Hyper-Shield System Achieves Automated Excavation

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Abstract

The hyper-shield system developed by Fujita Corporation is used to perform automatic excavation of tunnels. The system, applicable to either the slurry or the earth-pressure method, employs the pivotal technologies of artificial intelligence and fuzzy logic to automatically control excavation of tunnels. Also the system allows for its travel along a planned path, in ways which can prevent the ground surface immediately above the tunnel being excavated, from subsidence and upheaval. This paper outlines the hyper-shield system, together with the report of its first, field application as a slurry system. The major purpose of this study, which was to successfully control the position and attitude of the shield machine and also to support the natural ground in order to prevent it from subsidence and uplifting, was achieved with satisfaction through the execution results.

1. INTRODUCTION

In recent years, in Japan, shield work involves such severe conditions as sharper curves, longer distances and greater underground depth, therefore more advanced tunneling technologies are in demand. At the same time, the shortage of skilled operators and the increasing number of aging field workers have given rise to social issues. Through the recognition of these outstanding issues, Fujita Corporation has, since several years ago, taken a progressive attitude toward the development of information-based and automated tunneling methods using a shield machine. The results have provided for the industrialization of this hyper-shield system.

The primary objectives of this hyper-shield system are to enable a shield machine to automatically start and stop, as well as, through the application of artificial intelligence and fuzzy logic, to automatically control the position and attitude of the shield machine and also to support the natural ground. Although this hyper-shield system is compatible with both the slurry method and the earth-pressure method, which currently maintains the lead among all the shield tunneling methods, this paper focuses on description of the slurry hyper-shield system.

2. SYSTEM OVERVIEW

This section outlines the configuration of the slurry hyper-shield system and discusses the technologies of controlling the position and attitude of the shield machine, and of supporting the natural ground and controlling the excavation velocity.

2.1. System configuration

Figure 1 provides the configuration of the slurry hyper-shield system. In the figure, the system consists of three computers linked with associated control panels. These computers have the following functions:

(1) Excavation control system

The excavation control system collects various data, calculates data for position and attitude control, and executes such basic tasks as the preparation of daily reports.

(2) Position and attitude control system

The position and attitude control system determines a jack pattern to hold the shield machine with an optimal attitude through the collation of the machine's attitude data with the expert system rule.

(3) Automatic control system

The automatic control system automatically controls the start and stop of the treatment plant, the equipment of the shield machine, and the transportation of fluid. It also employs fuzzy logic to control the supporting of the facing, and the excavation speed.

These systems are provided in the central control room, which are collectively controlled by integrated management. It is the normal practice of the operator that from the central control room, he confirms the status of in-tunnel operating conditions through the monitor television and speaker, and that by pressing the single button on the control panel front, allows the shield machine to automatically travel on excavating.

2.2. Position and attitude control

2.2.1. Automatic surveying system

To control the attitude of the shield machine it is necessary to make a real-time measurement of both the position and attitude of the shield machine. With this system, the position and attitude of the shield machine are calculated based on the data derived from the surveying conducted by the system manager using four sensors (a gyro sensor, a level sensor, a pitching sensor and a stroke sensor) mounted on the shield machine. The data is used to calculate the position of the shield machine by the excavation control computer through the local micro computer provided in the tunnel, and transmitted to the position and attitude control computer.

2.2.2. Position and attitude control system

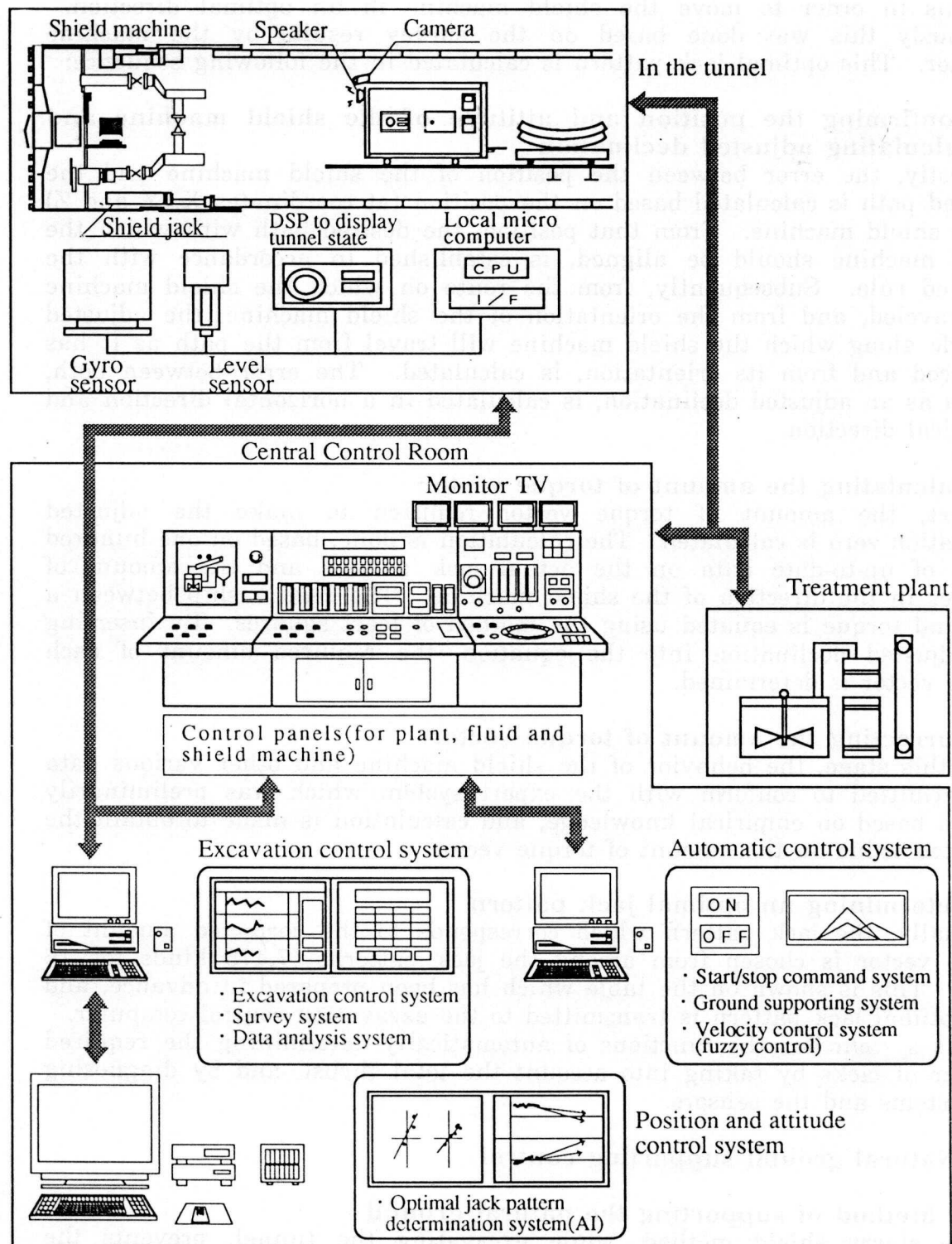This system uses artificial intelligence to automatically select jack

Figure 1. Slurry hyper-shield system outline.

patterns in order to move the shield machine in an optimal direction. Previously this was done based on the survey results by the machine operator. This optimal jack pattern is calculated in the following sequence:

(1) Confirming the position and attitude of the shield machine and calculating adjusted declination

Firstly, the error between the position of the shield machine and the planned path is calculated based on the position (at coordinates X, Y and Z) of the shield machine. From that position, the desired path with which the shield machine should be aligned, is established in accordance with the specified rule. Subsequently, from the route on which the shield machine has traveled, and from the orientation of the shield machine, the adjusted attitude along which the shield machine will travel from the path as it has advanced and from its orientation, is calculated. The error between both, known as an adjusted declination, is calculated in a horizontal direction and a vertical direction.

(2) Calculating the amount of torque vector

Next, the amount of torque vector required to make the adjusted declination zero is calculated. The calculation is done, based on one hundred pieces of up-to-date data on the actual jack pattern and the amount of changes in the direction of the shield machine. The relationship between a turn and torque is equated using the method of least squares. By inserting the adjusted declination into the equation, the required amount of each torque vector is determined.

(3) Correcting the amount of torque vector

In this stage, the behavior of the shield machine and other various data are permitted to conform with the expert system which was preliminarily created based on empirical knowledge, and calculation is made to obtain the corrected value on the amount of torque vector.

(4) Determining an optimal jack pattern

Finally, the jack pattern which corresponds to the corrected amount of torque vector is chosen from among the jack patterns (7,478 kinds for 16 jacks). This is shown on the table which has been prepared in advance, and this optimal jack pattern is transmitted to the excavation control computer.

This system has the functions of automatically determining the required number of jacks by taking into account the total thrust, and by diagnosing the systems and the sensors.

2.3. Natural ground supporting control

2.3.1. Method of supporting the natural ground

The slurry shield method, while excavating the tunnel, prevents the facing from collapsing by pushing the slurry with the properties corresponding to the natural ground conditions, thereby making the amounts of slurry being supplied and discharged well balanced. With this system, the following methods are used to support the natural ground against the

conditions mentioned above.

With the slurry shield method, to conduct real-time assessment of the balanced volume of excavated material, there is the "rate of deviation flow" which acts as an index. When this value is zero, it means that well balanced control is underway. In this regard, we assumed that, with this system, the facing's hydraulic pressure is controlled so that this index be zero.

As well, with consideration given to the stabilization of the facing, the facing's hydraulic pressure was assumed to be controlled within the range of natural hydraulic pressure < the facing's hydraulic pressure < natural hydraulic pressure + 0.5kgf/cm². Another assumption was that when deviating from this range, the rate of slurry discharged would be automatically modified to provide for other settings.

2.3.2. Method of controlling the facing's hydraulic pressure

The conventional method used to control the facing's hydraulic pressure, is to make the rate of deviation flow zero while the operator is watching it. In other words, when the rate of deviation flow is negative, the operator judges that the slurry is slightly deviating from the normal route. He accordingly reduces the facing's hydraulic pressure settings to a value smaller than the current settings. In lieu of such a conventional method, we have established a system to automatically control the facing's hydraulic pressure by using fuzzy logic, as mentioned below:

(1) Fuzzy-based control mode

The fuzzy-based control mode used for this system is the if-then mode as mentioned below:

if X is the fuzzy value X, and Y is the fuzzy value Y, then Z is the fuzzy value Z

in which the input variable X is the rate of deviation flow during previous control, and Y is the current rate of deviation flow. And the output variable Z is the changing range of the facing's hydraulic pressure.

(2) Membership functions

Figure 2 shows the membership functions representing the fuzzy values X, Y and Z referred to in (1) above. In the figure, there are five fuzzy functions, each being triangular.
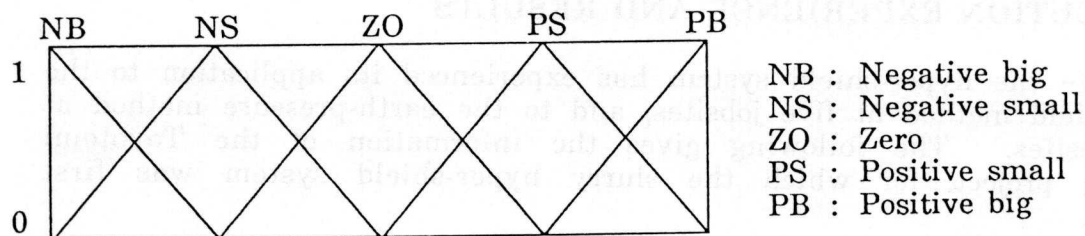

NB : Negative big
NS : Negative small
ZO : Zero
PS : Positive small
PB : Positive big

Figure 2. Membership functions.

(3) Fuzzy rule
Table 1 shows the fuzzy rule governing the control of the facing's hydraulic pressure.

Table 1
Fuzzy rule governing the control of the facing's hydraulic pressure

		Current rate of deviation flow				
		NB	NS	ZO	PS	PB
Previous rate of deviation flow	NB	NB	NS	ZO		
	NS	NB	NS	ZO		
	ZO	NS	NS	ZO	PS	PS
	PS			ZO	PS	PB
	PB			ZO	PS	PB

(4) Inference
For the control mentioned above, the inference method employs the method of algebraic product - addition - center of gravity. The control of the facing's hydraulic pressure is performed about at 1-minute intervals, which was established by taking into account the reaction time until the facing's hydraulic pressure reaches the value set against the control performed by the associated computer.

2.4. Excavation velocity control

In view of the collapse of the natural ground, advancing the shield machine faster would be more advantageous in shield excavation. Based on this concept, we decided that the velocity control of the traveling shield machine would be performed in a range which imposes less of a load on the various pieces of the machine's equipment. Velocity control includes two ways; velocity-up control and velocity-down control. The former control uses fuzzy logic while the latter uses a simple rule. This velocity control deals with the shield jack pressure, the cutter current, the density of discharged slurry and the revolutions of a P2 pump, as the control factors.

3. EXECUTION EXPERIENCE AND RESULTS

To date the hyper-shield system has experienced its application to the slurry shield method at five jobsites, and to the earth-pressure method at three jobsites. The following gives the information of the Toyotomi tunneling project, for which the slurry hyper-shield system was first employed.

3.1. Project rundown

(1) Shield outer diameter : ø4,480mm

(2) Total excavation distance : 2,270 meters
(3) Geological properties : sandy diluvium (sand: 88 ~ 94%)
(4) Construction period : May 1991 ~ June 1992
(5) Location : Onoda-cho, Funabashi City, Chiba Prefecture, Japan

3.2. Alignment and inner geometry of the tunnel route

This section classifies the route into sharp curves, linear or slow curves which were found through geometrical survey using segments. For the purpose of this project, sharp curve means a section with the radius of curvature of 50 meters while the linear or slow curve means the other sections. Table 2 summarizes the results.

Table 2
Measurement results of errors (mm)

	Number of data	Horizontal direction			Vertical direction		
		Average	Typical deviation	Max. value	Average	Typical deviation	Max. value
Sharp curve	180	4.1	10.5	28.0	3.6	10.0	-22.0
Linear or slow curve	1730	4.6	8.1	25.0	0.1	9.8	28.0

From the table above, it is known that the errors of curves and linear or slow curves in both the horizontal and vertical directions are within ±30mm.

3.3. Volumetric measurement results of excavated material

This section compares excavation data between the sections (561 ~ 625R: 75 pieces of data) where the parameters shown in the table below received automatic control, and those (626 ~ 650R: 25 pieces of data) where likewise the parameters received manual control. Table 3 shows the results.

Table 3
Comparison between automatic control and manual control

	Automatic control		Manual control	
	Average	Typical deviation	Average	Typical deviation
Facing's hydraulic pressure (kg/cm²)	1.91	0.09	1.82	0.01
Integrated rate of deviation flow (m³)	-0.12	0.10	0.72	0.59
Volume of excavated material (%)	95.5	0.80	96.2	1.5

In the table above, the integrated rate of deviation flow means the value attained by integrating the rate of deviation flow attained at real time, by the time interval at which the deviation flow occurs. The volume of excavated material (%) represents the ratio of the volume of excavated material to the cubage of the excavated material.

The table above provides an insight that the typical deviation of the facing's hydraulic pressure under automatic control is greater than that under manual control. Likewise, the average and the typical deviation of the integrated rates of deviation flow and the volumes of excavated material, under automatic control, are greater than those under manual control. This can prove that automatic control enabled greater sophistification of the control of the facing's hydraulic pressure than manual control did, and judging from the volume of excavated material, permitted more stable excavation by far.

3.4. Measurement results of geometrical changes on road surface

Throughout the shield execution period, survey points remained located at 20-meter intervals directly above the shield path in order to measure any subsidence of the natural ground. The results indicated that at sections with deep overburden, no geometrical change occurred, while at those with shallow overburden (G.L.-9 meters), changes in the range of 0 to -3mm were observed. This verifies the excellent effectiveness of the natural ground supporting system.

4. CONCLUSIONS

This article has provided an overview of the slurry hyper-shield system, which is an automatic excavation system using a shied machine developed by Fujita. The execution results mentioned indicated that the system enabled a tunnel to be excavated with the planned path geometrically achieved within the deviation of plus or minus 30mm. The results also showed that automatic control obviously allowed for greater stability in excavation than manual control did as a comparison between both excavation data proved, and that subsidence of the road surface did not exceed 3mm. This well confirms that the developed hyper-shield system has thoroughly satisfied the target accuracy in controlling the position and attitude of a shield machine and the supporting of the natural ground. The incorporation of the system with the control panels clustered in the central control room led to success in the reduction of operators from the conventional two down to one, and also made it possible for a less skilled operator to operate the system very easily. We believe this also achieved labor savings, which was one of the established goals.

Currently, research and development of a control system is underway at Fujita, which will give consideration to clearance, and a position and attitude control system which can automatically control a collapsible mechanism and act as a copy cutter. In the future, we will also take up the challenge to realize a natural ground supporting control system which can volumetrically feed back excavated material.