Bi-directional loading tests on irrigation tunnels in soft rock

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1. Background

Irrigation tunnels in Japan are at risk of damage from plastic earth pressure, particularly in geologically unstable regions characterized by faults and green tuff formations. The superimposition of plastic earth pressure on normal earth pressure poses a substantial threat to tunnel integrity, necessitating urgent reinforcement measures. This study investigates the effects of normal and plastic earth pressure conditions using multidirectional loads, and conducts model experiments to understand how the ground interacts with the tunnel lining.

2. Experimental method

A 500 mm × 500 mm × 250 mm ground was installed in a steel test apparatus with a D-shaped tunnel lining, having a thickness of 10 mm, a height of 120 mm, a width of 120 m, and a depth of 250 mm, placed at its center (**Fig. 1**) for biaxial loading tests. As shown in **Fig. 2**, two types of voids, namely, no void and a θ=90° void, were set above the tunnel lining. The void had a thickness of 10 mm. **Fig. 3** shows the position of the specimen and the arrangement of the measuring devices for the biaxial loading. To monitor the vertical and horizontal convergences, two non-contact sensors (No. 1) were installed. Displacement sensors (No. 2) were used to measure the displacements of the loading plate in the vertical and horizontal directions. Six strain gauges were installed on the top, bottom, left, and right inner sides of the tunnel lining, as well as on the top left and top right sections. Two hydraulic cylinders (No. 3) were used for loading in the vertical and horizontal directions, respectively, and PTFE sheets were placed between the ground and the steel plate on the back side of the steel test apparatus to reduce friction. The loading speed was set to be below 0.1 mm/s, and the hydraulic pump was operated at a frequency of once every 5 seconds. The experiment involved two loading cases: one in which the vertical load was kept at 0 kN without applying any force, and another in which the vertical loading was stopped when it had reached 250 kN, while the horizontal load, with a maximum of 570 kN, stabilized and remained nearly constant.

(Unit : mm)

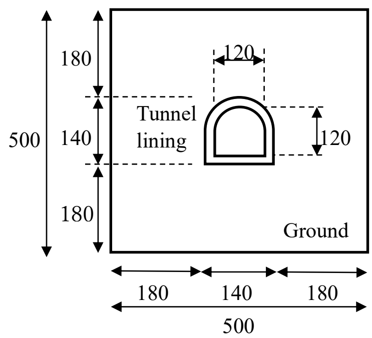

Fig. 1 Sample size

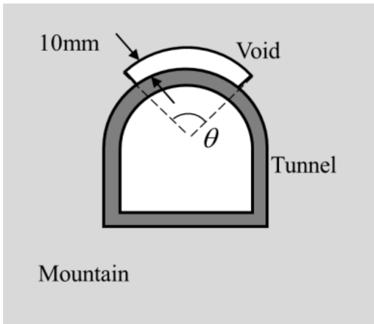

Fig. 2 Angle of void above tunnel lining

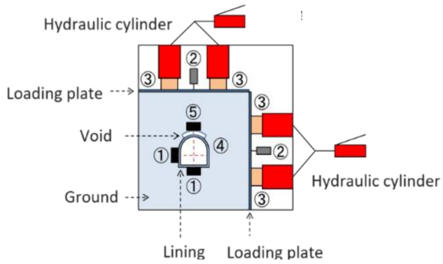

Fig. 3 Experimental setup and measurement positions tunnel lining

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3. Results

Figs. 4, 5, and **6** show the time histories of the stress, convergence, and strain in the case of the 90° void under vertical loading, respectively. In **Figs. 4** and **5**, the meanings of the symbols in the legend are as follows: "V0" indicates no void, "V90" indicates a void at 90 degrees, "NVL" indicates no vertical load, "VL" indicates vertical load, "HD" represents horizontal direction, and "VD" represents vertical direction. In **Fig. 4**, the stress is calculated from the applied load.

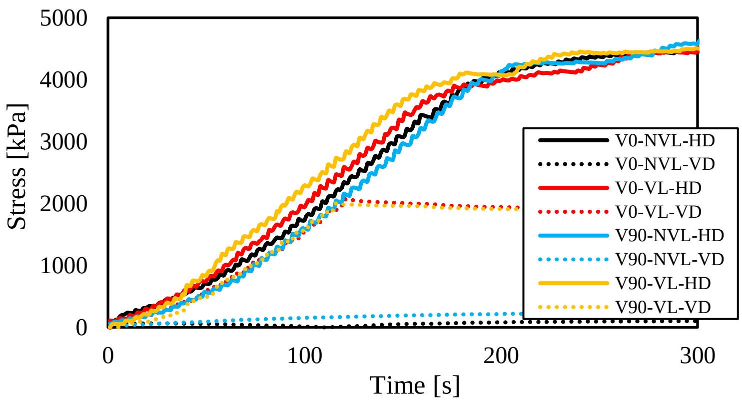

Fig. 4 Time histories of stress

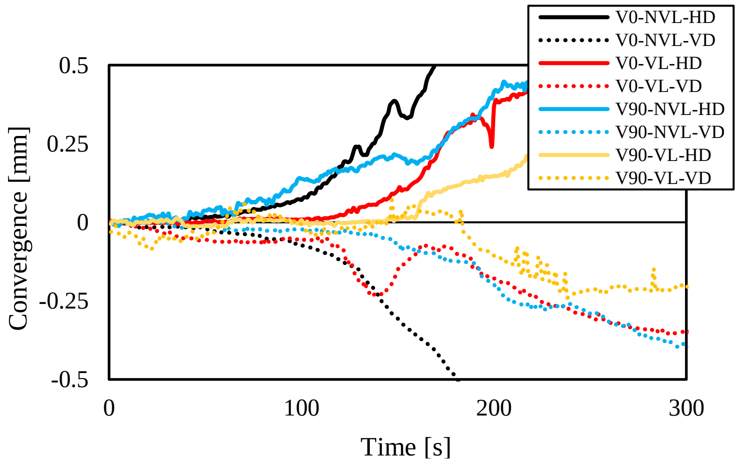

Fig. 5 Convergence

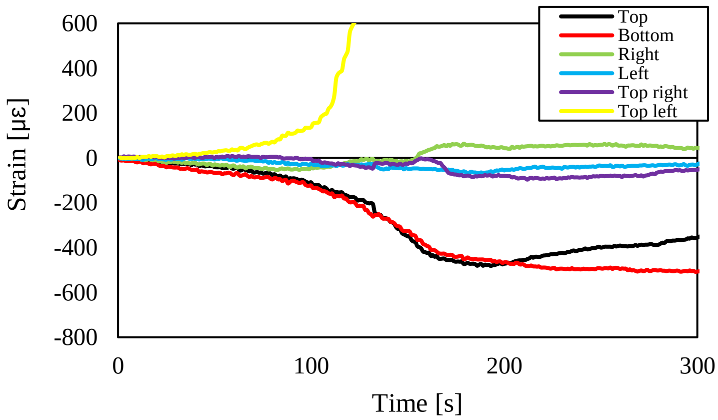

Fig. 6 Time histories of strains in case of void 90°

From the convergence in **Fig. 5**, it can be observed that, in the absence of vertical load, the convergence is greater compared to the case with vertical load. Additionally, under vertical loading conditions, the convergence increases more slowly. Simultaneously, the fact that the horizontal convergences are all positive, while the vertical displacements are all negative, indicates that the shape of the tunnel lining deformed vertically. From the trends in strain seen in **Fig. 6**, it can be understood that cracks appeared at the upper left and top of the tunnel 100 seconds after vertical loading.

4. Summary

This paper presents experiments conducted to investigate the interaction between the ground and the tunnel lining under bi-directional loading. The results show that, in the absence of vertical loading, the convergence is larger and increases more rapidly, while under vertical loading, the increase in convergence is slower. Moreover, when there are voids at the back of the tunnel back, cracks tend to first appear at the connection between the back of the tunnel and the void.