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TUNNELING BY ROBOT
SHIELD DRIVING AUTOMATIC CONTROL SYSTEM (Vol. 2)

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ABSTRACT

We have developed the shield driving automatic control system "SDACS" which has been introduced into a number of projects for realizing sophisticated constructions. In Japan, the mud pressure type shield (MP shield) method has become widespread as it is suitable for a variety of types of soil. But this type of shield method suffers from slow development of the execution control technology, which gives rise to such drawbacks as ground settlement. Now we have established the execution control technology and the automated control system for the shield machine by utilizing computers. This paper outline the SDACS, describing the 'face control system' of the MP shield and introducing applications of this system for three different underground excavation methods.

1. INTRODUCTION

The shield method is used for constructing a tunnel under ground where the soil is loose and soft and the face can easily collapse. Since in Japan many cities are built on such ground, the shield method has been widely used.

We have developed SDACS by utilizing sophisticated computer technology to automatate the shield method. SDACS consists of a system which automates the shield operation and a centralized control system by which operating conditions are controlled, processed and offered in an easy-to-understand form [1]. The SDACS development background is discussed below [2]. Recently the mainstay of the shield method has been replaced by the closed-mechanical type rather than the open-type shield for the reduction of the hazard of ground settlement resulting from the tunnel excavation. The closed-mechanical type shield is characterized by a chamber which is a compartment on top of the shield filled with slurry or mud, and slurry or mud is applied under pressure to the face to protect it from collapsing. And this type shield operation includes such activities as excavation, mucking of excavated materials, driving of the shield, back-filling and segment assembly.

There are two particularly important factors in the shield operation control. One is the technology to control the shield driving direction and the others is the face control technology to maintain stable face conditions preventing it from collape.

The former is a technique to determine the actual position of the shield with respect to the planned route of the tunnel and to control the shield direction accordingly by means of thrusting jacks.

Conventional direction control suffers from: Surveying in a narrow tunnel and the complicated position-finding calculations require much manpower and time. Experience is required in order to change the machine direction in a restricted underground environment, and, once the direction has significantly deviated, it takes a long distance to correct the direction.

Consequently techniques where the position is found accurately, quickly and automatically, and where the direction is controlled smoothly by finding the optimum direction correcting method are required.

The latter uses technology where the conditions of the face, excavation, mechanical load on the shield etc. are obtained from sensors such as speedometers, earth pressure gauge etc. and used to control the shield.

The face control used to work in such a way that an operator watched a variety of data on the analog indicators and then manually operated the machine. In practice, however, it was impossible for an operator to read such a variety of complex and mutually - related data to understand the incressantly changing conditions and to perform the optimum operation control.

Therefore the situation stated above required easy-to-understand indications of the face conditions, accuracy in judgment, standardization and, if possible, the automation of the shield operation.

The following will outline the SDACS, particularly the face control system of MP shield, the applications of the face control system and examples of applications of SDACS for underground excavation technology other than shield methods, e.g., TBM, diaphragm wall, etc.

2. SDACS OUTLINE

SDACS consists of two main system, i.e. the direction control and the face control, and several sub-systems constituting them. (Fig. 1: System Composition)

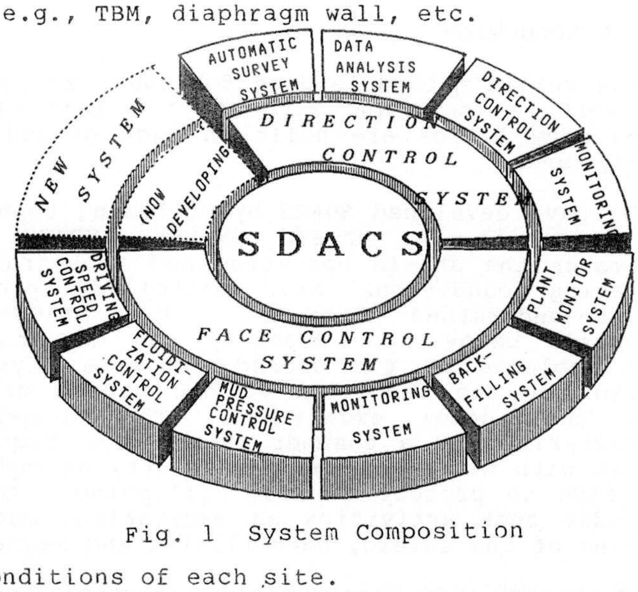


Fig. 1 System Composition

System features and effects are as follows

- Computer aid has allowed sophisticated operation control.
- It is possible to select systems suitable for the works conditions of each site.
- Accurate direction control and face stability by means of an automatic control system.

2.1 System Outline

Fig. 2 outlines the system. The following discusses the system configuration and performance. (Fig. 2 illustrates 1) - 7))

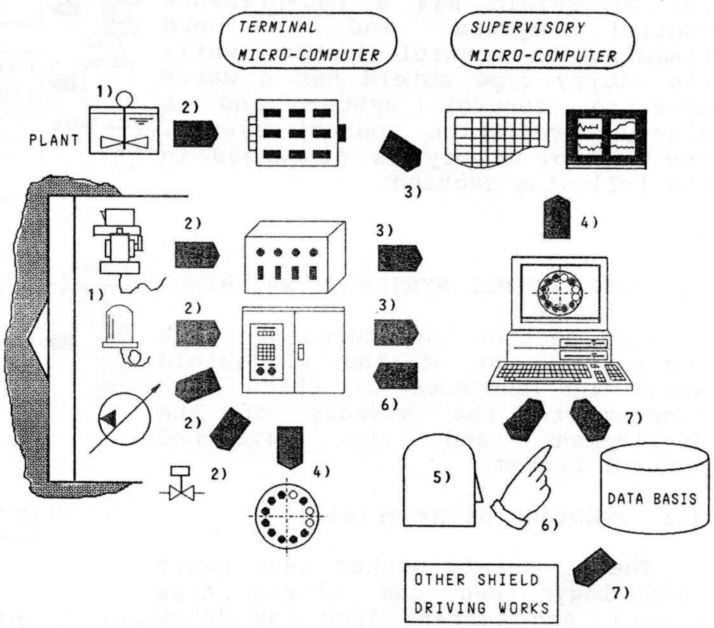


Fig. 2 System Outline

1) Shield operating information is obtained by means of sensors such as earth-pressure gauge speedometer, etc. and switches. Direction control information is obtained by means of a laser transit, gyro-compass and other automatic instruments as well as sensors like a pitching-rolling meter, stroke meter, etc.
2) All data from the sensors are input to the terminal micro-computer in the shield and plant. The terminal micro-computer accommodates the automatic control involved in the face control operation.
3) All data from the sensors are preliminarily processed by the terminal micro-computer and then transmitted to the supervisory micro-computer in the centralized control room.
4) The supervisory micro-computer is responsible for using the data to plot trend curves and a variety of charts, and for the output to the display and printer. The direction control is processed in the supervisory micro-computer.
5) The shield operator is provided with shield driving information of the data output of the supervisory micro-computer.
6) The operator is responsible for judging the data discussed in 5) and for inputting desired values and parameters of various controls from the supervisory micro-computer into the terminal micro-computer.
7) The essence of the data is translated into the data basis and fed back for other shield driving works.

2.2 Direction Control System [3]

The control is conducted in conformance with that shown in Fig. 3. First, after the completion of the initial excavation and before the start of the following excavation, the shield position is automatically surveyed by measn of a gyro-compass or laser-transit. Then the position detection and correction are analyzed using the survey data, planned route data as well as the direction correcting data basis. The automatic direction control is performed during excavation by monitoring and operation of the thrust jacks.

2.3 Face Control System [4]

The MP shield differs from the slurry type shield in the face control system. The common control systems of the two types of shields are the driving speed control system, the back-filling control system and the plant monitor system. In addition, the MP shield has a mud-pressure control system and a mud fluidization control system, while the slurry type shield has a water pressure control system and a slurry circulation control system. The control theory is discussed in the following section.

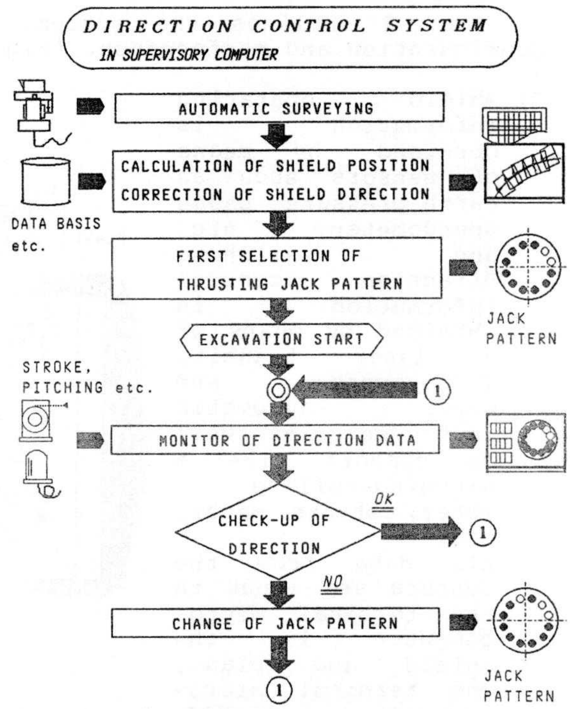


Fig. 3 Direction Control System Flow

3. FACE CONTROL SYSTEM OF MP SHIELD

This section introduces the face control system of the MP shield among the subjects of SDACS with respect to the history of the development and the developed control system.

3.1 Problems of MP shield.

The MP shield method uses newer technology than the slurry type shield, and suffers from the delay in development of the execution control technology, which gives rise to such drawbacks as ground settlement caving, etc. Comparison between the two types of shields of face stability shows that they are similar to each other with respect to the thrust that creates the mud or slurry pressure in the chamber.

The quick establishment of the technology and automation of the slurry type shield is attributable to ample accumulation of slurry data from the research of oil field excavation etc., applications of fluid process control technology and adoption of computer-aided remote control systems, etc.

In contrast, the delay in development of the face control technology in the case of the MP shield is attributable chiefly to the insufficient accumulation of data and basic research of mud and its fluidity, etc. However, the MP shield has rapidly become widespread by virtue of its immense applicability for a variety of types of soil and its inexpensive total construction cost. Under the circumstances, the MP shield method has had to establish the face control technology and automatic face control system.

3.2 Face Control of MP Shield by SDACS

Fig. 4 shows a common pattern of the MP shield configuration, where (1) - (6) correspond with the numbers in the following explanation. The MP shield is provided with a cutter (1) for excavating the ground; chamber (2) which is an isolated water-tight compartment and is responsible for stirring, improving and pressing the soil; screw conveyor (3) to discharge the excavated materials from the chamber and a thrust jack (4) to drive the shield.

In addition, the shield is equipped with devices (5) such as one which injects additives to accelerate the fluidization of the excavated materials, sensors (6) to provide information of excavation, etc.

Since 1983 we have introduced computers for operating the instrumentation and supervision of the MP shield, accumulating the execution data (about 40 cases at present), performing the analyses and establishing the system. The analysis of the above-cited data suggests the necessity of standardization and automation of the face control system consisting of the mud pressure control system, fluidization control system and driving speed control system. The following discussed the face control system which has been researched and developed as SDACS on the basis of the data analysis.

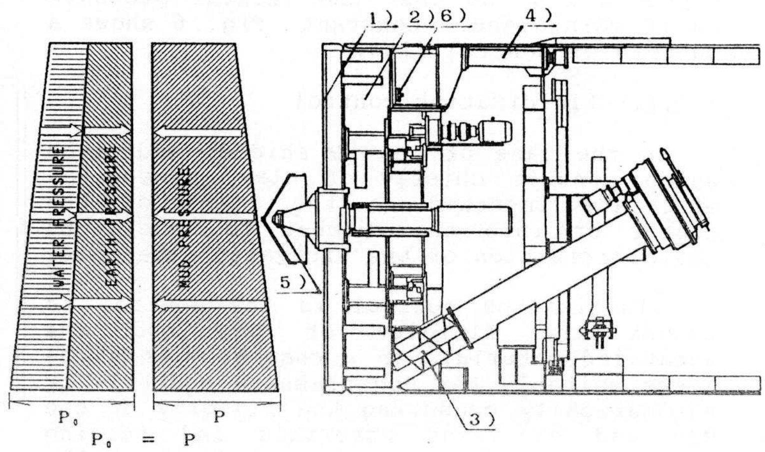


Fig. 4 MP Shield Configuration

3.2.1 Mud pressure control system

In the case of MP shield, the face stability theory is, as shown in Fig. 4, to protect the face from collapse by balancing the mud pressure in the chamber P against the lateral pressure (= water pressure + earth pressure) acting on the front of the face Po.

The mud pressure control requires the three following prerequisites :

- The chamber should be filled with mud and excavated materials.
- The mud and excavated materials should provide fluidity suitable for controlling the mud pressure.
- The mud pressure should not exceed such a degree which would break the face.

Fig. 5 shows the results of the test, which illustrates that the mud pressure P and the volume of excavate materials v are in proportion, provided that the mud pressure remains within the scope of work face stability [5]. The screw conveyor RPM is regulated and consequently the volume of excavated materials is governed so that ultimately the mud pressure is controlled.

In practice, first control the screw conveyor RPM in proportion to the driving speed v and then, calculate the pressure difference ΔP between P and P' which is the desired mud pressure. The screw conveyor RPM is controlled in such a way in order that the value of pressure difference, ΔP,

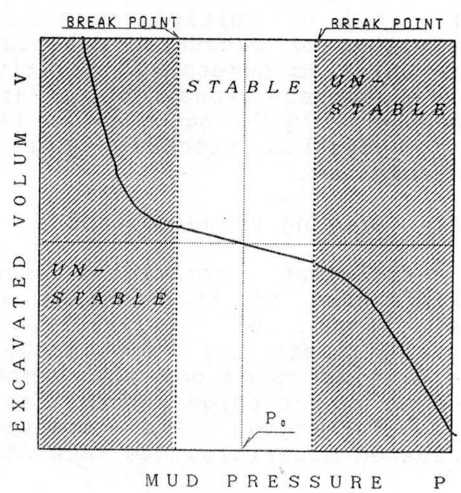


Fig. 5 P-V Relation

represents 0, so that the lateral pressure Po is maintained. Constant Fig. 6 shows a pattern of control flow.

3.2.2. Fluidization control

In the case of the MP shield, additives which consist chiefly of clay, bentonite, etc. are injected on the front of the cutter or into the chamber to accelerate the slurrization of the excavated materials.

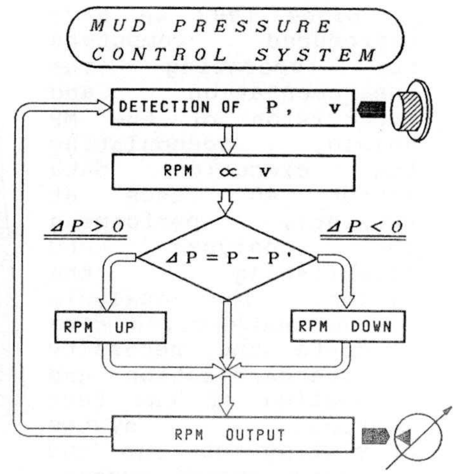
Fluidization control is the control to adjust the fluidity of the mud and excavated materials in a chamber within the range suitable for mud pressure control, by automatically measuring the fluidity of the mud and excavated materials and feeding back the measurements for controlling the flow amount of the additives.

The automatic control of the fluidity requires the measurement of the degree of fluidity. The screw conveyor discharging efficiency η (the ratio between the screw RPM and driving speed v) and the cutter torque T which depends upon the cohesion and friction of the excavated materials in the chamber are used as parameters to judge the degree of fluidization.

The control flow is such that the screw conveyor discharging efficiency η and cutter torque T are first calculated, feeding back the control error from the desired value into the ratio r between the quantities of additives and the volume of excavated materials. The quantity of injected additives per unit time q is calculated by multiplying the ratio r by the volume of excavated materials per unit time which is determined by driving speed v and excavated cross-section area A. The flow amount q is outputed to the injecting pump operation process. Fig. 7 shows a control flow.

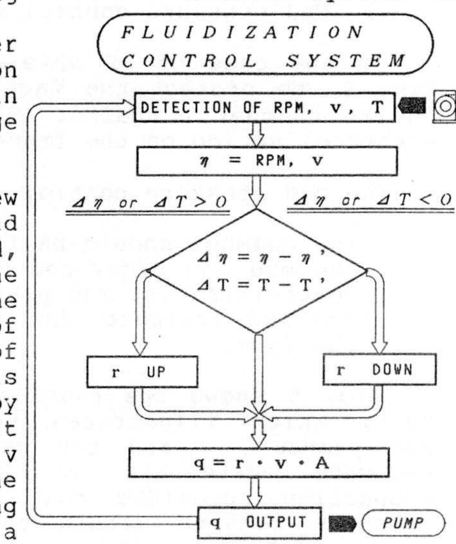
3.2.4 Driving speed control

Efficient excavation requires the maximization of the driving speed within the scope of tolerable conditions. Normally there are three factors on which the driving speed depends: mechanical loads such as cutter torque, thrust etc., capacity for discharging and transporting the excavated materials, and face stability.



P : MUD PRESSURE IN CHAMBER
P' : DESIRED MUD PRESSURE
v : JACK SPEED
RPM : SCREW ROTATION PER MIN.

Fig. 6 Mud Pressure Control System Flow



v : JACK SPEED
RPM : SCREW ROTATION PER MIN.
T : CUTTER TORQUE
T' : DESIRED CUTTER TORQUE
η : SCREW DISCHRGING EFFICIENCY
η' : DESIRED SCREW DISCHRGING EFFICIENCY
r : RATIO BETWEEN QUANTITIES OF INJECTED ADDITIVES AND EXCAVATED MATERIALS
q : QUANTITIY OF INJECTED ADDITIVE PER UNIT TIME

Fig. 7 Fluidization Control System Flow

Meanwhile the magnitude of the cutter torque and thrust depend not only on the physical properties of the ground, e.g., friction force, cohesion, etc. but also on the volume of the excavated materials per unit hour, which varies with the driving speed.

In order to perform an efficient excavation by utilizing the above-cited inter-relationship between factors, the driving speed control is designed to maintain the desired speed while controlling such mechanical loads as cutter torque, thrust, etc.

Consequently the control is conducted as follows : Set the desired driving speed v' and the upper limit of the cutter torque and thrust force T'. Maintain the desired driving speed v' provided the cutter torque and thrust force T do not exceed the upper limit T' during the excavation. If the cutter torque and thrust force T exceed the upper limit T', the driving speed v is reduced, so that the cutter torque and thrust force T are stabilized below the upper limit T'. Fig. 8 shows the control flow.

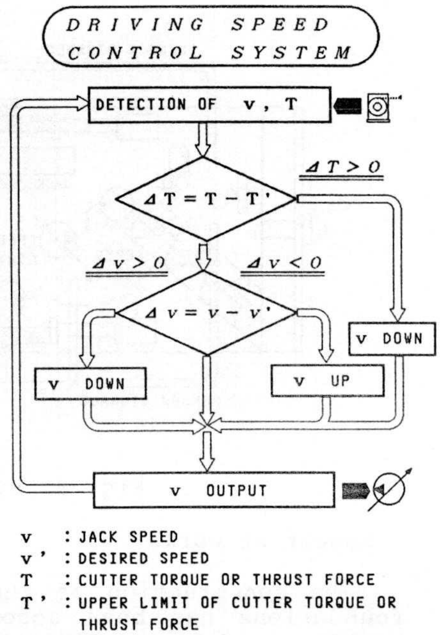


Fig. 8 Driving Speed Control Flow

4. APPLICATIONS OF SDACS

In the last five years since the development through to the present stage, SDACS has been found in more than 50 constructional applications in a variety of geological conditions ranging from very soft peat soil to boulder and rock bed. The execution data has been accomulated and improvements in the system has been accomplished, in parallel with the SDACS utilization.

Introduction of SDACS is being promoted progressively for underground excavation using equipment other than shield, i.e., TBM, diaphragm wall etc. Three examples of applications are as follows:

4.1 Application for big diameter MP shield

Project features and technical problems

Tunnel outside diameter: ø8210 mm   Tunnel length: 1410 m

Soil : Fine sand, silty sand and silt
(Underground water pressure: 2.0 kgf/cm^2)

Excavating machine : MP shield

This project represents the excavation of a sewage tunnel in an urban area congested with houses. The soil consists of soft silt and collapsible aquatic sandy layer. The tunnel route contains two sharp curves of 50 m radius and two proximities to pier foundations of a highway. It is therefore considered that the critical and technical problem includes the tunneling accuracy and face stability, and this consideration leads to the complete provision of direction control system and face control system of SDACS. (Fig. 9: System composition)

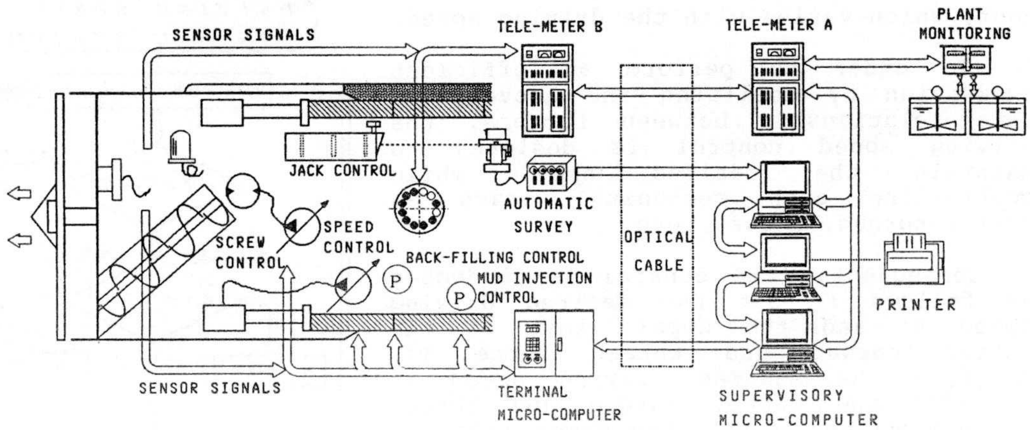


Fig. 9 System Composition for MP Shield

Result of works

The construction of the sharp curves and in the area of the highway foundations has been accomplished without a problem, with an tunneling tolerance of about 30 mm. and ground surface settlement upto 5 mm. The above-cited facts have verified the effectiveness of SDACS direction control and face control system.

4.2 Application of SDACS for TBM curve operation

A simple improvement in TBM which excavates the tunnel by the same mechanical means as the shield will suffice to provide ready access to SDACS direction control system, data handling and driving speed control system, promising a dramatic improvement in tunneling accuracy.

Project features and technical problems

Tunnel outside diameter:	ø3600 mm	Tunnel length: 600 m
Soil :	Diabase and gabbro (Compressive strength 1000 - 2000 kg/cm^2)	
Excavating machine :	TBM for hardrock (for pilot tunnel)	

The tunnel consists of a curve of 200 m radius and 270 m length, with a stringent tolerance of 50 mm. This requirement lead to the development of a survey system using a rap-top type hand-held computer and gyro-compass. This system serves to directly inform the operator of the TBM position and correction degree of driving direction by means of a rap-top type computer in the cockpit and a gyro-compass which finds the TBM driving direction. (Fig. 10: System composition)

Results of works

The operational error was 40 mm (maximum) which was within the tolerance. Further the analysis of the data collected during excavation as regards the excavation/direction control has described a concept of automation of the driving speed control and direction control.

4.3 Application of SDACS for diaphragm-wall construction

There is a trend towards large underground constructions which has resulted in the increase in excavation depth and wall width of the diaphragm-wall. The diaphragm-wall excavation which excavates the ground vertically has many techniques in common with the slurry type shield method and therefore SDACS technology is applicable.

Project features and technical problems

Diaphragm-wall thickness: 2.1 m

Excavation depth : 38.6 m

Soil : Sand, clay and silt

Excavating machine: Electromill (cutting wheels with teeth)

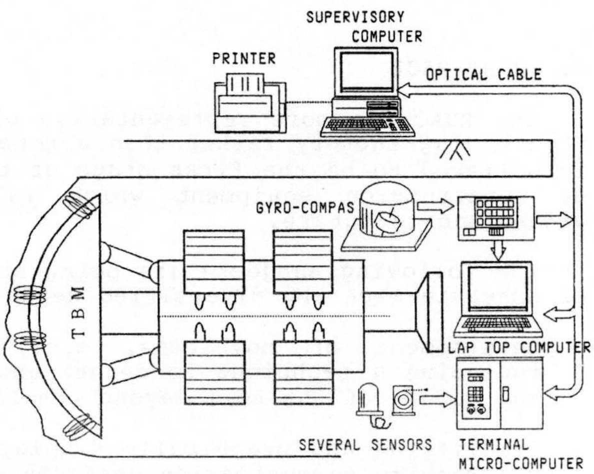


Fig.10 System Composition for TBM

Since in this project the wall thickness was larger than previous excavations and it was required that the vertical tolerance should be controlled to not more than 1/2000 of the wall depth. Since, in the case of diaphragm-wall construction, the excavating machine operates in slurry several tens of meters beneath the ground surface, the most difficult technique required may be the technique to find the excavating machine's position during operation. This requirement has led to the development of a new type of position detecting system by using CCD (Charge Coupled Device) for detecting the horizontal deviation in the vertical axis of the excavating machine. In addition, the SDACS direction control system and the newly developed face control system for diaphragm-wall excavating machines have been introduced. (Fig. 11: System composition)

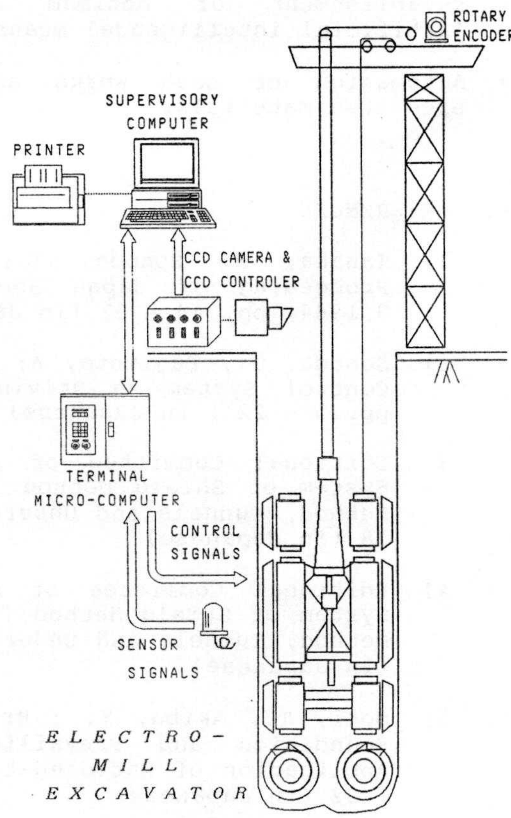


Fig.11 System Composition for Diaphragm-Wall Construction

Results of works

The excavation accuracy was acceptable, well within the requirement of 1/2000. Improvement is being achieved at present in the development of a more sophisticated, automatated total system, using the results of analysis of the excavation data from this system.

5. POST FACE

The SDACS is more representative of an FA (Factory Automation) system of a moving factory rather than a robot in construction. And this system is believed to be the first stage of the control system of the automation of construction equipment which is expected to become increasingly widespread in future.

The following subjects are being studied to solve the current problems of SDACS to meet the diversified needs for underground development:

- Development of novelties, e.g., sensors, control systems, etc., including a technique to detect underground obstacles and to determine the nature of the soil beyond the face.
- Simplifying and graphically displaying the operation for improving the man-machine communication performance.
- Establishment of optimum automatic control parameters by AI (Artificial intelligence) means.
- Automation of such works as segment assembly, transportation of excavated materials.

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