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Centrifuge modeling of segmental tunnel lining and ground responses under ground surface loading

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ABSTRACT

Segmental tunnel linings are susceptible to additional deformation induced by the loading/unloading from nearby construction activities, particularly in shallow tunnels where ground surface load variations significantly impact structural performance. This study investigates the response of a segmental tunnel lining and surrounding subjected to rectangular loading applied at the ground surface using an in-flight displacement-controlled vertical loading system within a centrifuge modeling framework. The prototype tunnel, with a diameter of 7.5 m located at a depth of 15 m, comprises eight segments per ring assembled through straight jointing. The response of the soil-tunnel system by asymmetric surcharge loading was analyzed. The analysis combines ground response, including surface settlement and shear wave velocity, and structural response, including bending moment and hoop force. Consequently, changes occur in both the distribution of internal forces within the lining segments and the resulting surface settlement troughs. Experimental findings underscore the crucial influence of joint characteristics on tunnel performance under varying external loads, offering valuable insights into soil–tunnel interaction for design and assessment of segmental tunnels.
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1. INTRODUCTION

Construction of shield-driven tunnels in urban areas continues to increase. The primary support of such tunnels, segmental tunnel lining, is composed of rings assembled by connecting prefabricated tunnel segments. This configuration allows for efficient construction in limited space. Consequently, two types of interfaces exist: circumferential joints between rings and longitudinal joints between segments within a ring, both of which significantly influence the structural performance of the lining.

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Previous studies have investigated the relationship between internal forces and relative rotations and displacements at the contact surfaces of flat concrete segments through analytical and numerical approaches. Analytical models derived from such studies are often validated by experimental research and field monitoring data. Among them, model tests have the advantage of capturing joint response under controlled conditions. However, 1g model tests are limited in that they cannot consider the stress-dependent behavior of soils. In contrast, geotechnical centrifuge tests provide a compelling alternative, as they can reproduce in-situ stress conditions by applying centrifugal acceleration to a scaled model (Schofield 1980). Existing centrifuge tests related to joint characteristics have primarily involved continuous linings, with indirect consideration of joints through artificial grooving. Explicitly modeling segmental joints in centrifuge experiments remains extremely limited.

This study presents a centrifuge model test aimed at evaluating the behavior of segmental tunnel linings subjected to asymmetric surcharge loading in shallow ground conditions. The results reveal that the joint characteristics play a critical role in altering the equivalent radial stiffness of the soil–tunnel system and contribute to inducing a three-dimensional deformation pattern. These experimental outcomes emphasize the importance of explicitly considering joint behavior when assessing the structural response of segmental tunnels under external loading, and they provide valuable data for understanding the interaction between the lining and surrounding soil.

2. CENTRIFUGE MODELING

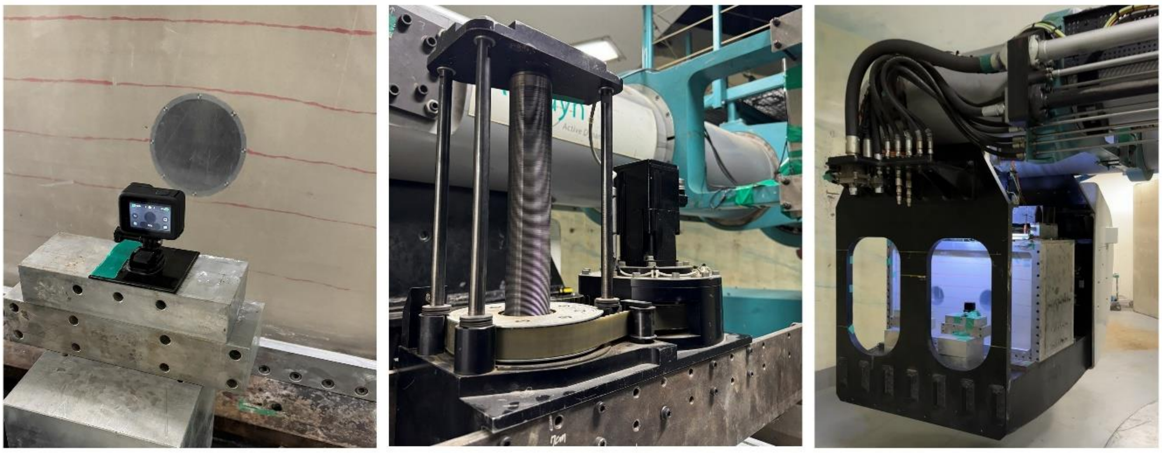

Fig. 1 Centrifuge model package: (left) front view of model after preparation; (middle) displacement-controlled loading setup; (right) after mounting on the centrifuge platform.

2.1 Centrifuge model package

The experiments were conducted at the KOCED Geotechnical Centrifuge Testing Center at KAIST, using a beam-type centrifuge with a 5-meter radius. The maximum payload is 1,300 kg at 130 g under static conditions (Kim et al. 2013).

Dry silica sand with a relatively fine grain size was selected to minimize particle effects. The mean particle size was 0.221 mm, resulting in a model-to-particle size ratio of 679. According to the USCS the soil was classified as poorly graded sand (SP), with a coefficient of uniformity of 3.07 and a coefficient of curvature of 1.02. The maximum and minimum void were determined to be 1.0748 and 0.5776, respectively. A dense ground model with dimensions of 120 cm × 45 cm × 60 cm (length × width × height) was prepared using the sand pluviation method, targeting a relative density of 70%.

The prototype segmental tunnel lining was composed of 15 rings, each formed by straight jointing of eight segments covering 45°, made of C50 concrete. To isolate the effect of joints, bolts and key segments were excluded. The model segments were fabricated from polylactic acid (PLA) using 3D printing to carefully scale the prototype's compressive and bending stiffness. These segments were then assembled into the model tunnel.

2.2 Test Program

A displacement-controlled loading setup was employed to simulate surcharge loading. A vertical actuator applied downward force to a rectangular loading plate (24 cm by 9 cm). The tunnel model was embedded such that its center was located 22.5 cm laterally from the centerline of the loading plate and at a depth of 30 cm, establishing an asymmetric loading condition. Each test involved a gradual spin-up of the centrifuge to 50 g, followed by stabilization. Loading was then applied to the capacity of actuator, after which unloading was performed, and finally, the system was spun down.

2.3 Instrumentation

To measure surface settlement, four LVDTs were installed transversely across the target section. To monitor stress redistribution in the soil, four pairs of bender elements were embedded at varying depths. For evaluating the structural response, eight pairs of strain gauges were attached to both the intrados and extrados of the target ring at 45° intervals to capture circumferential strains.

3. TEST RESULTS

All test results are presented in the model scale. Figure 2 shows the load–displacement curve obtained during the surcharge loading test. To perform bender element testing, the total load was applied incrementally in nine stages. The maximum load reached 45.6 kN, corresponding to the full capacity of the actuator. Following unloading, a permanent deformation of approximately 10 mm was observed.

Figure 3 illustrates the variation in ground surface settlement above the tunnel crown. The settlement increased progressively with the applied load, which is attributed to soil–tunnel interaction resulting from the deformation of the tunnel lining. At the maximum loading stage, the measured settlement reached 1.18 mm. Even after unloading, a residual settlement of 1.15 mm remained. This indicates that irreversible and excessive deformation was induced in both the tunnel lining and the overlying ground.

Figure 4 presents the bending moment distribution induced in tunnel lining measured clockwise from the tunnel crown. The results indicate that the maximum positive moment occurred at the tunnel shoulder. The magnitude of the moment peak increased with higher load levels. These findings suggest that the centrifuge modeling in this study successfully captured the response of the soil–tunnel system subjected to asymmetric surface loading.

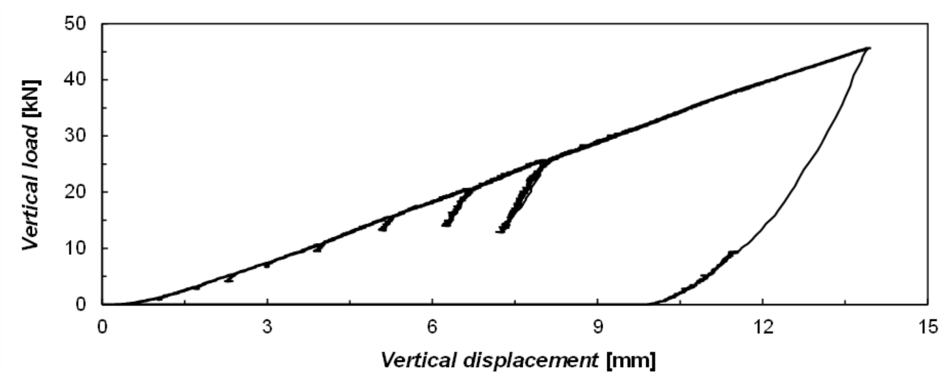

Fig. 2 Load-displacement curve during surcharge loading test.

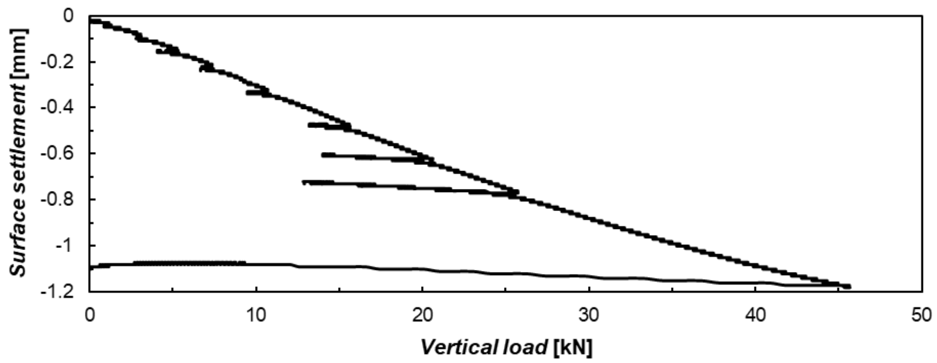

Fig. 3 Ground surface settlement above the tunnel crown during surcharge loading test.

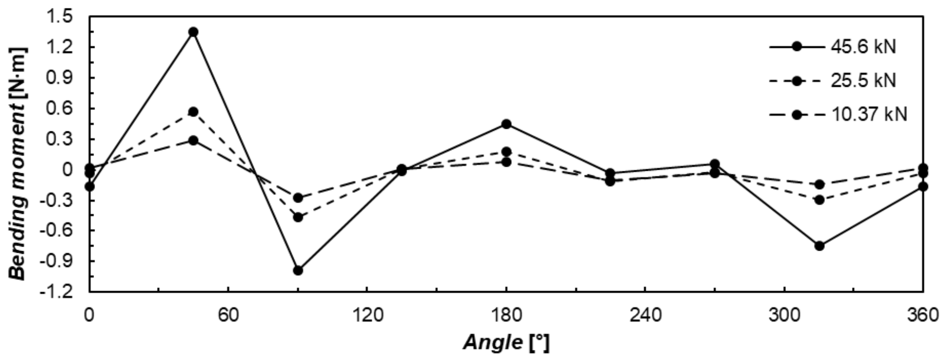

Fig. 4 Induced bending moment in tunnel lining during surcharge loading test.

4. CONCLUSIONS

This study presented a centrifuge modeling approach for segmental tunnel linings subjected to asymmetric surcharge loading. The results demonstrate that the centrifuge model test effectively captures the soil–tunnel interaction even under complex loading conditions. Furthermore, it highlights the centrifuge test as a powerful tool for providing invaluable data to validate numerical models. A numerical back-analysis of this experiment is expected to enable a quantitative assessment of the contribution of joint characteristics to the overall tunnel response.

ACKNOWLEDGEMENTS

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