Monitoring and control system of friction cut plates in the box jacking tunnelling method

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Abstract

The face-less tunnelling method (FLTM) is a new simple tunnel construction method without a working face excavation. The box roof and the friction-cut plate (FCP) are placed along the outer periphery of a box culvert so that soil is enclosed by these elements in the undercrossing area. The box roof connected with the box culvert is pushed out towards the arrival side. During the advancement of the box culvert, the FCP is separated from the box roof and anchored to the starting shaft to reduce friction between the box culvert and soil. The FCP monitoring and control system (FMCS) that is a real-time control system to fix the FCP automatically during the box culvert advancement is developed. The system restrains the FCP by monitoring the displacement of FCP and controlling tensile forces acting between control jacks and the FCP. The FCP is systematically controlled via the solenoid valve control unit while switching between high-pressure and low-pressure states for each control jack based on the measurement of stroke sensors. When the displacement of the FCP exceeds the control value defined in advance, each control jack is automatically switched to high pressure control. In the high-pressure state, the pressure required for the control jack to correct the displacement of the FCP is estimated using the dead load above the FCP. The FCP monitoring and control system was applied to tunnelling work in Nagano. In the project, a single-layer four-span box culvert road tunnel was constructed at the intersection of railway track. A cast-in-place reinforced concrete structure with a width of24.4 m and a height of 7.7 m was placed 0.66 m deep under the ground surface at a section of 11.604 m. Measured horizontal displacements of locations along the railway track showed less than plus/minus 3 mm.

Keywords: Box jacking tunnelling method, Friction cut plate, Face-less tunnelling method, Monitoring, displacement, Pressure

1. Introduction

The box jacking tunnelling method, such as the roof and culvert tunnelling method, and the face-less tunnelling method (FLTM), is one of non-excavation methods used for constructing an underpass tunnel underneath a railway line or road without disrupting traffics for shallow earth coverage. The box jacking tunnelling method has been grade-separated intersections underneath a railway line. In this method, square-shaped steel elements called box roof are placed along the outer periphery of a box culvert into the ground across the existing railway/road to protect the tunnel face and railway/road. Subsequently, a box culvert placed behind the box roof is pushed forward and replaced with the box culvert in place. An advantage of this method is that it can construct an underpass tunnel with shallow earth coverage without leaving a box roof as a protective shield in the ground. A sliding-steel plate called friction-cut plate (FCP) is placed between a box culvert and its surrounding soil to reduce frictional forces during the jacking process of the box culvert. Further, the FCP plays an essential role in suppressing ground deformation. The FCP needs to be fixed in the construction yard of the launch side because the drag force acts on the FCP during the advancement of the box culvert.

It is important to effectively perform the box jacking operation while minimizing railroad-track displacement during the advancement of the box culvert and the pipe roof incorporating automatic controlled system including the railroad-track monitoring, construction operation and mitigation measures (Nakamura et al., 2016; Nakamura et.al, 2017). An effective FCP fixing method can be selected depending on construction scale and topographic condition.

This study presents construction cases for adopting a FCP fixing method called an automatic friction plate monitoring and control system (FMCS) comprising stroke sensors, hydraulic pumps, solenoid valve control unit, FCP control jacks and control computer (Funakoshi, 2015). FMCS is a real-time control system that automatically controls to restrain the FCP by monitoring the behaviour of the FCP and tensile forces acting between control jacks and the FCP. The FMCS is used to a FLTM construction work of a four-span rectangular tunnel under passing a railway track in Nagano prefecture, Japan. The measured horizontal displacements of locations along the railway track due to the construction work showed within 3 mm.

2. Overview of FLTM and FMCS

2.1 Face-less tunnelling method (FLTM)

The FLTM is a refined the box jacking tunnelling method and it is a simple tunnel construction method without a working face excavation.

As shown in Fig. 1, the box roof and FCP are placed along the outer periphery of a box culvert so that soil is enclosed by these elements in the undercrossing area. Then, the box roof connected with the box culvert is pushed out towards the arrival side. During the advancement of the box culvert, the FCP is separated from the box roof and anchored to the arrival shaft to reduce friction between the box culvert and soil. After the box roof and soils enclosed within the box roof are pushed towards the arrival shaft, box roofs are disassembled and soils are removed.

In this construction site, a total of 56 rows of box roofs with a 12-m long (3 m * 4 pieces) culvert was arranged (Fig. 2), and box roofs integrated with the box culvert was moved forward.

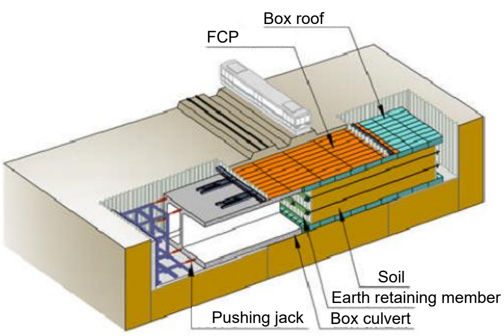

Figure 1: Schematic diagram for FLTM.

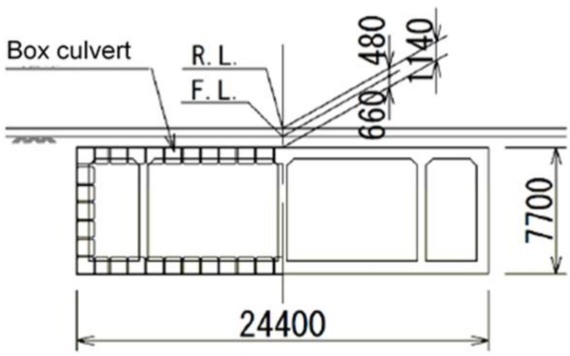

Figure 2: Cross section of box culvert.

2.2 Friction-cut plate monitoring and control system (FMCS)

FMCS is the automated control system to restrain the FCP by monitoring the displacement of the FCP and tensile forces acting between control jacks and the FCP. FMCS comprises stroke sensors to measure the horizontal displacement of FCP, hydraulic pumps, solenoid valve control unit, FCP control jacks and control computer (Fig. 3). The FCP is automatically controlled via the solenoid valve control unit while switching between high-pressure state and low pressure state for each control jack based on the measurement of stroke sensors. When the displacement of the FCP exceeds the control value defined in advance, each control jack is automatically switched to high-pressure control.

In the high-pressure state, the pressure required for the control jack to correct the displacement of the FCP is estimated using the dead load above the FCP. In the low-pressure state, the control jack to apply constantly transmits the tensile force to the FCP during the advancement of the box culvert and to maintain the horizontal position of the FCP. In this way, FMCS repeatedly switches to the low-pressure state for maintaining the horizontal position of the FCP and the high-pressure sate for correcting the displacement of the FCP if it exceeds the control value, as shown in Fig. 4.

The control value for the displacement of the FCP varies depends on the scale of construction and site conditions.

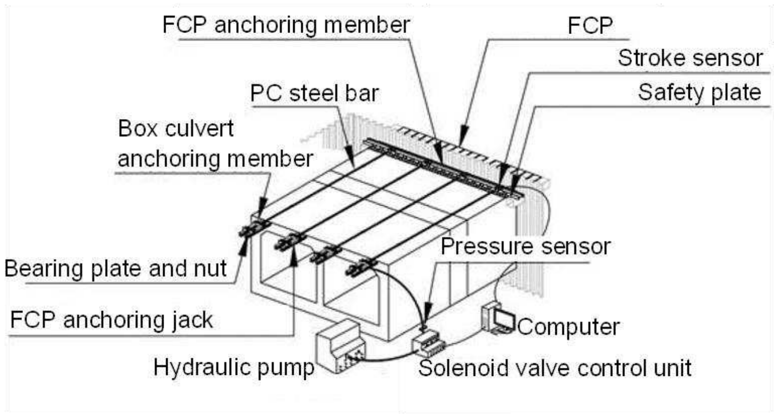

Figure 3: Schematic diagram for FMCS

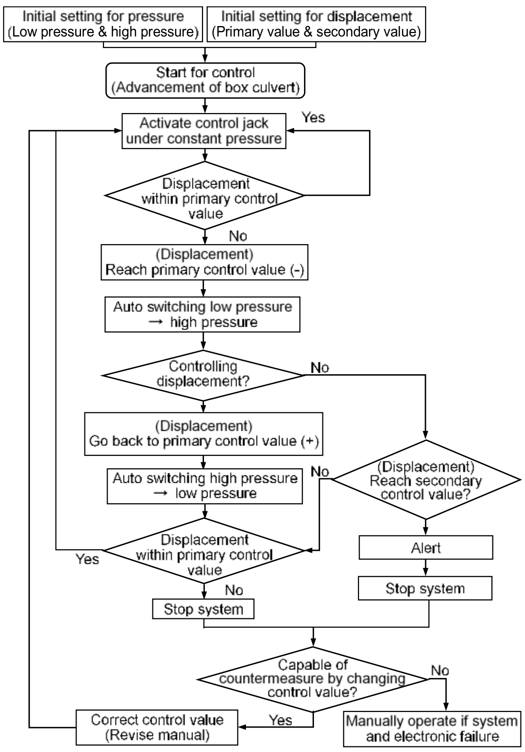

Figure 4: Flow of FMCS

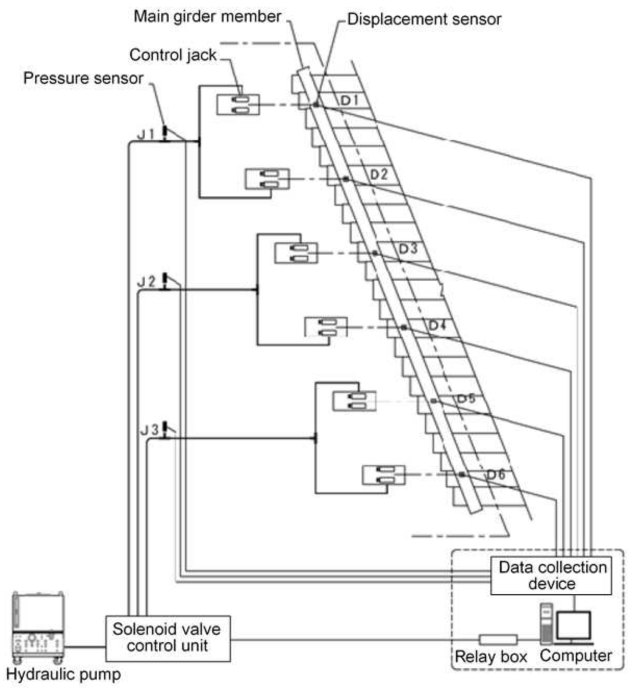

Figure 5: Entire system of control jacks controlling displacement sensors and pressure sensors

3. Field Investigations

3.1 Construction overview

A construction work as a part of the development project by Nagano prefecture was conducted in a 900-m unconstructed section at the intersection of Nagano Yoshida High School East and Kirihara on Takada Wakatsuki Line Urban Planning Road connecting the northern and central parts of Nagano City. In this project, a single layer four-span box culvert was constructed at the intersection of Nagano Line of Nagano Electric Railway and Takada Wakatsuki Line (Fig. 2). Using the FLTM, a cast-in-place RC structure with a width of 24.4 m and a height of 7.7 m was placed 0.66-m deep under the earth’s surface at a section of 11.604 m.

3.2 Implementation of FMCS

3.2.1 FMCS equipment

The entire FCPs were horizontally connected at the edge of FCPs via the main girder member. These integrated FCPs were adjusted via six control jacks attached to the top of the box culvert. The six control jacks were divided into three groups (J1, J2, and J3). Here J1 (Nagano side), J2 (centre part) and J3 (Suzaka side) comprise two control jacks each. The movement and applied pressures of these six control jacks were independently controlled based on the output of horizontal displacements measured at D1-D6, as shown in Fig. 5.

3.3 Setting for FMCS

3.3.1 Control value

The control value for switching from low-pressure to high-pressure states is set to ±3mm because the standard value for the track maintenance of Nagano Electric Railway is±7mm.

3.3.2 Setting value for low pressure

A setting value for low pressure is calculated using the following equation based on the idea that the frictional resistance as the tensile force acts on the FCPs due to the dead load above the advancing box.

Table 1 presents the values calculated using Eq. 1.

$$T = W \cdot A \cdot \mu \tag{1}$$

where T: Tensile force acting on FCP (kN)
W: Dead load acting on FCP (kN/m^2)
A: Top surface area of box culvert (m^2)
μ: Coefficient of friction (0.5 for assumed value)

	Calculated value	Note
Dead load acting on FCP: Z	20.56 kN/m^2	Railway truck structure + Earth coverage
Top surface area of box culvert: A	243.56 m^2	Width 22.4 m x Length 99.993 m
Tensile force acting on FCP: T=2,506.6 kN		

Table 1: Calculated value of tensile force action on FCP.

A setting value for low pressure exceeding the expected T (kN) is calculated by the following equation

$$T \leqq P = X \times k \times N \tag{2}$$

where P: Required tensile force (kN)
X: Setting value for low pressure (MPa)
k: Conversion factor (30.6)
N: Number of control jacks

Since 12 control jacks were used, the setting value for low pressure X becomes $X \geqq 6.83$ (MPa). During the construction, the value of 8 MPa was used as the initial setting and the degree of pressure was adjusted as the construction progressed.

3.4 FMCS operation record

Figs. 6 and 7 show the control records of the displacement and pressure during the advancement of the box culvert on the night of 4 February, 2016, respectively. As shown in these figures, displacements of the FCP and pressure are plotted between 23:00 and 2:30, respectively. Further, these figures show the measurement results obtained from displacements at D1 to D6 corresponding to locations of control jacks and pressures in J1-J3. The discontinuous parts of the graph indicate the duration of the suspension of the advancement of the box culvert.

On this night, the advancement process of the box culvert was divided into five categories. During the advancement, the horizontal displacement of the FCP lay within the control value of ±3 mm and a pressure of 10MPa was applied. Additionally, there was no correction of the FCP displacements at the high-pressure state. The advancement process of the box culvert was performed for 11 days (26 January and 6 February, 2016). Similarly, the horizontal displacement of the FCP was within the control value of ±3 mm with a pressure of 8-12MPa.

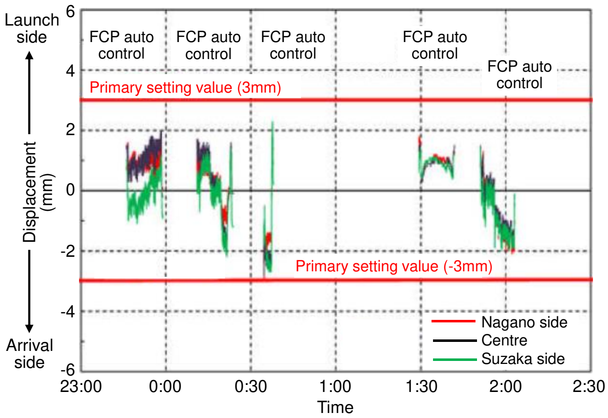

Figure 6: Automatic control records of the displacement during the advancement of the box culvert on the night of 4 February, 2016.

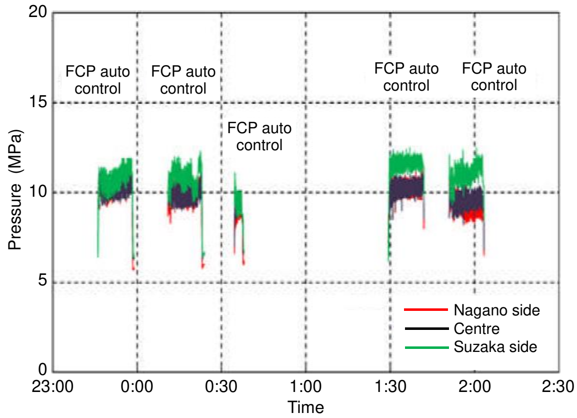

Figure 7: Automatic control records of pressure during the advancement of the box culvert on the night of 4 February, 2016.

3.5 Horizontal displacement of railway track

During the advancement process of box culvert, the railway line inspection was conducted to check rail gauge, vertical and horizontal level and rail distortion. Additionally, the lateral displacement of the railway track was measured at the construction site. The main purpose of this measurement was to compensate for the horizontal displacement of the railway track due to the movement of the FCP controlled by FMCS. A total of 12 measurements located 5 m apart (6 locations/railway line × 2 lines) were selected along the inbound and outbound railway lines where the box culvert crossed (Fig. 8).

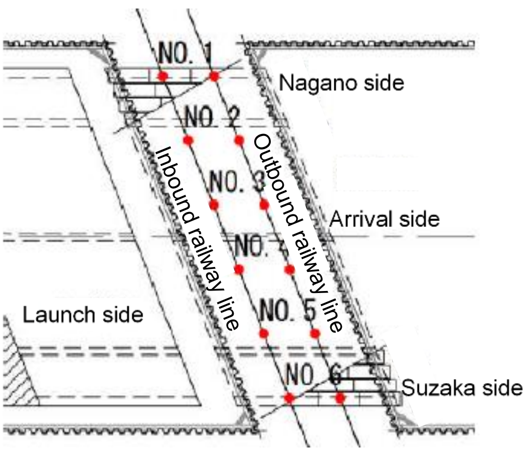

Figure 8: Measurement locations for horizontal displacement of railway track.

Table 2 lists the measurement results for the inbound railway line during the advancement process of the box culvert on 26 January 2016. Since the construction site was located within the straight railway section, the reference line of 190 mm apart from the rail was set along the railway track. The horizontal distance of the railway track for each location was measured on the basis of the reference line. The initial values presented in the table were measured before the advancement of the box culvert; these values were used as the reference values.

The distance measured before and after the advancement of the box culvert was used to calculate the horizontal displacement of the railway track. If the distance before the advancement is longer than one after the advancement, the displacement will have a positive value, including that the railway track is moved towards the launch side. Alternatively, if the distance before the advancement is shorter than one after the advancement, the displacement will have a negative value, indicating that the railway track is moved towards the arrival side. Since the horizontal displacement of the railway track was secondarily measured, values of the displacements before and after the advancement were obtained for nine days among 11 days of the advancement processes.

Table 3 presents the horizontal displacements of 108 locations (6 locations/railway line * 2 lines * 8 days). Based on the operation of FMCS with the control value of ±3 mm, 80% of measurement locations along the railway track show horizontal displacement values within ±3 mm. So far, beneficial outcomes have been gained from FMCS adopted in this construction to control displacements of the FCP and railway track.

Measurement location		Control value (mm)	Initial value ① (mm)	Before advancement (mm)		After advancement (mm)		Direction of displacement To launching side → To arrival side ←
				Measurement value ②	Difference from ①	Measurement value	Difference from ②	
Nagano side	No.1	190	187	186	1	185	1	←
	No.2	190	180	179	1	180	-1	→
Centre	No.3	190	180	181	-1	182	-1	→
	No.4	190	184	184	0	186	-2	→
Suzaka side	No.5	190	180	180	0	182	-2	→
	No.6	190	186	185	1	185	0	0

Table 2: Measurement results for inbound railway line during the advancement process of the box culvert on 26 January 2016.

Measurement location		← Launching side			Movement		Arrival side →		Total number of locations
		6<*d*	3<6≤d	0<d≤3	0	-3<d≤0	-6<d≤-3	d<-6	
Nagano side	No.1	0	1	5	5	6	1	0	18
	No.2	0	1	5	3	7	1	1	18
Centre	No.3	0	1	5	3	8	1	0	18
	No.4	0	3	3	2	8	1	1	18
Suzaka side	No.5	0	3	6	0	8	0	1	18
	No.6	0	3	3	2	8	1	1	18
Total		0	12	27	15	45	5	4	108
Rate (%)		0.0	11.1	25.0	13.9	41.7	4.6	3.7	100%
		11.1		80.6			8.3		100%

Table 3: Horizontal displacements of 108 locations (6 locations/railway line * 2 lines * 8 days).

4. Conclusions

This study described an application of the Friction-cut plate monitoring and control system (FMCS) used to the Face-less tunnelling method (FLTM) in the construction work of four-span rectangular tunnel under passing a railway track in Nagano prefecture, Japan. The integrated friction-cut plates (FCP) were adjusted via six control jacks attached to the top of the box culvert and the railway line inspection was also conducted to check rail gauge, vertical and horizontal level and rail distortion during the advancement of the box culvert. Overall, in most of the measurement locations over 108 locations, horizontal displacements along the railway track indicated less than plus/minus 3 mm. So far, the adoption of the FMCS can be anticipated to control displacements of the FCP and railway track effectively in the FLTM.

Factors such as earth coverage, railway track structure, elongation of the FCP, directional correction of the advancement of box culvert affects the results of the horizontal displacement of the FCP, correction of the displacement controlled by FMCS and displacement of railway track.

Therefore, further progress in the analysis of recodes obtained from the present construction and collection of data from similar construction cases is required to improve the presented system and to make clear the characteristic of the interactions.

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