Selection of Displacement Control Measures using Three-dimensional Numerical Analysis in Tunnel Construction Right under the Monorail

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Project outline

The Akamine Tunnel is located in Naha City, Okinawa Prefecture, and consists of two road tunnels, one upper and one lower, with a total length of approximately 1 km. The monorail runs on this route and the minimum separation between the monorail piers and the tunnel is 10 m (Fig. 1). The challenge was therefore to control the displacement of the monorail piers during tunnel excavation so that monorail operations were not severely affected. To meet this challenge, displacement control measures were adopted using three-dimensional numerical analysis, and the displacement was monitored 24 hours a day.

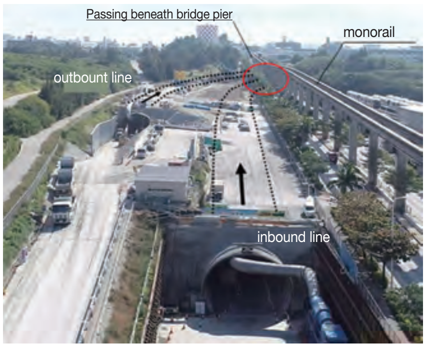

Fig. 1 Site condition

1. Selection of displacement control measures

The displacement control measures for the monorail piers were selected based on simulations of the pier displacement using three-dimensional numerical analysis (FDM analysis: Fig. 2).

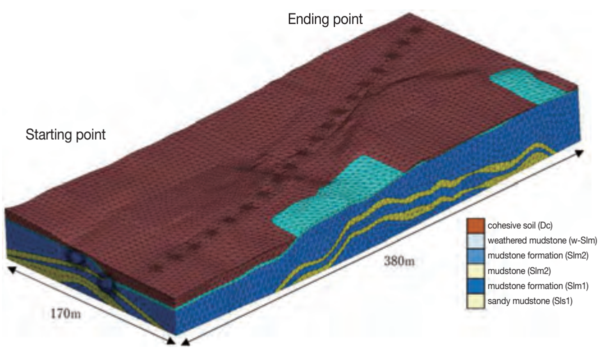

Fig. 2 Three-dimensional model for three-dimensional numerical analysis

Numerical analysis was carried out in two stages: during the design phase and during construction. In the design phase, predictive analysis was carried out to narrow down the countermeasure works. As a result, long steel pipe piling (steel pipe length 9.5 m, one shift length 6 m, circumferential casting interval 450 mm) and early interlocking with primary invert were selected as countermeasure works in the design phase.

Numerical analysis during construction was performed to check the validity of the countermeasure works previously determined. For that purpose, the ground displacements were measured in a test construction to understand the actual ground behavior while the countermeasure works are being implemented. Based on the displacements obtained for each stratum from the test construction, the ground constants were re-established by inverse analysis and predictive analysis was reperformed. The analysis predicted the absolute settlement of the piers to be more than 16 mm (in excess of control level III), so countermeasure candidates A, B and C with upgraded specifications were investigated again. As a result, countermeasure B (with an increased length of the long steel pipe support: 9.5 m → 12.5 m, and an increased angle of hammering: 120° → 160°) was selected capable of reducing the absolute settlement to about control level II (11 mm).

2. Displacement monitoring method

The permissible displacements and control levels of the monorail piers were determined through consultation between the parties concerned. To ensure the safety of monorail operation (trains departed every 10 minutes), the displacement had to be monitored in real time, so automatic measurement of pier settlement and inclination was adopted. The latest measurement results could be viewed on a web page, and an automatic warning e-mail is automatically sent to relevant parties when control levels II and III are exceeded or when displacement increases rapidly. By adopting such a measurement system, the displacement of the monorail piers was monitored 24 hours a day.

3. Construction result

The absolute settlement graph of pier P55, located right above the tunnel, is shown in Fig. 3. All settlements were below control level I. The characteristics of the settlement are as follows:

(i) Although the numerical analysis predicted preceding displacement, no such displacement occurred.
(ii) The maximum settlement per 4 m of tunnel excavation (1.7 mm) was almost the same as the predicted value (1.6 mm).
(iii) The actual settlement turned out to converge when the face had advanced to approximately 25 m forward of the pier.
(iv) The final settlement (7.5 mm) was approximately 60% of the predicted value (12.3 mm).

Compared to the numerical analysis, the actual settlement was smaller, however, the difference was only less than 5 mm. Therefore, it can be concluded that the numerical analysis was able to properly assess the effectiveness of the countermeasure works and substantially predict the actual settlement.

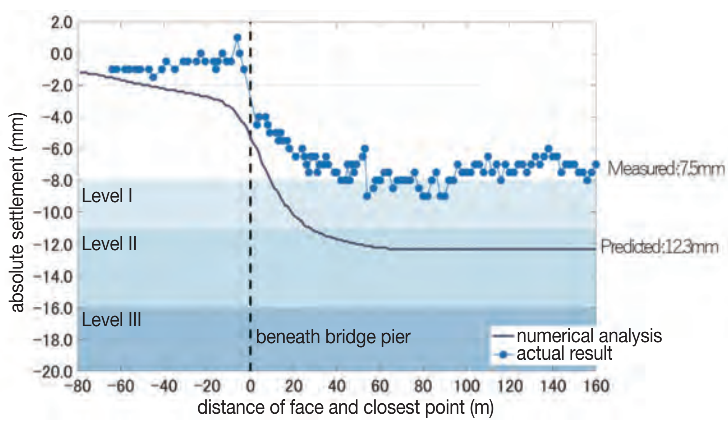

Fig. 3 Settlement graph of P55 (measured and predicted)