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# Prospects for Applying Automation/Robotization of Shield Method Work

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## INTRODUCTION

The shield method, which is one of methods to construct a tunnel under the ground, was first employed on a full-scale in urban tunnels around 1960 in Japan.

Initially, the shield machine was mostly of an open type with open face. The method has since developed into a closed type mechanical shield, with resultant improvement of the reliability and safety of the work. At present, the closed type mechanical shield plays a leading role in the shield tunneling method, enabling the work in the ground where the work has been difficult to execute with the former method (aquifer gravel stratum, etc.). As the scope of applicable geological conditions widens and the reliability of the work method rises, the tunnel of larger section can be installed in the larger distance and depth. The shield tunneling method is now employed for wide-ranging urban underground works, including water, gas, and electricity supplies, sewage systems, subways, and roads. There are even elliptical shape and eye glasses shape shields.

Utilization of the underground space is currently highlighted. And, the construction technology of shield tunneling methods is expected to become more and more sophisticated along with increase in construction of the underground facilities. The aims of automation will be, for the time being, establishment of the rapid construction work, elimination of hazardous operation, and improvement of the work environment. The future course of development will be toward the full-automatic unmanned shield method by systematizing various automation technologies.

This paper is intended to analyze the present state of automation and robotizing of the shield tunneling method in Japan, followed by extraction of subjects and build-up of the concept of the high-level system. In the course of analysis of the present state, the operation items of the pressurized slurry shield method were extracted, then these items were evaluated in terms of the technological level of automation and robotics, followed by review on the problems of the present technological level. During evaluation, the technologies, which are currently under development and not yet put into general application, were also assessed as the technology in the trial and testing field, in addition to the technological level of general construction sites. As regards the future subjects, those concerning regulations such as laws, standards, and codes and those related to the systems such as the type of contract bids and awards were reviewed, along with technological subjects, on the basis of the analytical result of the study group on the present state. This paper describes mainly a part of technological subjects.

## 1. Present State of Automation and Robotics in Japan

To understand the present state of automation, the operation items of the slurry shield tunneling method are extracted and classified in as much detail as possible (primary, secondary, and tertiary), with evaluation of the technology level made on these items.

The technological subjects are divided into three levels as shown in the Table.1 and the evaluation is made separately for each of the technology level in the general field and that in the trial and testing field.

The operation items evaluated are shown in the Table.2.

Note: In the table, "・" indicates problem factors of robotizing while ":" the present state of robotizing.

Table.1 The technology level made on the operation items

| Classification for evaluation | Technology level in the general construction site | Technology level in the trial and testing field |
|---|---|---|
| Information from sensors is available and the judgment function is provided. Subsequent operations are made automatically. | A | *A |
| Information is available from the sensor, but the judgment is made by human being. | B | *B |
| Mechanized level and below without any information from the sensor | C | ......... |

Table.2 The operation items evaluated

| Work item | Technology level | Present state and problem factors of robotizing |
|---|---|---|
| 1. Preparation | C | · High percentage of manual operation |
| 2. Construction of the shaft | | |
| 2-1 Construction of wall | C | · Unstable construction accuracy, with wall collapse accidents reported.<br>· Flooding accidents reported during excavation inside the vertical shaft |
| 2-2 Excavation of the shaft and earth retaining | C | · Possibility of soil collapse<br>· Possibility of fall of heavy materials during work |
| 2-3 Concrete work in the bottom slab | C | |
| 2-4 Measurement | B | : Automatic measurement and alarm of earth pressure<br>: Automatic measurement and alarm of gas concentration |
| 3. Primary lining | | |
| 3-1 Installation of shield equipment | C | · Equipment varies in kind, with large amount of manual work required for installation and assembly |
| 3-2 Preparation for excavation (Protection for start of excavation) | C | · High possibility of accidents related to workers or machines buried due to collapse of soil |
| 3-3 Excavation | | |
| 3-3-1 Shield tunneling | B | : Control, central monitoring, and remote control of the slurry circulation system |

| Work item | Technology level | Present state and problem factors of robotizing |
| --- | --- | --- |
| | | • Reliance substantially on know-how of of experts concerning selection of the shield jack, position control, and adjustment of the excavation volume in spite of overall progress of automation<br>• Excavation impossible when facing obstructions such as an existing pile, driftwood, etc.<br>• Slow-down of the excavation speed due to worn bit, excavation of long distance impossible<br>• Degradation of tail seal, inflow of water |
| △Operation/control of shield propulsion | *A | : Automatic control of jack stroke and speed |
| △Control of position | *A | : Automatic measurement of the machine locus, automatic jack selection |
| △Operation/control of excavation | *A | : Automatic measurement of the excavated soil volume and over break space. Control of the slurry circulation system |
| △Self-standing of the cut face | *A | : Automatic control of slurry pressure |
| 3-3-2 Transport and Treatment of slurry | B | : Remote operation from the central monitoring board<br>• Large volume occupied by the treatment equipment. Unsatisfactory in efficiency and cost of operations fordehydration of excavated soil, etc.<br>• Noise and vibration |
| △Supply of materials for preparation of slurry | *A | : Automatic slurry preparation plant |
| △Mixing and specific gravity adjustment of slurry | *A | : Automatic specific gravity measurement and adjustment for slurry |
| △Storage and volume control of the prepared slurry | *A | : Automatic control of the storage volume |
| △Circulation of slurry | A | : Automatic operation of the pump and automatic water pressure and flow control |
| △Dehydration of excavated soil | B | : Remote operation of the treatment plant |
| △PH treatment | *B | : Automatic operation of the drain treatment plant |
| △Storage and stiffening of treated soil | *A | : Automatic press and automatic measurement of the storage volume |
| 3-3-3 Assembly of the segment | C | • Large manpower required for seal lining and supply of segments to cutting face.<br>• High percentage of clamp or catch accident during the erector operation in a narrow space.<br>• Large number of segments and bolts in the present standard |

| Work item | Technology level | Present state and problem factors of robotizing |
|---|---|---|
| △Transport of the segment into the tunnel | *B | : Unmanned transport system |
| △Supply of segment | *A | : Automatic assembly of segments.<br>・Application into a medium or small machine difficult |
| △Holding and positioning of the erector | *A | |
| △Thrust of the erector | *A | |
| △Shield Jack operation | *A | |
| △Tightening and retightening of bolts | *A | ・ Retightening made manually |
| 3-3-4 Backfill grouting | C | ・Time-consuming hose connection.<br>・Many troubles due misjudgment of the injection timing and filling amount.<br>・Frequent clogging of the filling pipe |
| △Material suppply, weighing, and mixing | *A | : Automatic plant to manufacture backfill material |
| △Pressurized feed in the tunnel | B | : Automatic control and recording of the pressure and quantity |
| △Simultaneous filling | *B | : Automatic backfill grouting system |
| △Valve/pump operation | *A | : Automatic operation |
| 3-3-5 Transport within the tunnel | C | ・ Large manpower required for unloading, simple work<br>・Long transport time for transport over long distance |
| △Transport operation | *B | : Unmanned transport system |
| 3-3-6 Extension of the support equipment | C | ・High percentage of simple work.<br>・ Extension and connection totally executed manually with efficiency remaining low |
| 3-3-7 Measurement and survey | C | ・ Manual measurement around once/day when the excavation is suspended.<br>・ Laser and gyro used for survey of the control point and base line, with low accuracy for the curved portion |
| △Survey of the machine locus | *A | : Automatic measurement system |
| △Snaking survey | *A | |
| △Pitching survey | *A | : Automatic selection of the system jack |
| △Oxygen and gas concentration measurement in the tunnel | *B | : Automatic measurement and alarm for gas concentration |

| Work item | Technology level | Present state and problem factors of robotizing |
|---|---|---|
| △Vibration and noise measurment | *B | : Automatic measurement and recording |
| △Preparation of the control chart | *B | : Automation of data analysis and recording |
| 3-3-8 Maintenance and inspection | C | |
| 3-4 Shield arriival work | C | · High possibility of water inflow and collapse due to faulty protection work<br>· Machine dismantlement requiring large manpower and highly dangerous |
| 3-5 Clearing | C | · Large manpower |
| 4. Secondary lining work | | |
| 4-1 Removal and transportation of support equipment | C | · Large kinds of equipment, requiring large manpower for dismantlement and removal |
| 4-2 Cleaning inside the tunnel | C | · Simple work with large manpower |
| 4-3 Water-proof work | C | · Large manpower |
| 4-4 Assembly of reinforcement | C | · Simple manpower work. Inconvenient handling because of long and heavy materials |
| 4-5 Form work | C | · Poor work environment for cleaning off fouled form<br>· Possibility of occupational disease |
| 4-6 Concrete placement | C | |
| 4-7 Repair | C | · Large manpower |
| 4-8 Survey | C | · Large manpower |
| 5. Clearing | C | · Large manpower, simple work |
| 5-1 Various clearance works | C | |
| 5-2 Restoration of the land | C | |

Automation and robotizing development has been made and reported in relatively large number concerning the shield tunneling method. Items related to the Technology Level A, *A are summarized as follows:

Shield tunneling: Driving operation, position control, excavation operation, self-standing of cut face

Slurry transport/treatment: Supply of materials, mixing for preparation of slurry, adjustment of specific gravity, storage control of slurry, circulation of slurry, dehydration of excavated soil

Segment assembly: Supply of segment; holding, positioning, and push of erector, shield jack operation, tightening of bolts

Backfill grouting: Material supply, weighing and mixing, pressurized supply in the tunnel (valve and pump operation)

Survey and measurement: Survey of the locus of the shield machine, survey of the central line (snaking), and level survey (pitching)

Though automated and robotized in higher degree when compared with other kinds of work, the shield tunneling method still remains in a trial stage before practical application. Besides, automation is concentrated to the primary lining work where application of mechatronics (control of the shield machine, etc.) is relatively easy, but delayed in the shaft construction, secondary lining process before and after the primary lining process. It is therefore necessary to proceed with automation of shaft construction and secondary lining work to enhance the safety and alleviate burden of workers. Needless to say, automation toward the higher level must also be made in the primary lining work to achieve labor saving and enhancement of the productivity.

## 2. Proposition of the advanced system

Here, some possible advanced construction systems with automation and robotics for works which have not relatively yet applied any automation/robotics are described.

### 2-1 Shaft construction robot

The shaft construction robot may be divided into two kinds: a sheet piling robot and a shaft excavation and shoring robot. Full automation is planned through build-up of an integrated system. The sheet piling robot determines the position automatically while carrying out automatic auger boring and H pile insertion with high accuracy. The excavation robot performs underwater excavation while traveling on the basis of the recognized depth and determining the necessity or non-necessity of the shoring. The shoring robot moves down through telescopic operation to install shoring in the specified position.

### 2-2 Excavation and assembly robot

The excavation robot has a sensor to know the state in front of the face, proving highly compatible with boulders. This robot helps promoting automation of survey and shield. The assembly robot can perform a series of works from segment supply to assembly.

### 2-3 Automation of extension of supporting equipment

For extension of the supporting equipment, automation is considered for each equipment.

(1) Transport cart

A few units of transport carts are operated automatically without collision according to the signal from the sensor cable incorporated beforehand in the segments. The use of tires will enable elimination of sleepers, passage plates, and rails.

(2) Ventilation duct

A bellow type duct piping will enable follow-up extension of the bellow according to the tunneling length.

(3) Slurry feed/drain piping

The pipeline is constructed in a telescopic multiple pipes, enabling follow-up extension of the pipeline according to the tunneling length.

(4) Power and signal lines

A cable reel with torque motor is installed halfway of the wiring to enable follow-up extension of the cable according to the tunneling length.

### 2-4 Tunnel cleaning robot

A vacuum nozzle, nozzle arm, vacuum generating system, and slurry discharge system are installed on a self-propulsion vehicle. The vehicles moves along by itself without attendance and detect residual soil, collect with vacuum nozzle, and discharge soil in a form of fluid to the outside of the shaft. The vehicle also detects the bolt box position and cleans it with the vacuum nozzle.

### 2-5 Automatic slide form for secondary lining

The form position is adjusted for continuous placement of concrete while allowing it to slide automatically. Movement of the center beam and checking of the concrete hardness are also made automatically by the sensor.

## 3. Technical Plans for Realization of the Advanced System

When automation and robotics of the shield method is viewed from an element technology aspect, improvement and new development may be necessary in many cases because of variation in the operating environment and conditions, though certain technologies of the general industry may be used as they are. Element technologies considered necessary for future automation and robotics are discussed here.

### 3-1 Computer technology

As regards computer-aided control technology, automatic assembly and transport of segments within the shaft and tunnel, which is currently tested, may be direct application of the control technology in the general industry. On the other hand, the machine position control and handling of heavy materials, currently dependent greatly on judgment of experienced workers, are expected to employ fuzzy or neuro technologies (which are under practical application currently in the general industry).

It is essential for automation of the medium to small section shield in future to improve the environment resistance ( vibration, humidity, temperature, fine dusts ) as well as size reduction of a computer system.

### 3-2 Sensor technology

A sensor to be developed for the new system is required to have new functions, such as detection of underground obstructions, detection of over break excavation space, and visualization of substances in slurry, etc. With these functions made available, automation of the shield work can made a great step forward. It is also expected that a sensor and a system to enable real-time measurement of the excavated soil amount correctly are developed. The sensor is also expected to be provided with a function which allows the sensor itself to announce the failure or abnormality in the case of sensor failure and function abnormality, that is, the self-diagnosis function and trouble prediction function.

These functions are necessary not only for a sensor, but also for the system as a whole. A technology to enable the system itself to judge and point out the points in trouble may be necessary in future.

### 3-3 Material technology

Certain points delaying in automation in a series of shield operations can be attributed to difficulty of heavy material handling. The core material (H steel) of the earth retaining wall, strut material, primary lining segments, rails, sleepers, and slurry feed/drain pipes can be changed to lightweight materials, enabling size reduction of an automation system and transfer of the existing technology to this field. For reinforcement used in secondary lining, the new material must be used to reduce weight. In this context, review of the construction standard and design guide must be made as soon as possible.

### 3-4 Hydraulic technology

Hydraulic pressure is used frequently as a power source because lots of jacks are used in the shield driving machine. As the slurry shield machine for medium and small sections is narrow in the interior space, with follow-up carts extending as long as 50 - 60 m in the present state, size reduction of hydraulic units is demanded for automation in view of space restrictions.

If position control and operation are to be automated, all of shield jacks need to be provided with a stroke detection function. In order to utilize the interior space efficiently, the jack to be used must incorporate this stroke detection function. This kind of jack will also be necessary for a copy jack to control position, middle folding jack, and cutting plate slit open/close jack.

### 3-5 Other element technologies

There are other technologies to be developed, such as laser, radio, tightening, underground exploration, survey, or soil dehydration technologies.

## CONCLUSIONS

The Civil Engineering Sub-group conducted study and research of automation and robotizing of the shield method, which is one of the most popular methods for underground development, a primary project for the 21st century. This report is based on the above result.

The subject content for research and study of automation and robotizing of the construction work may vary depending on the aspect from which these subjects are viewed. This time, the stress was placed on elimination of hazardous and burden works to enable the favorable work environment to be established in future, offering an ideal image of a work place. As a conclusion, we would like to present a part of our ideal work place.

Future Image - A work place in the 21st century -

Tension was felt momentarily in a central control room. An obstruction detection alarm was activated in front of the cutting face. As far as the picture on the monitor is concerned, a hard material can be viewed about 20 m forward. Since the hard stratum far below the driving level is considered to rise to reach the excavation level only in future, delivery of a bit for a hard layer or a multi-function robot for cutting face work is scheduled one month ahead. Depending on the analytical result of forward monitoring data of the cutting face, it is necessary to check the present bit wear state in detail to determine whether or not crushing drive is possible.The analytical result need be known as soon as possible.

At present, pupils of an elementary school, future construction engineers, have looked around the in-tunnel equipment as a part of the social observation and are in the middle of fabricating porcelain souvenirs using ceramic material from a surplus soil recycling system inside a hobby space or a construction game using an operation training system of a shield driving machine. Though there is no apparent danger, an underwater inspection robot should be introduced into the cutting face if detail inspection of the bit is to be made. We do not want to give unnecessary excitement to them.

The analytical result is sent from the construction central information center to which face forward exploration data have been transmitted one by one. To this center, various data are sent one by one from the shield driving yards all over the country. At reception of the alarm signal from this yard, the center has conducted analysis of the nearby accumulation data and data from this yard, informing us of the possibility of the excavation by the existing equipment. The analytical result shows that there exists a partial clay lump and the existing equipment can perform excavation without problem.

In addition to analytical result, the information center requests speed-up of the delivery of the multi-functional cutting face working robot to another yard as its delivery to this yard is made in early time. Since the start ofthe excavation of the shaft, about 5 km has been excavated through vertical and horizontal conversion under favorable soil conditions.The excavation diameter was changed twice in the course of excavation. From now on, excavation will proceed into the hard stratum and the preparation is under way now for excavation for further 5 km. Inspection of each equipment was completed with the inspection robot two months ago, and data sent already to the information center. As regards replacement parts and units, the information center has completed arrangement with each maker, with the entry schedule and process prepared for the parts and repair multi-function robot. These schedules and process are already transmitted to us. It appears that favorable and satisfactory work progress has been achieved in all work yards using the same type equipment as in this yard and the information center has judged substantial cut-down of the work period possible. The center also considered that the driving speed up to the hard stratum may be increased by 1.5 times.Though this may cause increase in the number of replacement parts more or less, addition of one repair multi-function robot will lead to three-week reduction of the work period, the information notified.

As the excavation and maintenance requires almost no manpower for daily works as the equipment is more and more automated. The greatest subject here includes selection of improvement points, review of the manual, and preparation of the construction planning and control procedure because this yard is the first to which the surplus soil recycling technology. Such so-called recycle is limited to recycling of soil for lining and back-filling materials in the yard. The yard is requested also to create ideas for expanded application of recycled soil after screening and selection. On the other hand, a movable power supply system movable in tunnel with fuel cell (whose performance has been proved as the first application in the neighboring section A) and a magnetic levitation type transport system in tunnel (whose practical application has been confirmed in the section C) have suddenly determined to be employed in the next-term work, demanding urgent change of equipment in tunnel and associated revision of the construction plan and control procedure. The next-term work incorporating these new technologies will be rationalized substantially because there is no wire or rail extension work. Daily operation will include addition and renewal of new case information to the knowledge base of various AI systems used in the yard and the information center.

During the initial period of 1990s, robotizing of the construction work leveled off because of inhibiting factors and cost increase. Under understanding and cooperation of the Construction Ministry and the advanced construction technology center, numerous construction robots have been developed, and thus, the robotics of shield methods have made a great advancement. During this period, principal technologies as listed below are developed:

(1) Shield tunneling method compatible with all kinds of soil
(2) Continuous construction shield technology for vertical shaft and tunnel
(3) Simultaneous shield technology of excavation and secondary lining
(4) Automatic cutting bit replacement technology
(5) Automatic extension technology for interior support equipment
(6) Detection and elimination technologies for buried objects
(7) Automatic magnify and reduction technology of excavation diameter
(8) Inspection and repair robot technology
(9) Surplus soil field recycle technology

As these technologies are put into practical application, human operations have decreased to nearly zero. Only complicated troubles require human being, yet such is limited mostly to checking of software. As a result, a dangerous or burden work is a story told in the past. Numerous hurdles have been cleared before reaching this level.

The most difficult includes continuous construction and shield technology for a vertical shaft and a tunnel, simultaneous construction technology of excavation and secondary lining, automatic extension technology for support equipment in tunnel, and automatic cutting bit change technology. These have been themes to be solved since the year 1990 when automation and robotizing started. As they are put into practical application, specific effects (shorter work period, labor saving, and extension of the tunnel length) have become evident, motivating automation of the shield tunneling method. For control, entry of the planned route is enough to drive the shield machine correctly according to the instruction.

Who can imagine the present state in 1990? The construction industry which was ignored completely by young people because of the danger, dirtiness, and hard work associated with this industry has now become an important industry creating and maintaining the favorable global environment. Now this industry is quite popular among young people because of offering an opportunity of creativity, worthiness of living, and pleasure to workers in this industry.

The proposals made in this paper are the results of the study performed by the Subcommittee of the Construction Robotic Committee, Japan Society of Civil Engineers. The names of the people who participated in this study are as follows.


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