The 9th International Symposium on Automation and Robotics in Construction June 3-5, 1992 Tokyo, Japan

# Automatic control system for the shield tunnelling machine

Tsutomu Nakanishi, Mamoru Hirabayashi
Technology Development Division
Kumagai Gumi Co., Ltd.

2-1 Tsukudo-cho Shinjuku-ku
Tokyo, 162, Japan

## Abstract

In the recent shield tunnelling, various requirements are singled out as targets to overcome for the purpose of meeting the varied social needs; as such requiremets, there are lengthening of tunnels, boring at deeper levels, construction of tunnels of larger section, etc. But, for solving these problems, the works management is assumed to become more and more difficult. Having taken sufficient account of the background, development of an automatic control system of the shield tunnelling machine was started setting up the target of labour saving and ensuring of higher work quality.

This system is composed of two sub-systems ; one is the automaticsurvey system which features measuring continuously the position and direction of the shield machine referring to the planned tunnelling route, and the other is a computerized direction control system which maintains the shield machine in an appropriate position or attitude in relation to the planned tunnelling route.

## 1. Introduction

In recent years, automation and labor-saving of the construction works have been seeked for, because we are now entering into the high aged society suffering lack of qualified workers. On the other hand, the shield method, as technology of driving tunnels which, for enhancement of underground utilizations, is attracting keen attention of people, does itself justice in stabilization of cutting faces, driving and segment-lining, but confronts necessity of automation and labour-saving for the reasons of improvement of environmental and working conditions, higher efficiency of works and enhancement of safety.

The shield method needs an adequate direction control in such a way that tunnelling may be performed accurately along the planned route, always grasping the position and attitude of the shield machine to implement the construction of high precision and high efficiency.

This project is intended to develop a system capable of selecting an optimum jack pattern so that the shield machine may advance precisely along with the planned route, using the real time data of position and attitude.

## 2. Configuration of the system

As shown in Figure 1, the attitude control system is composed of an automatic survey system and direction control.

(1) Automatic survey system ; having an optical receiver unit and a signal processing unit on the shield machine's side, the survey system receives laser beams from the laser emitting unit which is located backwards in the tunnel to detect the position and the azumith. Furthermore, there is an electro-optical distance meter at the laser

emitting unit; this distance meter measures the distance to the leaser receiving part to transmit the data to the central control room on the surface for the purpose of calculating and displaying the deviation azimuth from thc planned route.

(2) Direction control system : this direction control system sends driving and control information from the shield machine control panel to a control computer. After receiving survey data, the system sends an optimal jack pattern which is selected from the calculation based on the already excavated route to the shield control panel so that the shield machine may arrive precisely at the target on the route.

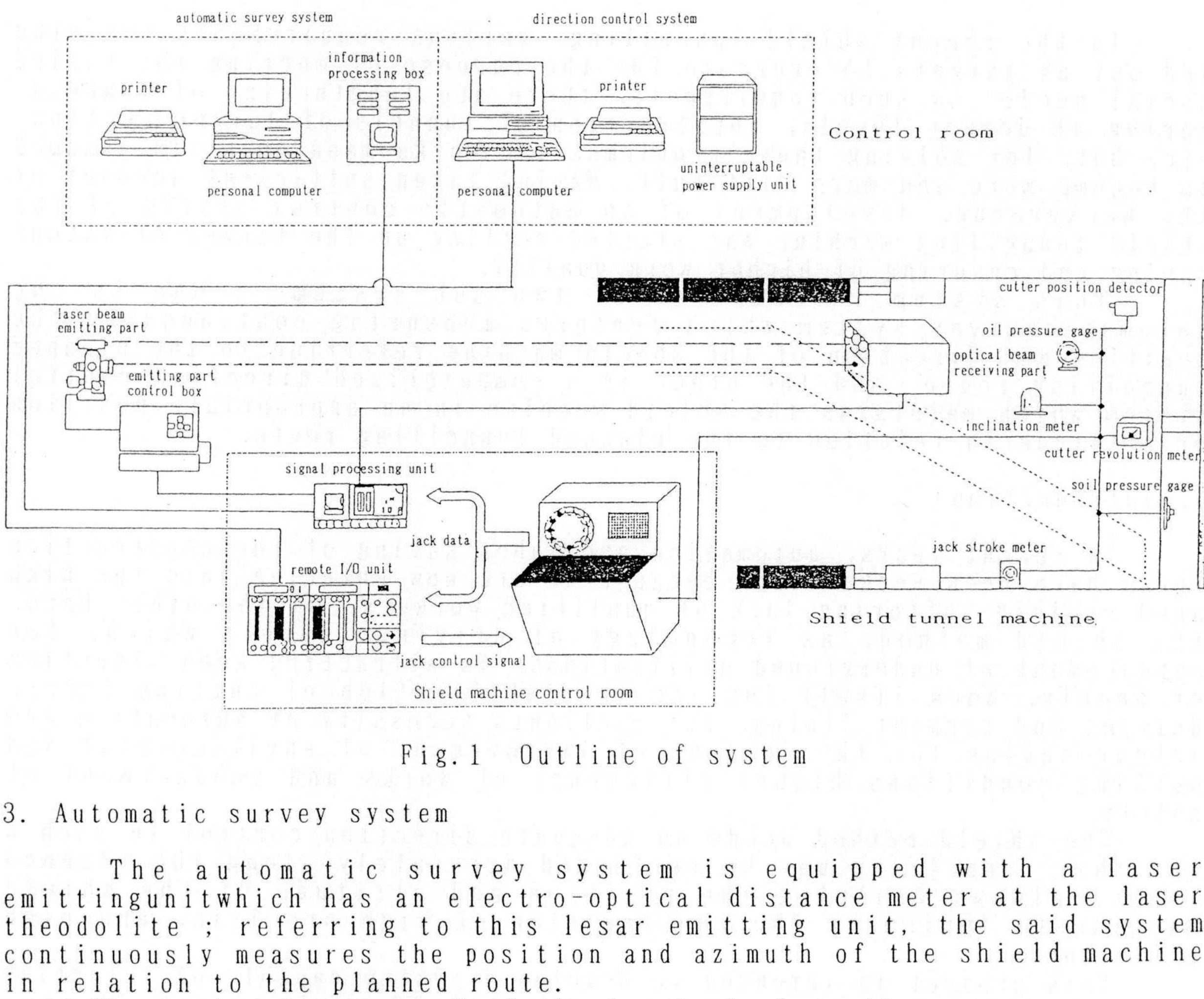



Fig.1 Outline of system

## 3. Automatic survey system

The automatic survey system is equipped with a laser emittingunitwhich has an electro-optical distance meter at the laser theodolite ; referring to this lesar emitting unit, the said system continuously measures the position and azimuth of the shield machine in relation to the planned route.

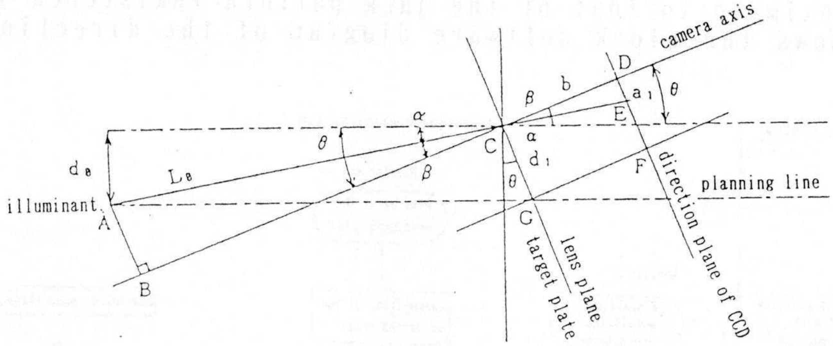
The system is composed of the 4 principal sections ;

(1) Laser beam emitting part
(2) Optical beam receiving part
(3) Signal processing part
(4) Information processing part

The magnitute of deviation is detected by a CCD camera, emitting the laser beam to the receiving plate of the optical receiver which is installed in the shield machine, and using as a reference beam (He-Ne laser) the laser beam coming from the laser theodolite at the laser emitting part.

Detection of azimuth is made by a CCD camera existing at the optical receiver, aiming at the point laser beam (Ga-As laser) coming from the electro-optical distance meter at the emitting part, and the azimuth thus detected is represented in pitching angle and yawing angle.

Fig. 2 shows the principle of measurement, and the deviation from the reference route is calculated by determining the horizontal deviation and yawing angle, and the vertical deviation and pitching angle.




$L_0$ : Distance between the illuminant and the target plate (lens plane)

$d_0$ : Deviation amount from the planned tunnelling route

$\alpha$ : Directional correction angle

$\beta$ : Angle formed between the shield machine in relation to the planning route

$\theta$ : Deviation in yawing of the shield machine in relation to the planning route

$d_1$ : Slanting distance detected by the deviation detecting camera (primary data after rolling correction)

$a_1$ : Deviation amount on CCD detected by the azimuth detecting camera (primary data after rolling correction)

b : Distance between the lens center and CCD plane of the azimuth detecting camera

Fig. 2 Principle of measurement

In Figure above, the deviation amount and azimuth are expressed by the following equations :

Deviation amount : $d_0 = d_1 \cos \theta$

Azimuth depending on deviation : $\alpha = \sin^{-1}(d_0/L_0)$

Azimuth of the shield mancine axis to the illuminant : $\beta = \tan^{-1}(a_1/b)$

Azimuth of the shield machine in relation to the planned route : $\theta = \alpha + \beta$

## 4. Direction control system

In this system, the turning moment of the shield machine which isnecessary for the directional correction angle-based azimuth control is calculated using the data on the already tunnelled route, so that the shield machine may successfully arrive at a target provided on the planned route, referring to the data of the vertical and horizontal deviations as well as yawing and pitching angles.

From this turning moment, the movement equation of external forces at the in situ and the thrust exerting the shield machine in the soil are modelled and the model parameters are determined using the tunnelling-directional data of the already completed route to establish the optimal jack pattern. Furthermore, the shield machine is given the jack pattern whose force-exerting point (jacking point) is the most approximate to that of the jack pattern registered in advance.

Fig.3 shows the block software diagram of the direction control system.

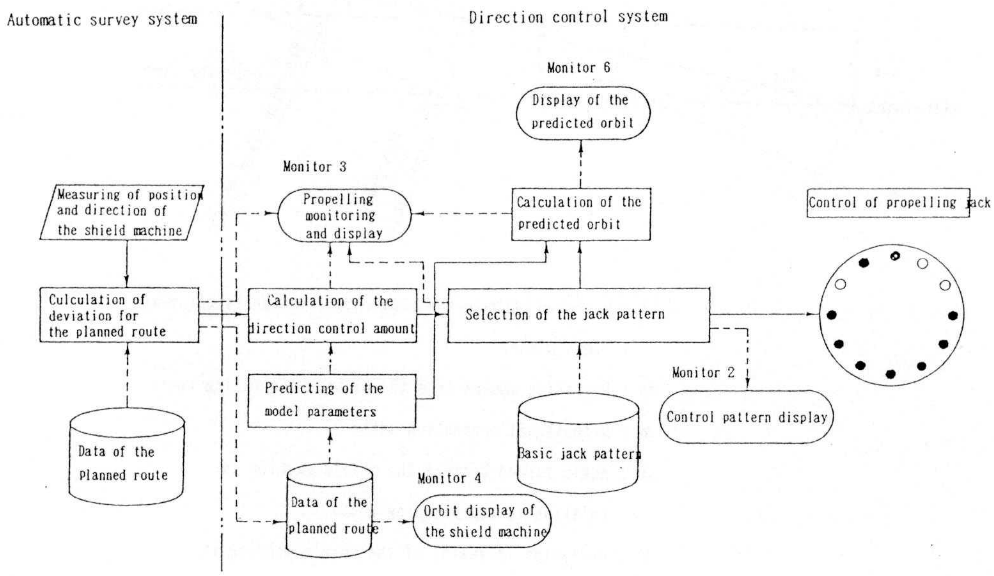



Fig.3 Block software diagram

The control and calculation method for the direction control system is given below;

(1) Calculation of the directional control amount

Based upon the deviation and direction data of the shield machine from the planned route, the directional correction angle is determined which is required to reduce to zero the deviation which may occur after the shield machine has covered the target distance. Fig. 4 shows the direction control amount.

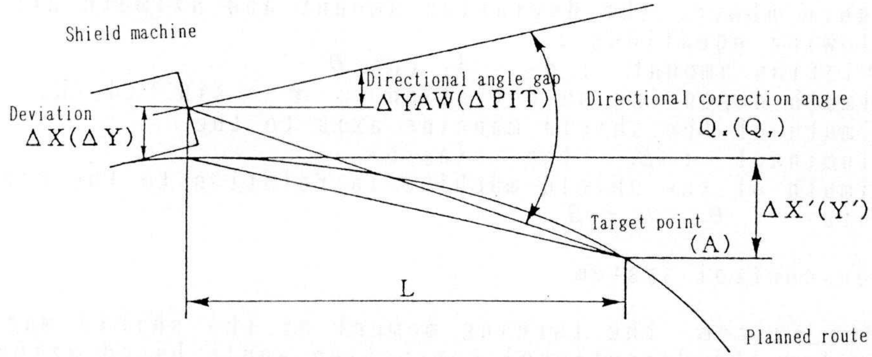



Fig.4 Calculation of the direction control amount

Letting L be the distance to the target (A), and $\Delta X(\Delta Y)$ and $\Delta YAW(\Delta PIT)$ respectively the deviation and azimuth from and to the planned route, the correction angles in horizontal and vertical directions are Qx and Qy are given by the following equations;

$$Qx = \Delta YAW + \tan^{-1}((\Delta X + \Delta X')/L) \quad (1)$$
$$Qy = \Delta PIT + \tan^{-1}((\Delta Y + \Delta Y')/L) \quad (2)$$

From the correction angles Qx and Qy above, the stroke differences between the propelling jackes are determined .

(2) Deviation model of the shield machine

The relationship between the horizontal/vertical moments and the stroke difference, which is necessary for the shield machine to turn adequately during its advancement by one ring is computed from the data concerning the already tunnelled route.

The turning movement of the shield machine is modelled by the expressions below;

$$\Delta STx/\Delta t = Ax \cdot Fj\ (X + Bx) \quad (3)$$
$$\Delta STy/\Delta t = Ay \cdot Fj\ (Y + By) \quad (4)$$

In other words, the variation amount of stroke differences per time can be expressed in moment (thrust x force-exerting point).

Here, the parameters Ax, Bx, Ay and By are calculated through a statistical processing, as they are determined according to the in situ soil, driving direction (straight and curved lines), etc.

(3) Force equilibrium model

As shown in Fig. 5, the force equilibrium model is constructed with the external forces, friction force and jack-propelling force which exert from the in situ to the shield machine when the said machine is propelling.

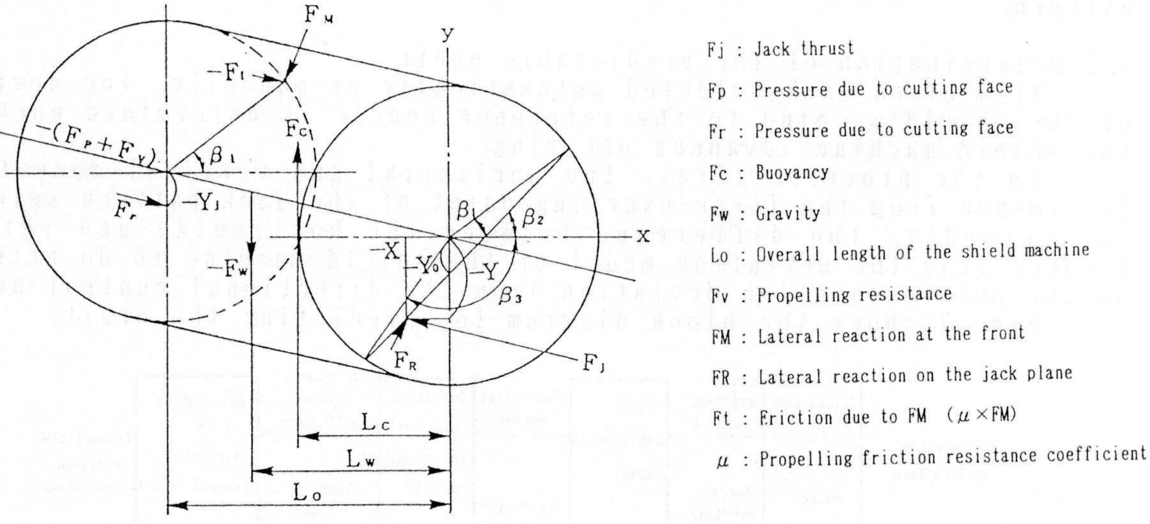



Fig.5 Force equilibrium model

For this model, the unknown constants are the propelling resistance (Fv) and propelling friction coefficient ( $\mu$ ) both of which are estimated from the available data on the already excavated route to determine the relationship between the exerting force and the thrust for the next ring.

(4) Selection of the jack pattern

From the direction control amount calculated, the difference in stroke between the horizontal and vertical direction is determined to calculate the horizontal and vertical moments on the basis of the deviation model of the shield machine.

The optimal force-exerting point which may generate the this moment shall be determined from the force equiliblium model.

Futhermore, the most approximating pattern, for the purpose of realizing the determined force-exerting point, is selected from those on the Table of Registered Basic Jack Patterns.

Fig. 6 shows the block diagram for selection of jack patterns.

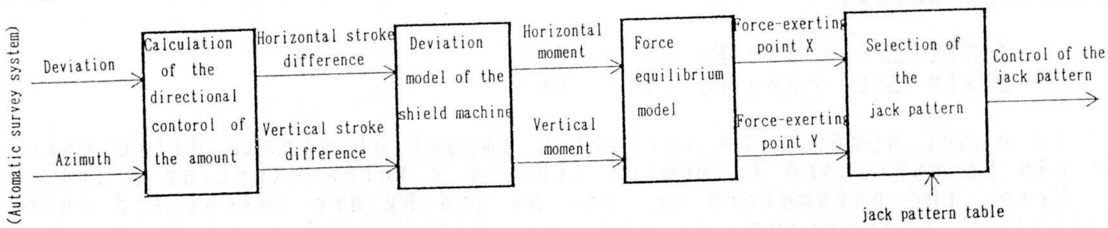



Fig.6 Block diagram for selection of the jack pattern

The modification of the jack pattern during its advancement by one ring is made by putting on or off some of vertical and horizontal jacks, in the case the jack stroke difference or yawing and pitching angles exceed their respective reference values every time the jacks are extended 20 mm.

In addittion, at each jack stroke of 100 mm, determination of the optimal force-exerting point is made again to establish a new jack pattern.

(5) Determination of the predictable orbit

At a given jack selected automatically or manually, the deviation of the shield machine to the reference course is determined each time the shield machine advances one ring.

In the process, first, the horizontal and vertical moments are determined from the force-exerting point of the jack pattern selected, and secondly, the difference between the horizontal and vertical strokes from the deviation model of the shield machine to do arthmetic on the post-excavation deviation from the directional control amount.

Fig. 7 shows the block diagram for predicting the orbit.

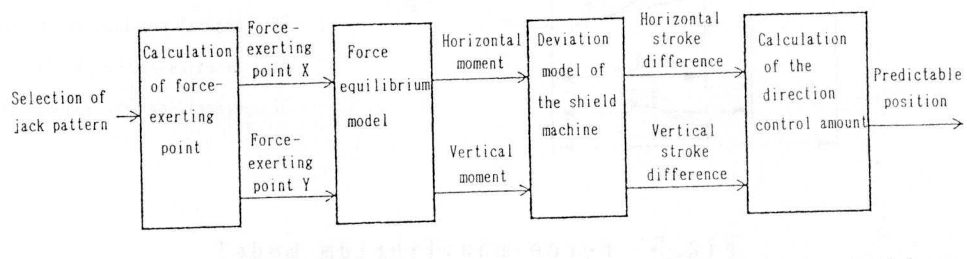



Fig.7 Block diagram of determination of the predictable orbit

The directional control system is provided with 6 CRT screens for the dialogue between the man and shield machine via computer; the CRT screen changes as the excavation advances and it is possilbe as well for the operator to change the screen from the keyboard.

## 5. Experiment

The results of the shield excavation which was started in June 1990 at Yokohama City is discussed as a site experiment.

The shield machine is of the closed type which measures 6,150mm in outer diameter and 6,950 mm in length. The tunnel is of the inner diameter of 5,000 mm in finished state, and of the total length of 2,060 m with a rising gradient of 0.9‰.

As an experiment result, the deviation traces in horizontal an d ertical directions are shown respectively in Figs. 8 and 9, estimating the model parameters from a straight manual excavation of about 50 m.

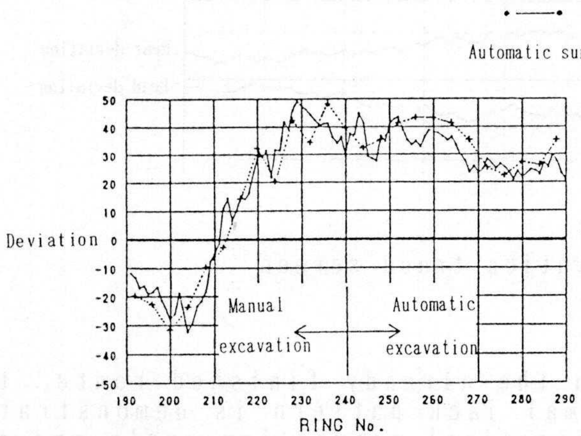



Fig.8 Horizontal direction deviation trace

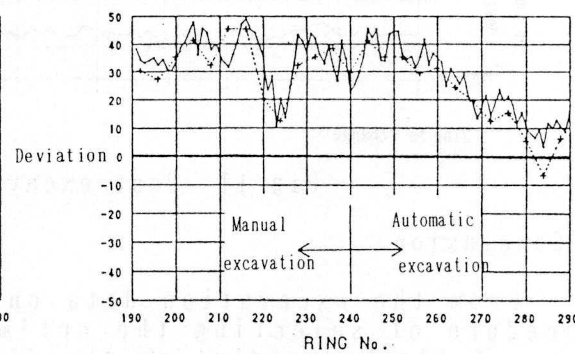



Fig.9 Vertical direction deviation trace

When compared with the manual excavation, the automatic one is revealed to be a rather smooth trace approximately following the planned route.

If the survey modes, automatic survey and site survey are compared in precision, the difference between them is +/- 10 mm or less

The length automatically measurable for the straight section is about 250 m, and if the shield machine bores exceeding this limit, the laser emitter should be reajusted in location.

Fig. 10 depicts, for the directional control system, the excavation-monitoring screen and Fig. 11 the post-excavation trace screen.

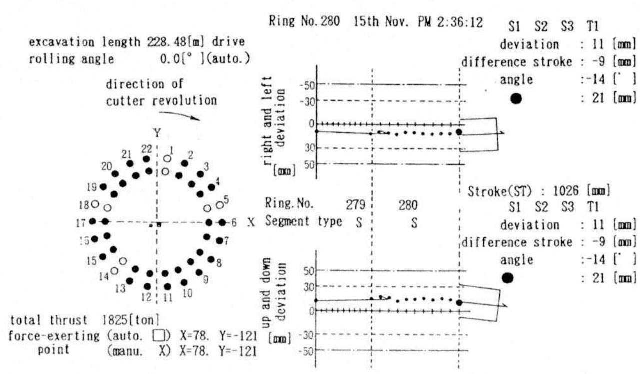



Fig.10 Excavation monitoring screen

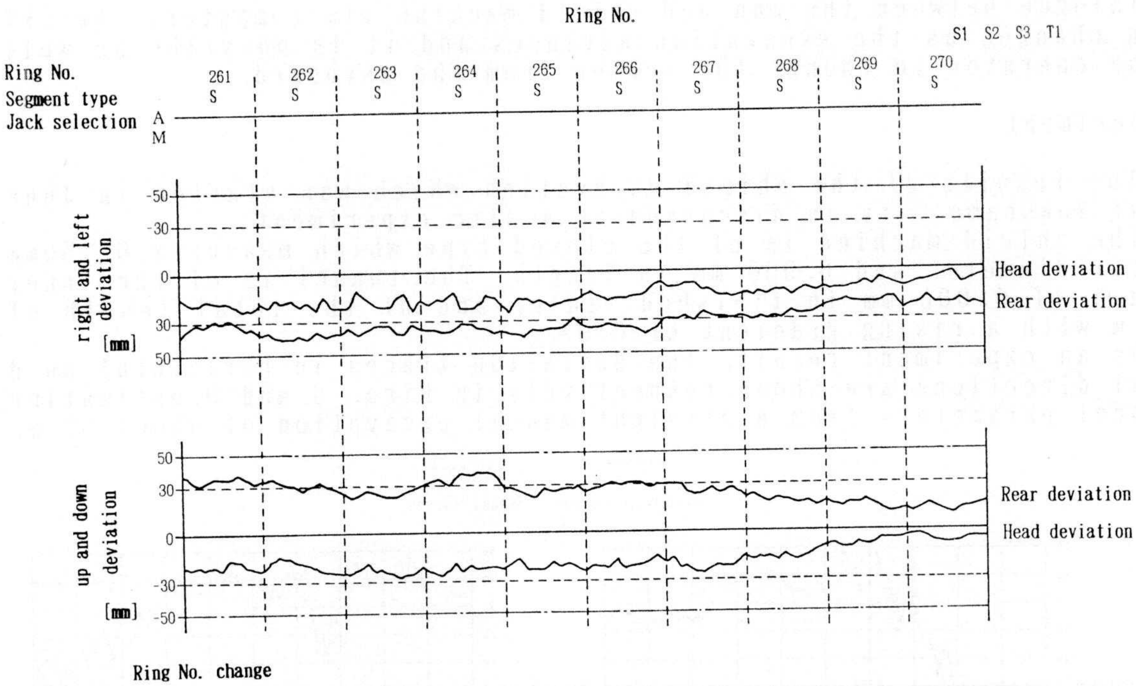



Fig.11 Post-excavation trace screen

## 6. Conclusion

From the excavation data on the already finished route, the procedure of selecting the optimal jack pattern is demonstrated successfully by predicting the directinal correction angle and the deviation moment for the shield machine, and computing the relationship between the thrust and the force-exerting point of the jack.

In the future, We Kumagai Gumi schedule development of a furth er advanced control system for the shield machine, compiling the data of soil, machine type and machine form.

### Reference

"Development of the Direction Control System for the Shield Tunne lling Machine with an Orbit Prediction Function",
S.Kanno, N.Sasaki, A.Hirata
Mechanization of Construction, 88.11.