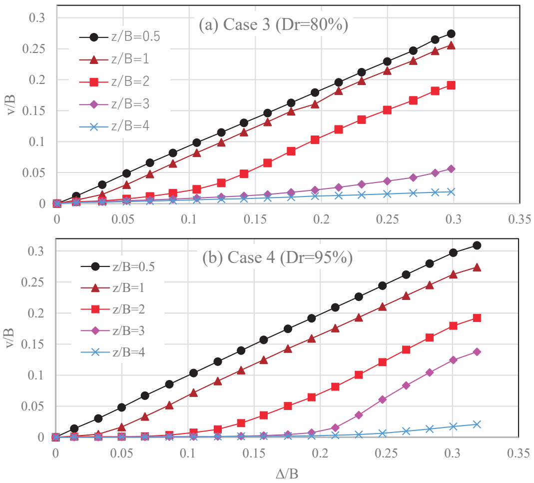

Fig. 5 Progress of vertical displacement with Δ above the center of trapdoor (x=0).

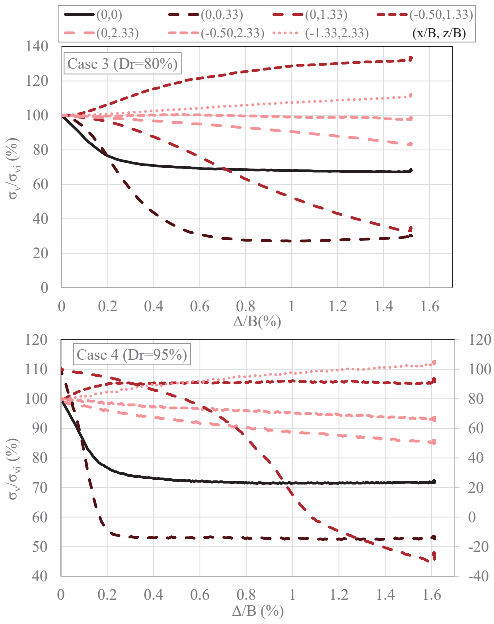

Fig. 6 Variation of vertical earth pressure with trapdoor movement in small Δ (~1.6%B).

caused the vertical displacement in a narrow width and the upward progress of loosening area became larger than the medium dense sand. The effects of small volume loss corresponding to the closure of tunnel tail void on the ground loosening is smaller for the very dense sand. However, in deep tunnel excavation the effect of over excavation may appear at ground surface at smaller volume loss for the very dense ground than medium dense sand.

3.2 Earth pressure variations

Variations of vertical earth pressures (σ_v) measured by small pressure cells in the small TD movement are shown in Fig. 6. The measured pressures were not consistent to the overburden stress before TD tests especially for the dense sand, in which ground was compacted with the cells by a vibration. Therefore, the variations in the figure are given by the percentage of the initial value before TD lowering (σ_v/σ_{vi}). At the center line (x=0) near the bottom (z=0.33B), the stresses decreased rapidly and became constant almost the same trend of that on TD in the very dense sand compared to the medium dense sand, implying the earlier formation of arch for the dense sand. Though at relatively distant point (z=1.33B, and 2.33B) the gradual stress reduction was observed not reaching constant or minimum stress at the end of the first TD lowering, similar trend could be seen, the earlier decrease in Dr=95% than Dr=80%. Stress increases were observed at the location out of trap door |x|>0.5B, as a result of stress diversion over the arch portion (See Fig.4).

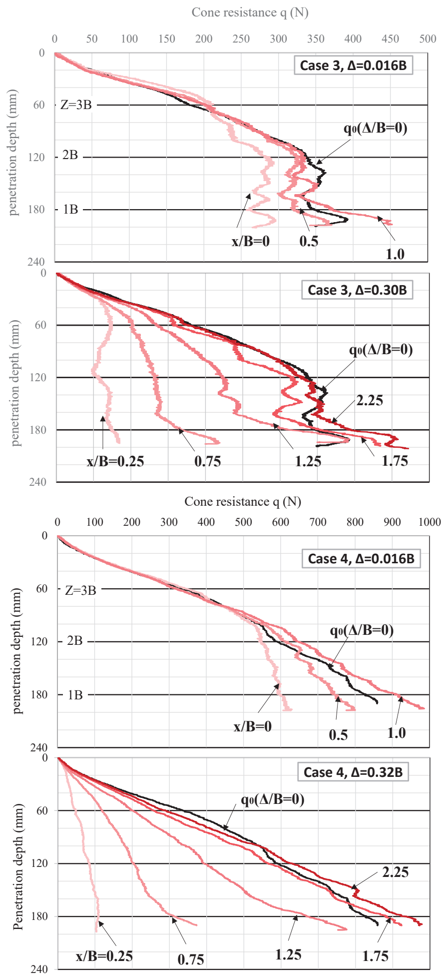

Fig. 7 Cone penetration resistances measured at small Δ (1.6%B) and large Δ(~30%B).

3.3 Cone resistances

Figs. 7 show the variations of cone resistance with penetration depth in a model scale. The average of two cone tests done before lowering TD (q_0) are also presented in the figures. As the resistance was measured by a loadcell attached to the top of cone rod, it includes the tip resistance and the rod shaft friction. However, from the fluctuation of the resistance measured below

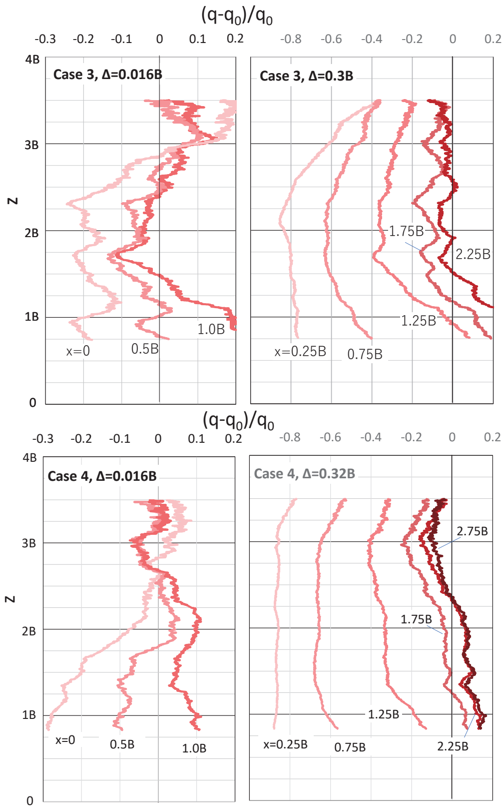

Fig. 8 Resistance reduction ratio for small Δ (1.6%B) and large Δ(~30%B).

120mm depth in D_r=80% sand, which was caused by local disturbance by the manual leveling to install the pressure cells, it can be inferred that the measured resistance reasonably reflects the strength and stiffness of the sand near the cone tip. Except of the disturbed depth, the resistance increases almost linearly with depth and the mobilized resistance of the very dense sand is about double of the medium dense sand. According to Tasuoka et al. (1986), internal friction angle of Toyoura sand obtained from triaxial compression tests of sand are about 42° and 45° for the void ratios of D_r=80% and 95% respectively.

The reduction of resistance is quantified by using the resistance reduction ratio $(q(z)-q_0(z))/q_0(z)$ and its depth variations are depicted at different locations for the small and large TD movements (Δs) in Fig. 8. Though some potential error could be inevitably included in the reduction ratio, especially at the shallow depth, the affected area and degree of reduction by the specific Δ can be confirmed from the figures. For the small Δ, the resistance reductions are relatively small less than 20 - 30% of the intact one in very narrow area above the TD, |x|<0.5B and z < 2B. While for the large Δ, the reductions are over 80% and the reduction area extends near the ground surface. In Dr=95% sand, the loosing area reached to very shallow depth, z>3.0B, as shown in Figs. 3-5. The reduction ratios are rather constant at the depth from z~1B to the top end of loosing, i.e., z~3B, for the specific locations, which decreases with increasing the distance from the trapdoor. While for Dr=80% sand the loosening area reaches below z=2.5B and arching effects could be remained, which can be confirmed by relatively small reduction ratio at shallow depth and the increase of the resistance at the area out of arch, z<2.0B and |x|>2.0B (see Fig. 4). Although there are some differences in the effect of over excavation on the penetration resistance depending on the sand density, the effects became very small at the location |x|>2.0B in the conditions of the tests, that is, the cover depth of 4B.

4. CONCLUSION

From the centrifuge trapdoor tests, the following conclusions are derived.

1) Small trapdoor movement, corresponding to small tunnel volume loss, formed very clear arch above TD in smaller area for the very dense sand than the medium dense sand. This could cause the 20-30% reduction of the pile resistance from the intact condition at the depth of twice TD width (B) only above TD.
2) In deep tunnel excavation in sand, the effect of over excavation may appear at ground surface at smaller volume loss for the very dense ground than the medium dense sand due to the narrow loosening width above TD.
3) Although there are some differences in the effect of large over excavation on the penetration resistance depending on the sand density, the effects became very small at the location |x|>2.0B for the cover depth of 4B.

REFERENCES

Boonriri, I. & Takemura, J. 2015. Observation of Ground Movement with Existing Pile Groups Due to Tunneling in Sand Using Centrifuge Modelling. *J. Geotech & Geol Eng*, 33. 621-640.

Iglesia, G..R., Einstein, H. H. & Whitman, R.V. 2011. Validation of Centrifuge Model Scaling for Soil Systems via Trapdoor. *J. Geotech & Geoenv Eng*, 137 (11), 1075-1089.

Iglesia, G..R., Einstein, H. H. & Whitman, R.V. 2014. Investigation of Soil Arching with Centrifuge Tests. *J. Geotech & Geoenv Eng*, 140 (2),

JRTT(Japan Railway Construction, Transport & Technology Agency). Report of the review committee on sinkholes caused by Shinyokohama tunneling at Kanagawatobu new railway line. August. 2020. https://www.jrtt.go.jp/project/asset/pdf/kanagawa-east/GroundCommitteeFinal.pdf. (in Japanese).

Mair, R.J., Taylor, R.N. & Bracegirdle, A. 1993. Subsurface settlement profiles above tunnels in clays. *Geotechnique,* 43(2):315–320

NEXCO East Japan. 2021. Report of 7th Tokyo Gaikan Tunnel Construction Review Committee, https://www.e-nexco.co.jp/en/news/important_info/2021/0319/00009597.html..

Tasuoka, F., Toto, S. and Sakamoto, M.1986. Effects of some fators on strength and deformation characteristics of sand at low pressures. *Soils and Foundations,* 26(1), 105-114.