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Risk mitigation with measurements while constructing second tunnel adjacent to existing tunnel

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Abstract

In Japan, expressway construction projects have been progressed in which the temporary operated two-way traffic road is converted into separated two-lane for each way traffic roads. Those projects often require the second tunnel close and parallel to the first one. In the Tokai-Hokuriku Expressway, the second tunnel of the 3,221 m long Johana Tunnel is now being constructed by enlarging the existing small tunnel used for an evacuation. The second tunnel, originally excavated by a tunnel boring machine (TBM) for most sections, is enlarged by a conventional drill and blast method. It locates parallelly to the first tunnel with a finished wall-to-wall distance of 17 m. In addition, some of evacuation connection tunnels with a small cross-sectional area between the first and the escape tunnels are going to bere-profiled to provide vehicles with emergency evacuation areas.

To investigate and to restrain the influence of ground deformation and vibration caused by face advances of the second tunnel on the first tunnel, the lining soundness evaluation (crack investigation) has been carried out in advance throughout the entire sections of the first tunnel. During excavation of the second tunnel, tunnel convergence, lining strain for stresses evaluation, and vibration of the first tunnel have been monitored to mitigate the construction risk.

The connection tunnels requiring re-profiling excavation in the proximity of the first tunnel in service may necessitate special consideration on ground conditions and deformation characteristics between two main tunnels. If necessary, auxiliary support methods may have to be adopted in proper time and condition to ensure ground stability. Therefore, horizontal and vertical ground displacements were measured with fiber optic sensing during excavation of the second tunnel before re-profiling the connection tunnels. While re-profiling of the connection tunnels, ground subsidence ahead of the excavation face of the connection tunnel was also monitored to check the ground stability.

This paper reports those measurement methods for mitigating the risk under severe tunnel construction conditions, together with measurement results of the two connection tunnels completed so far.

Keywords

Conventional tunnelling method, Monitoring, Fiber optic sensing, Risk mitigation.

1 Introduction

The construction of the second tunnel in the Johana Tunnel project along the Tokai-Hokuriku Expressway has advanced by enlarging the small tunnel initially excavated by the TBM for the most sections, which serves as an evaluation route. The main purposes are to solve problems with two-lane for two-way traffic expressways such as chronic traffic congestion during tourist seasons and significant car accidents. The second tunnel is parallel excavated 30 m distance away from the center of the first tunnel (the finished sidewall distance will be about 17 m after completion) by a conventional drill and blast method (Fig.1). The excavation was initiated from the North portal in rock layers alternately consisting of andesite and tuff breccia. In the latter half of the tunnel, the excavation face is expected to encounter the tuff and Rhyolite tuff layers which show the long-term swelling behavior. Fig. 2 shows the longitudinal geological profile along the tunnel route. The project started in September 2022 and will complete in September 2027. As of end of 2025, the main tunnel face reached the section 1,900 m from the North portal.

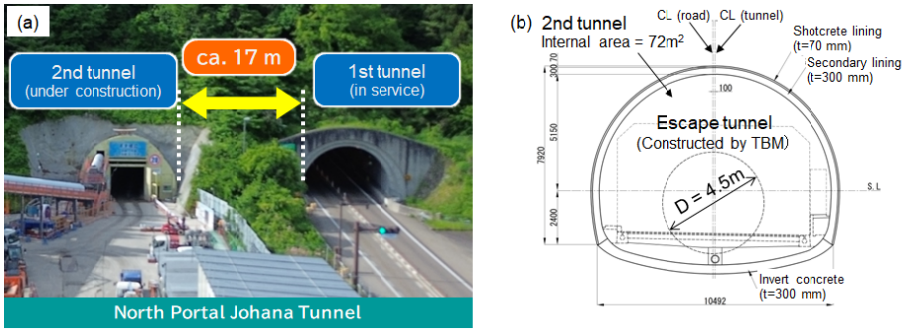


Fig. 1 Photo of the Johana Tunnel and typical cross-sectional drawing of the second tunnel. (a): North portal of Johana Tunnel, (b): Representative cross-sectional view of second tunnel.

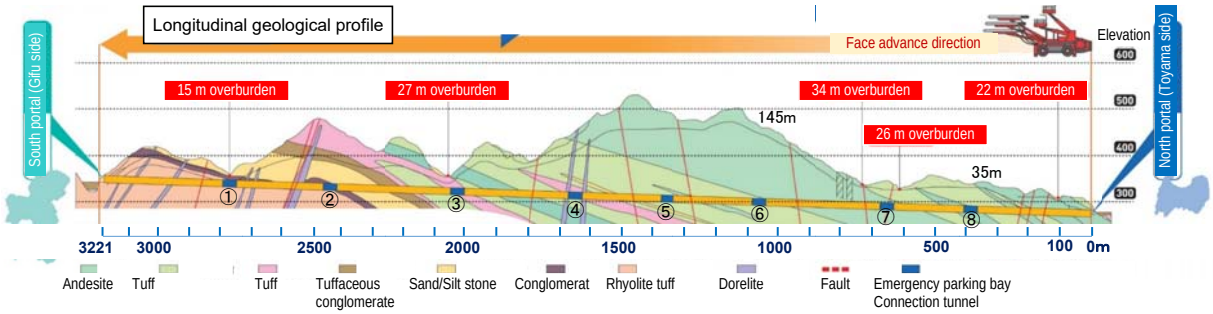


Fig. 2 Longitudinal geological profile of Johana Tunnel.

Besides the excavation of the second tunnel, some of the connection tunnels with small cross-sectional area between the first and the second tunnels are designed to bere-profiled to serve as emergency evacuation routes for vehicles upon completion. In particular, the three connection tunnels out of eight, numbered 2, 6, and 8 (hereinafter, CN2, CN6 and CN8) are to be re-profiled as presented in Fig. 3 (a). After the excavation face of the second tunnel passes these locations, those connection tunnels are excavated by the rock splitting method to minimize excavation influence on existing first tunnel. The main re-profiling procedure is shown in Fig. 3 (b). CN8 and CN6 close to the North portal in Fig. 2 have been completed so far.

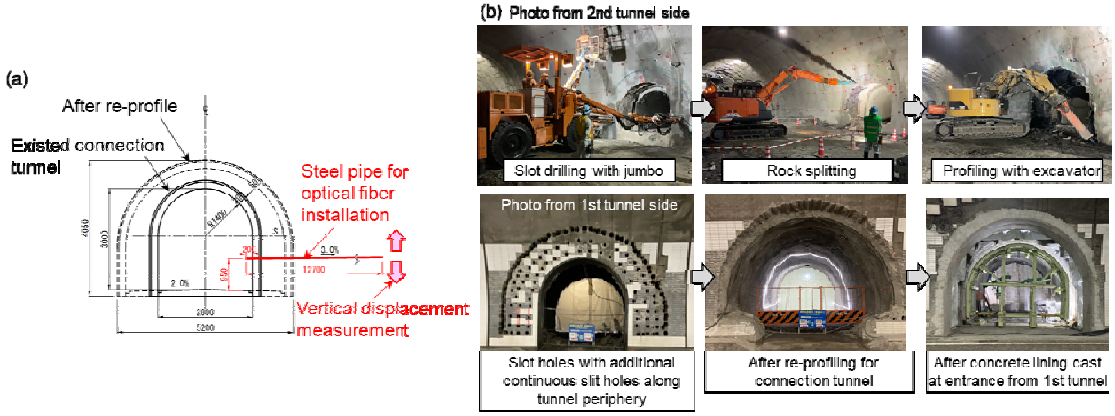


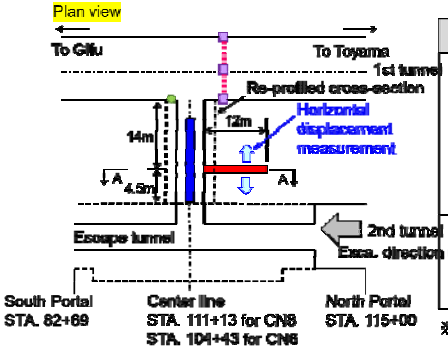
Fig. 3 Cross-section of connection tunnel to be re-profiled (a) and re-profiling procedure (b).

Due to the close and parallel excavation near the existing tunnel, a comprehensive lining soundness evaluation, including crack investigation was carried out the entire sections of the first tunnel prior to the excavation of the second tunnel. While excavating the second tunnel, tunnel convergence, lining strain for stresses evaluation, and vibration of the first tunnel have been monitored to mitigate the construction risk. Especially, the connection tunnels requiring re-profiling excavation in the proximity of the first tunnel may necessitate special consideration on ground conditions and deformation characteristics between two main tunnels in advance. Then, auxiliary measures may have to be adopted to ensure ground stability in case unexpected large deformation is monitored. Therefore, there have been some additional measurement methods installed. The following chapters will report those measurement methods for mitigating the risk under severe construction conditions, together with the measurement results at the two evacuation connection tunnels, namely, CN6 and CN8.

2 Measurement methods

2.1 Measurement items

Fig. 4 summarizes measurements conducted at CN8 and CN6. It is noted that the plan view and the table show special measurement items only, and do not include standard displacement monitoring performed by the geodetic method both in the connection and the second tunnels.



Tunnel	Target	Legend	Quantity	Period	Measurement method
First tunnel	Lining stress (before construction)		1 cross-section	Before construction	Borehole stress relief method (only CN8)
	Lining strain		3 points at a cross-section	During 2nd and connection tunnels excavation	Strain gauge
	Displacement		1 cross-section		Laser displacement meter
Connection tunnel	Ground displacement		12m	During 2nd tunnel excavation	Fiber optic sensing method
	Displacement ahead of face		14.5m	During connection tunnel excavation	Multi-point inclinometer

※Not including displacement monitoring with a certain distance interval in both 2nd and connection tunnels

Fig.4 Measurement items around the connection tunnel.

To assess the increase in displacement and strain of the secondary lining in the first tunnel due to the excavation of the second and connection tunnels, tunnel convergence has been measured using laser displacement meters, while lining strain has been measured by strain gauges on the cross-section close to the opening of the connection tunnels. Fiber optic sensors were implemented during the second tunnel excavation for measuring horizontal and vertical displacements and evaluating ground deformability around the connection tunnels. While re-profiling of the connection tunnels, ground subsidence ahead of the excavation face was also monitored with a multi-point inclinometer to check the ground stability. The following sections will provide a detailed explanation of displacement measurement methods using fiber optic sensors and a multiple-point inclinometer.

2.2 Ground displacement monitoring with fiber optic sensors

One of the authors has developed a tunnel pre-displacement measurement method using fiber optic sensing, which can simultaneously evaluate ground vertical and lateral displacement distributions at the sensor locations in a longitudinal direction (Sakai et al. 2023). The method was applied to monitor ground deformation between two main tunnels. A measurement hole was drilled to a depth of 12.5 m from the inner surface of the connection tunnel (Fig. 3 (a)). The equipment was positioned 4.5 m away from the sidewall of the second tunnel to avoid potential damage from 4-meter-long rockbolts. The instrument with a length of 12 m was then installed in the hole. A steel pipe protected the hole, and its tail end of 200 mm stood out from the lining surface to attach additional measurement instruments.

Fig. 5 illustrates the layout of fiber optic sensors in a steel pipe. Selected All Grating Fibers (AGF) draw gratings on the entire length of the fiber cable (Lindner et al. 2011). The Optical Frequency Domain Reflectometry (OFDR),which realizes a spatial resolution narrower than 1 mm (Igawa et al. 2005) is used to interrogate the AGF. Two pairs of long flat plates composed of polyvinyl chloride (PVC) with an AGF cable attached with an epoxy resin are inserted in a square pipe. In conjunction with the flat plates an inflatable rubber packer is also positioned at the center of the pipe. At the measurement, the rubber packer is inflated by nitrogen gas and allthe flat plates are stiffly impressed

against the inner surfaces of the square pipe. Ground deformation caused by tunnel excavation deflects the longitudinal shape of steel pipe. Correspondingly, the deflected square pipe changes longitudinal strain of the optical fibers on the inner surface of the pipe. The differences in the longitudinal strain of fibers on surfaces facing each other can provide horizontal and vertical curvature factors respectively. Deflection curves in both directions of the square pipe can be acquired by integrating the curvature factors twice from front to end edges. Vertical and horizontal displacements of the steel pipe are also monitored by geodetic measurement at the tail edge of the steel pipe standing out from the lining surface by 200 mm. Vertical and horizontal angle changes of the steel pipe are also monitored by evaluating displacement differences of two contact-type displacement sensors in both directions (Fig. 6 (a)). Fig. 6 (b) depicts the layout of data acquisition devices in the connection tunnel. After the measurement, the flat plates with the AGF cables can be retrieved by deflating the packer. The systems used in CN8 were re-installed in the measurement hole drilled in CN6.

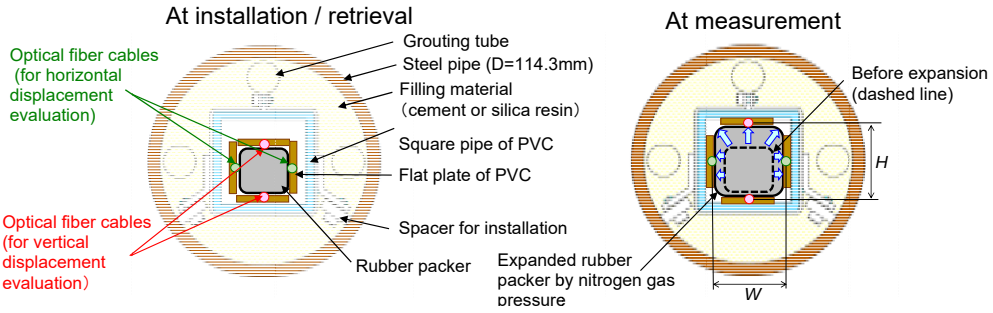


Fig. 5 Structure of ground displacement measurement instrument with fiber optic sensors.

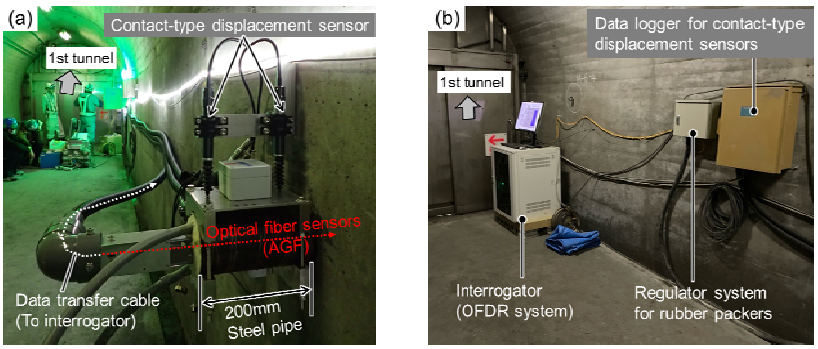


Fig. 6 Measurement instrument for fiber optic sensing: (a) Tail edge of steel pipe; and (b) Data acquisition devices.

2.3 Vertical displacement ahead of excavation face

Vertical displacement ahead of re-profiled excavation face in the connection tunnel was measured with the multi-point inclinometer using Micro-Electrical-Mechanical Systems (MEMS) accelerometers (brand name: Shape Array) measured. The MEMS accelerometer enables to evaluate change in tilt angle as the change in the electrostatic capacity. The inclinometer is a cable-like sensor and serially concatenated in segments through flexible joints (Fig. 7 (a)). Each segment with a MEMS accelerometer is 50 cm in length and 25 mm in diameter. With a guiding pipe (ϕ=38mm), the inclinometer is installed horizontally in a steel pipe drilled from the second to the first tunnels and at the crown level of the connection tunnel, before re-profiling of the connection tunnel starts. During re-profiling, relative settlement to the deepest segment (assumed fixed) is evaluated, integrating the products of each segment length and inclination.

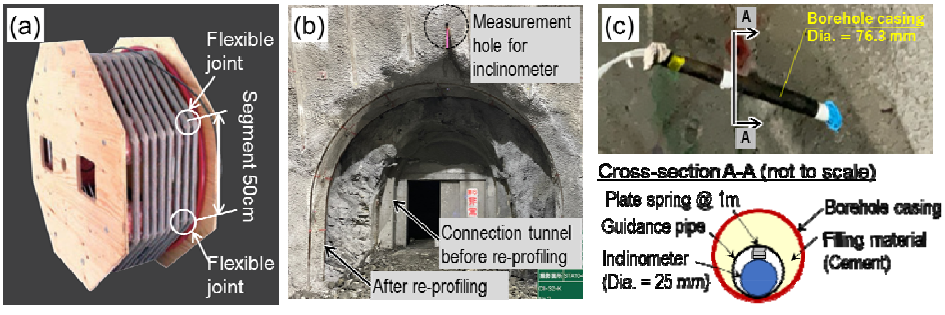


Fig. 7 Measurement instrument for vertical displacementahead of excavation face: (a) multi-point inclinometer (Shape Array); (b) measurement position; and (c) layout of inclinometer in a casing.

3 Measurement results at connection tunnel No. 8

Fig. 8 shows measurement results obtained at CN8. Fig. 8 (a) is measurement results of lining stress and horizontal displacement in the first tunnel, when the excavation face passed the connection tunnel location, and the connection tunnel was re-profiled. Lining stress is evaluated as the product of strain, assuming concrete stiffness is 20 GPa. Measurement data indicated that their chronological developments were less than the lowest alert levels given by previous construction experiences, which were 2.7 N/mm^2 for compressive stress, 0.54 N/mm^2 for tensile stress, and 2.5 mm for both expansive and contractive displacements. It could therefore be concluded that neither the face advances of the second tunnel nor the re-profiling excavation CN8 influenced significantly on the first tunnel.

Fig. 8 (b) shows ground horizontal and vertical displacement developments with face advances of the second tunnel on the cross-section STA. 111+21.5 which is 8.5 m before the center of CN8. Face observation results in the second tunnel's heading clarified competent rock mass mainly composed of stiff andesite around CN8 and categorized as CI (good condition) in the rock mass classification system for highway tunnels in Japan. In the figure, displacement developments predicted by numerical simulations are also drawn, where the rock mass is modeled as elastic continua with the stiffness of CI class (E = 2,000 MPa) and as poorer condition of DI class (E = 500MPa). Those numerical simulations exhibited quite small displacements at the monitoring point during the second tunnel's face advances. In the actual measurement, displacements more than those in the numerical simulations, (1.3 mm of ground settlement and 2.1 mm of horizontal displacement toward the second tunnel) were recorded. It was however concluded that the ground behavior between two main tunnels was in stable condition, since significant increment in the displacement did not develop over time.

Fig. 8 (c) represents crown settlement development versus connection tunnel's face advances on the cross section TD9 m which is the middle cross-section between two tunnels andin which the largest settlement was recorded by the inclinometer. Before the face passed the cross-section of interest, only small settlement was monitored. After face passage, the settlement, however, increased up to 6 mm which was larger than the predicted as the ground subsidence in CI class. Since the value was still lower than alert level I and no noticeable increment was monitored until completion of re-profiling, the behavior was considered local one caused by loosened ground zone around the borehole casing.

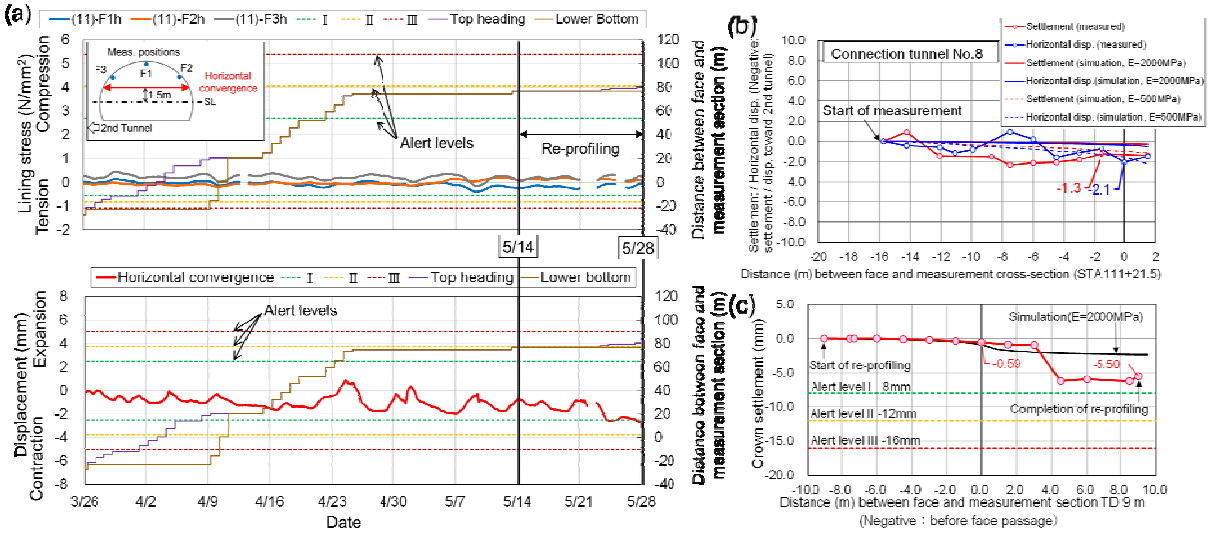


Fig. 8 Measurement results atCN8:(a) Lining stress and displacement development in first tunnel;(b) ground displacement by fiber optic sensing; and (c) ground subsidence ahead of excavation face of connection tunnel.

4 Measurement results at connection tunnel No. 6

Fig. 9 (a) is measurement results of lining stress and horizontal displacement in the first tunnel. The lining stresses measured at crown (F1h) and opposite shoulder of the opening area for the connection tunnel (F2h) sometimes exceeded alert level II in tension when the excavation face of the second tunnel passed the connection tunnel area. After close examination, it was judged that it was the influence of temperature change, since no significant stress development over the face advance was observed. As a fact to reinforce this interpretation, there were no remarkable stress change during re-profiling of the connection tunnel.

Fig. 9 (b) is ground displacements observed on the second tunnel's cross-section STA. 104+55.7 which is 13.7 m before the center of CN6. Larger displacements at CN6 in both directions than those at CN8 were measured since CN6 has larger over-burden and relatively weaker ground conditions classified as CII (one rank poorer than CI) than those of CN8. The measurement revealed that horizontal displacement was almost the same as the estimation by the numerical simulation when the elastic modulus was set at E=1,000MPa, representative stiffness of the ground in CII category. It, however, indicated that the subsidence behavior of ground around CN6 was significantly greater than predicted. Therefore, particular attention was paid to the crown settlement ahead of the face during re-profiling. Nonetheless, the excavation was completed safely without any notable displacements before and after face passage, as shown in Fig 9 (c).

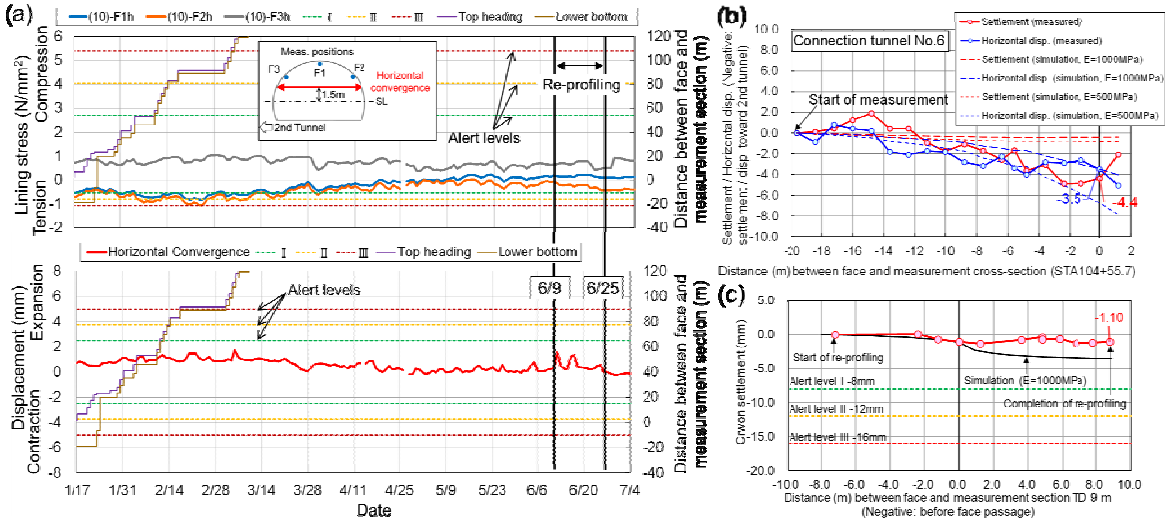


Fig.9 Measurement results atCN6: (a) Lining stress and displacement development in first tunnel; (b) ground displacement by fiber optic sensing; and (c) ground subsidence ahead of excavation face of connection tunnel.

5 Conclusions

This paper reported the schemes and the results of field measurements in the second tunnel construction project of the Johana Tunnel. The second tunnel has been excavated close and parallel to the first one. The measurement objectives in the project were two-fold; to evaluate the influence of the second tunnel excavation on the existing first tunnel in service; and to mitigate construction risks. In particular, the measurements around the re-profiled connection tunnels were explained in detail. They consisted of convergence and lining stress measurements for structural health monitoring in the first tunnel, ground horizontal and vertical displacements measurement by fiber optic sensing, and ground vertical displacement measurement ahead of the connection tunnel with the multi-point inclinometer. Measurement results obtained so far at CN8 and CN6 have exhibited relatively stable ground and safe tunnel structural conditions, and their re-profiling constructions have been successfully completed. Since re-profiling at another connection tunnel is designed in less favorable ground condition, safe and secure construction method should be applied there utilizing these monitoring and evaluation experiences and if necessary, implementing auxiliary ground stabilization methods so as not to suffer from severe damage. The authors hope this case study will serve as a useful reference for similar tunnel construction projects.

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