Tunneling by Robots - Shield Driving Automatic Control System

Yoshihiri Shimomura and Tetsushi Sonoda[1]

1. INTRODUCTION

For fully automatic control of construction machinery, it is necessary to have functions of measurement of the attitude and position of the machinery, analytical functions of the measured data and controlling functions of the machinery.

SDACS has a measuring function using sensors to collect the requisite data for the automatic direction control of the mechanical shield machine; a data analysis function using a personal computer; a controlling function of shield driving jacks and a signal transmitting function using the optical fiber communication system that connects all equipment in the system.

At the same time, it has a controlling function that is a combination of the muddy water control system and the earth pressure control system, for the stabilization of the excavation face which can be the cause of problems in shield driving.

With SDACS, the shield driving machine can be automatically controlled under a stable excavation face and continue excavation with high accuracy in accordance with the planned route. This thesis introduces such control equipment, taking the example of subway construction with an outside diameter of 7.45m and length of 925m.

---

[1]Engineering Department, Civil Engineering Division, Hazama-Gumi, Ltd.

2. A SUMMARY OF THE PROJECT

2-1 The Shinjuku line in the Tokyo Metropolitan Subway is part of the No. 10 line in the Metropolitan Rapid Transit Railway system. The Minami-Shinozaki work section is a total of 925m, with its portal located in a vertical shaft west of Shinozaki Station, and designed to be tunnelled by the slurry shield method using a shield of 7.45m in outside diameter to construct two single track subways. This method is employed to fulfill a necessity to minimize, under the geological and locational conditions of this work section, adverse effects against the ground surface.

This work section is unique in the following points:

1. Passing through, throughout the whole length of shield section, under a privately-owned land congested with residential houses and factories.
2. A small overburden of 0.8D to 1.1D, and
3. Passing through Expressway Route 7 (the Keiyo Expressway).

Work Title: Shinjuku Line (No.10 Line) in the Tokyo Metropolitan Subway.

Construction Time: 14 October 1982 to 13 July 1985 (a total of 33 months)

Total Track Length: 925m, 2 Tracks

Shield Work:

Total Length: 925m, 2 Tracks

Shield Machines: Slurry type with 7.45m in its outside diameter and 6.35m in its length. Two units used.

Segments: Made of reinforced concrete, flat type, outside diameter 7.30m, inside diameter 6.70m, girder depth 0.3m, girder width 0.9m. Each complete segment comprises seven componenets.

Overburden: 6.7m - 8.1m

2-2 Slurry Shield Tunnelling Method

The Slurry Shield Tunnelling Method is a method by which the shield thrusts forward by stabilizing the tunnel face by applying a predetermined slurry pressure thereto. In this manner, collapse due to the earth and ground water pressures is prevented.

2-3 Slurry Shield Tunnelling Machine

This machine consists mainly of a cutter head, an electric power unit, an agitating chamber, skin plates, agitators shield jacks, a segment elector, a slurry feed pipe, a slurry discharge pipe, an air lock and a power unit, etc.

The main features of this machine are as follows:

1. A cutter head excavates the ground being rotated by an electric motor.
2. An electric motor is a power source to operate a cutter head and an agitator.
3. An agitator chamber is a chamber to mix the excavated dirt with slurry.
4. Skin plates cover the peripheral surface.
5. Agitators are provided at the bottom of slurry chambers to prevent the accumulation of gravel, etc.

6. Shield jacks propel the shield
7. A segment erector assembles the segments
8. A slurry feed pipe is a pipe to feed slurry to the agitating chamber.
9. A slurry discharge pipe is a pipe to discharge the excavated dirt mixed with slurry.
10. An air lock provides compressed air, so that the operator can enter the face when troubles or problems take place.
11. A power unit is a power source to operate the shield jacks.

3. THE OUTLINE OF SDACS

SDACS consists of sensors for the measurement of the position, for machinery data and for excavation data in the underground tunnel; a main computer in charge of arithmetic analyses, installed in the ground control center; a direction control computer in charge of direction control of the shield and an excavation control computer in charge of analyses of excavation data.

These sensors and each computer are connected by the optical fiber communication system and each piece of equipment functions organically.

Chart 2 shows the outline of SDACS.

Measurement Of the Position

The position of the shield machine is measured by the Hazama Position Measurement Sensor that is composed of, the measuring point fixed in the tunnel with the Traverse Measurement, the laser digital transit and two laser targets.

The attitude of the shield machine is also measured with the inclination gauge and the stroke gauge at the time of measurement of its position.

Arithmetic Analyses

Based on the planned route which has been stored in advance and the position measurement data, the main computer analyzes the direction control and sends the results to the direction control computer.

Direction Control

According to the jack stroke data, measured under the instruction of the main computer, the direction control computer chooses a jack pattern to control direction by driving jacks.

Management of Excavation

The muddy water control system stabilizes the face during excavation, while the excavation control computer analyzes the excavation data given from sensors to prepare a control chart, based on which engineers fix a control value for the feedback.

4. MEASUREMENT OF THE ATTITUDE AND POSITION OF THE SHIELD MACHINE

4-1 The Automatic Control Functions of the Measuring System.

The measuring system has not only such functions as measurement, analysis and control, but also the following functions for the independent control of each piece of equipment:

1) The laser beam measuring function to check up on which part of the target the laser beam spot.
2) The analytical function to check the distance and direction of discrepancy between the center of the laser beam and that of the target, and to check the transit control.
3) The control function of the pulse motor, which runs the transit.
4) The target search function in case of temporary interception of the laser beam.
5) The communication function with the main computer.
6) The function of data conversion from analog to digital.

With these functions, the position and attitude of the shield are automatically measured and the data is transmitted to the main computer.

4-2 Composition

The measuring equipment consists of:

- a laser target installed on the shield machine measuring position
- A digital transit with light wave reflecting mirror and with a light wave distance gauge for the measurement of distance, horizontal angle and vertical angle.

- a laser beam transmitter to fix the direction of the transit
- A BS laser target to fix the basic direction for the measurement and
- the controller, using a micro processor to control this equipment

An automatic measurement system is shown in Chart 3. Photo 1 shows a laser digital transit.

4-3 Function

The measuring equipment installed at a measuring point has functions for the direction follow up of the transit, to make up for the moving shield machine, and for the measurement of the machine according to instructions from the main computer.

The follow up of the transit to the machine movement takes the following proceedure: the laser beam is transmitted from the optical axis of the transit; the optical receiving signal of the laser target is analyzed by the micro processor; the direction of movement of the transit is selected and the drive signals are sent to the pulse motor which controls the laser beam, so that the beam always strikes the center of the target.

The micro processor receives measurement signals from the main computer and sends them to its light wave gauge and light wave distance gauge; the distance to the target is measured by the light wave distance gauge; the horizontal and vertical angles are measured by the transit and this data is sent back to the micro processor.

The micro processor converts analog signals from the pitching gauge and the rolling gauge installed in the shield machine and from the 3-shield-jacks stroke gauge, into digital signals and sends them to the main computer together with the measured data.

Photos 2 and 3 show the actual installment conditions.

5. POSITION OF THE SHIELD MACHINE AND ARITHMETIC ANALYSES OF DIRECTION CONTROL

5-1 Input of Data on the Planned Route

The data on the planned route, given by the ground measurement should be divided into plane alignment and longitudinal alignment and be seperatly input to the main computer from the keyboard, to be stored.

An input model of the planned data is shown in Chart 4. Chart 5 shows a CRT indication of input data on the planned route.

5-2 Analyses of Discrepancies Between the Planned Route and the Position of the Shield Machine.

Discrepancies between the planned route and the actual position of the shield machine such as the discrepancy of the plane position, that of the longitudinal position and that of the direction are analyzed with the calculated data of 5-1 and 5-2.

The results of the analysis are shown in Chart 8.

6. ANALYSES OF THE DIRECTION CONTROL OF THE SHIELD MACHINE

6-1 The Plane Direction Control

The horizontal control of the shield machine is carried out by analyzing the direction change per ring, in comparison with the point that the shield machine should reach, assuming that the shield machine advances from the current measurement position by five rings (0.9m x 5).

Chart 9 is the analysis model and Chart 10 shows an analysis on CRT presentation.

6-2 The Longitudinal Direction Control

The advance direction of the shield machine in terms of longitudinal direction does not necessarily go ahead to the direction of the axis on the shield machine

The reasons for this are:

- Changes in earth pressure and water pressure in accordance with depth
- Changes in strata
- Changes in bouyancy of the shield machine and of segments

Measured data of those factors of the past 10 rings are fully analyzed for the longitudinal control.

Chart 11 shows a model of the analysis.

Assuming that the shield machine advances by five rings from measured positions, direction changes per ring, compared with the point where the shield machine should reach on the planned route are fully analyzed, and with this data the longitudinal control of the shield machine is obtained.

Chart 12 shows a survey of the longitudinal data.

6-3 Instruction to the Direction Control Computer on Direction Control of Shield Machine

Setting the current position of the shield machine as a standard, the direction of excavation for the next ring is instructed by the main computer to the direction control computer by transmitting the horizontal change angle (0h) and the longitudinal change angle (0v) of the shield machine axis.

7. DIRECTION CONTROL OF THE SHIELD MACHINE

7-1 Mechanism of the Direction Control

By measuring strokes of 3 shield driving jacks, the current direction of the shield machine is given, setting the assembled segment face as a base; the target direction is calculated with the direction control(0h, 0v) instructed by the main computer; the driving direction of the shield machine is controlled by choosing the shield driving jacks required for the direction correction as a result of contrast analyses of the current direction of the shield machine and direction of the target.

Chart 13 is a shield direction control model.

7-2 Function and Structure of Direction Control System

The Direction Control System is composed of:

- Driving jacks and stroke sensors for measurement of the shield machine direction from the assembled face of the segment
- Solenoid valves for ON/OFF of driving jacks
- Relay to transmit ON/OFF signal of driving jacks from a computer to solenoid valves
- An arithmetical analysis computer for selection of the shield machine and driving jacks.
- The optical fiber communication system to transmit input signals from sensors and output signals to relays.

Chart 14 shows the system block chart

With these functions, the shield machine direction from the assembled face of the segment is always measured to control the target direction of the shield machine by choosing shield driving jacks.

Chart 15 shows the direction control flow.

7-3 An Example of Analyses of Direction Control of the Shield Machine with an Outside Diameter of 7.45m

The most suitable driving should be taken by changing jacks, selection in accordance with the extent of discrepancy between the current direction of the shield machine, and the target direction.

In the case of Chart 16, the direction discrepancy with the target direction is large and the selected driving jack can increase the revolving torque to correct the direction.

In the case of Chart 17, the direction discrepancy with the target direction is small and a driving jack is selected to decrease the revolving torque to correct the direction.

8. MANAGEMENT OF EXCAVATION

The mud conveyance and draining control system of Toyo Kogyo Co., Ltd. is introduced to control the face stability during excavation.

This system automatically controls conveyance and draining of mud water, to keep a fixed chamber pressure, by detecting excavation speed of the shield machine with sensors. The real time information can be grasped by computer analyses with data regularly collected from sensors installed in the shield machine and pipelines, such as pressure gauges, flux pressure gauges and hydrometers.

Charts 18 and 19 show a system flow.

9. RESUME

SDACS has a self-control function as a total system, and each piece of equipment has an independant self-control system so that the shield machine can be led along the planned route without the workers' assistance.

As this is the first execution of SDACS as a total system, it is under experiment with the manual operation to check the system capabilities.

After the completion of this execution data of manual operation and that of SDACS, they will be compared, in order to solve the problems of SDACS.

This system should be further modified for practical use.

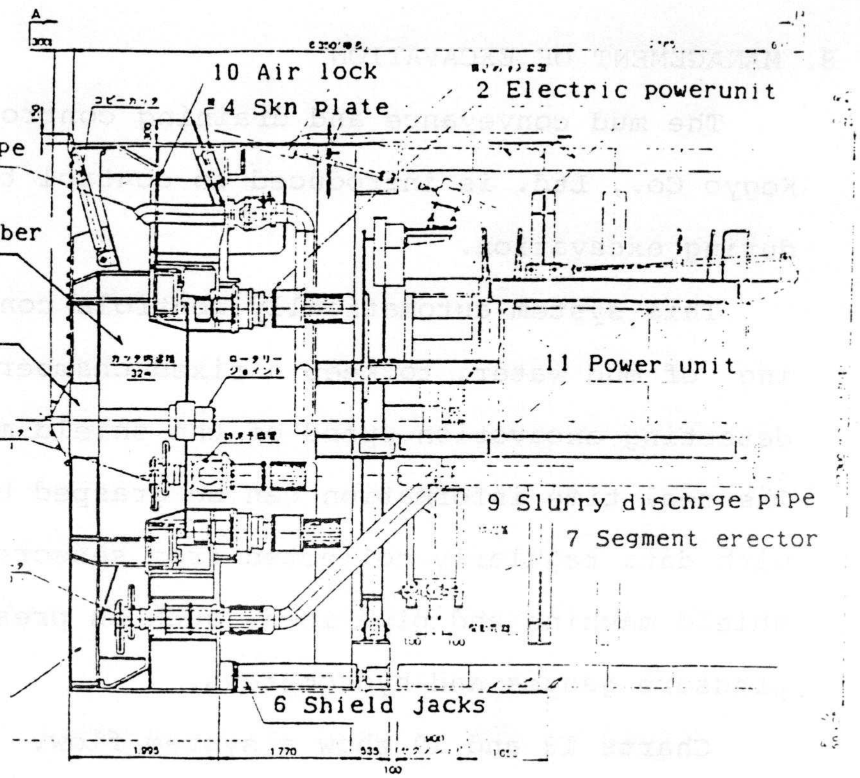


Chart 1. SLURRY SHIELD TUNNLING MACHINE

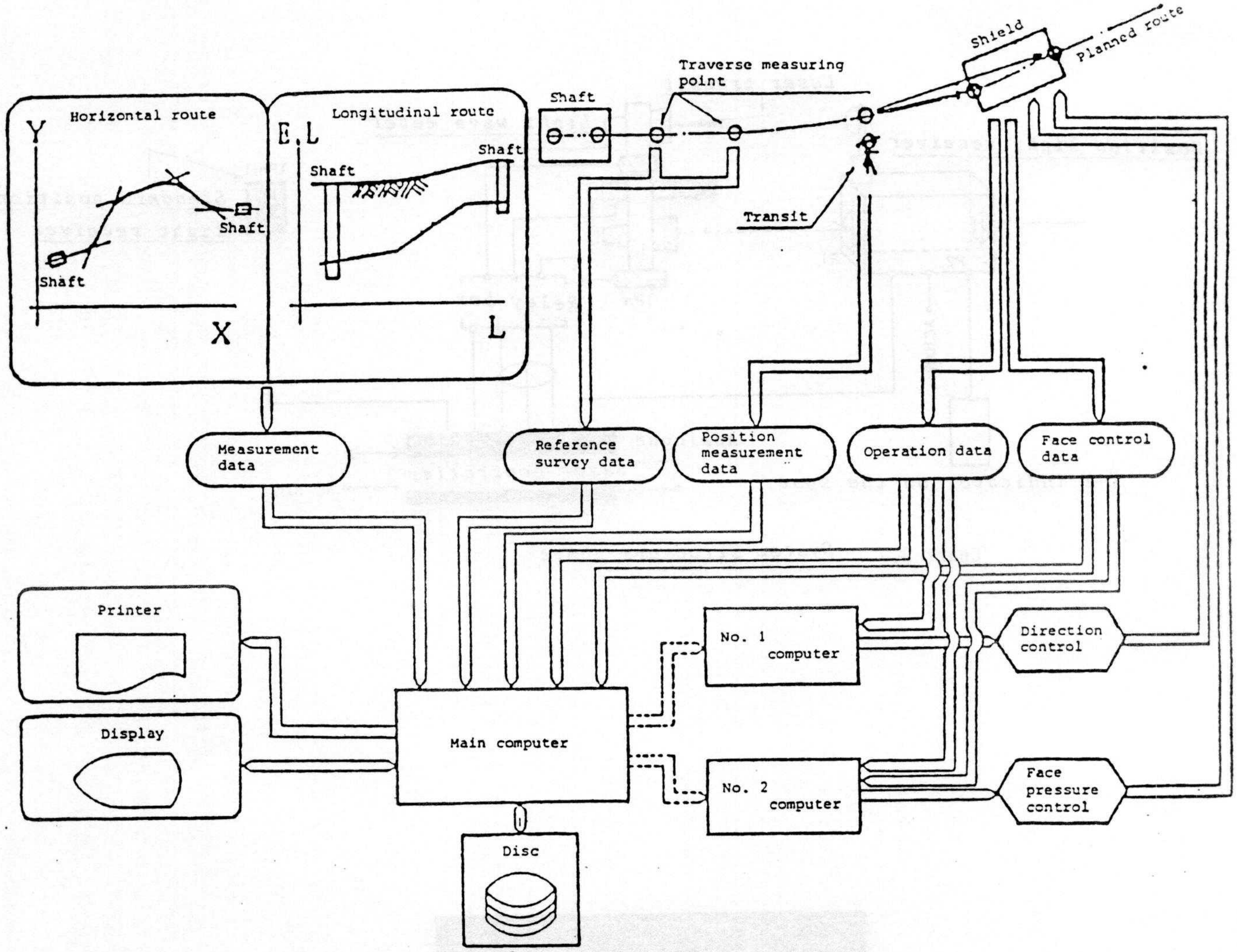


Chart 2. Outline of the SDACS

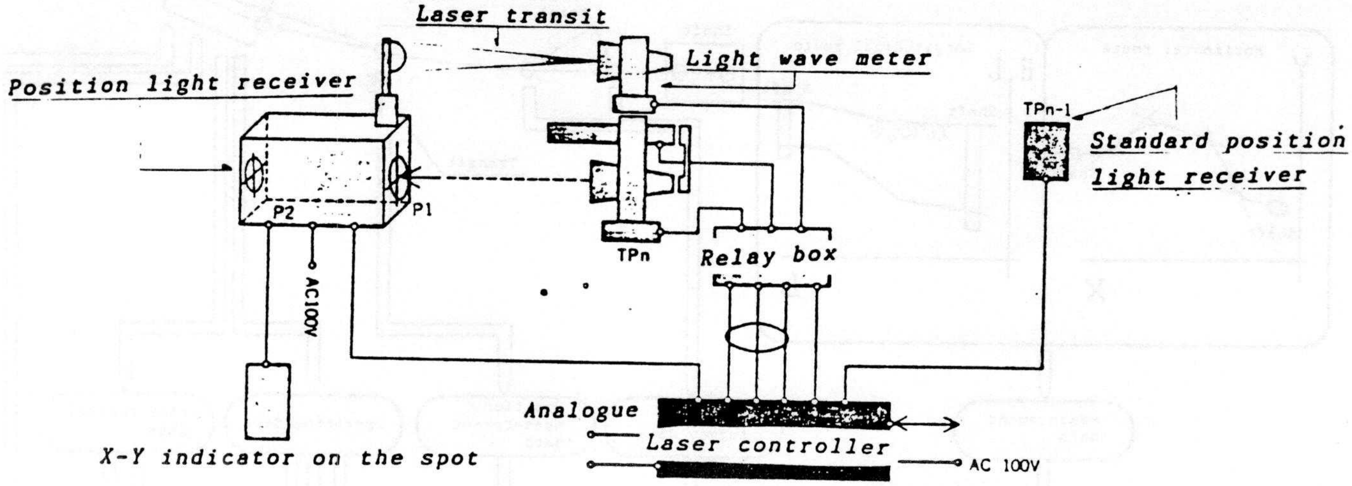
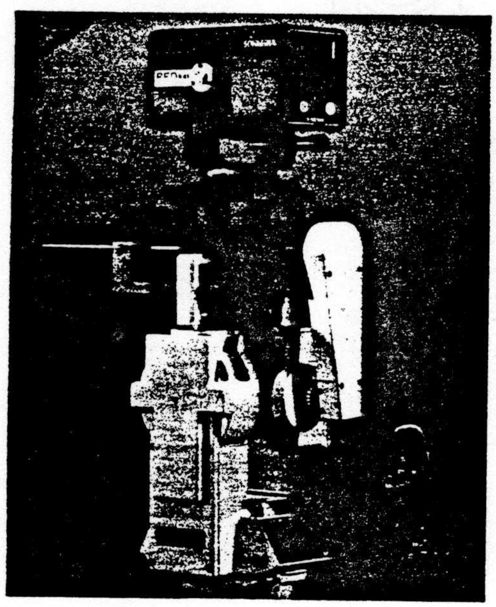


Chart 3. *System structure chart*



Photos 1.

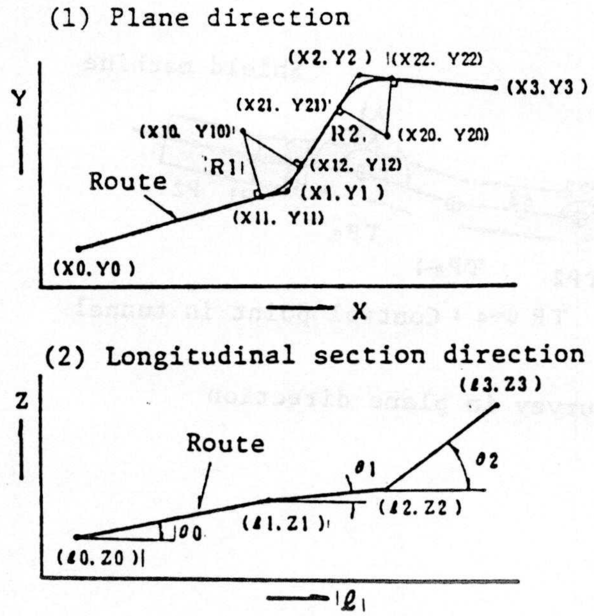


Chart 4. **Planned route data in plane and longitudinal section directions**

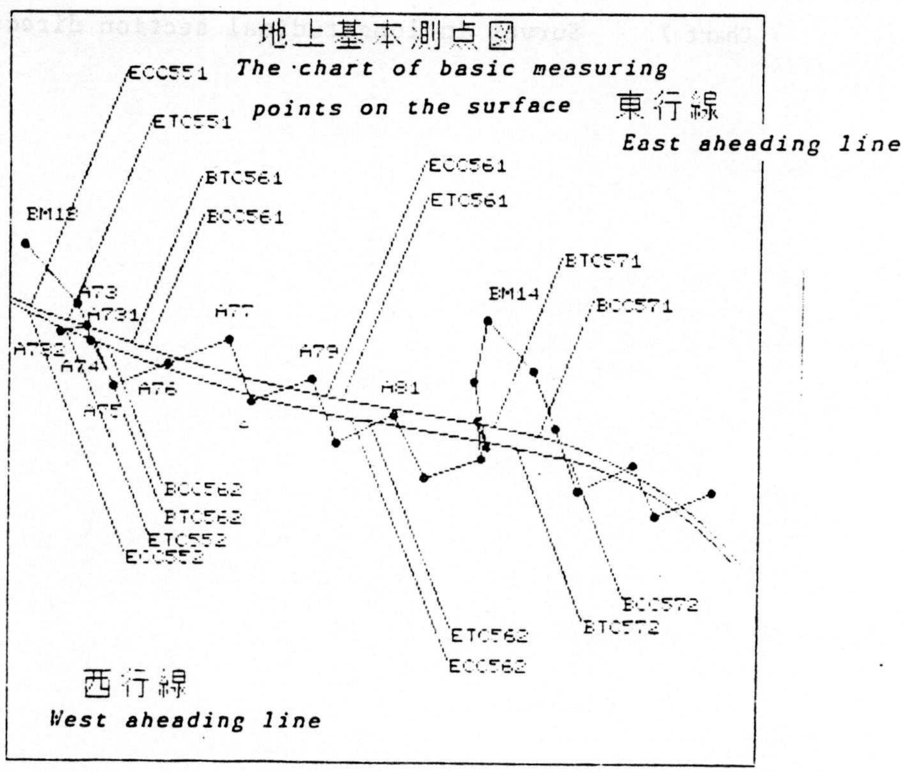


Chart 5.

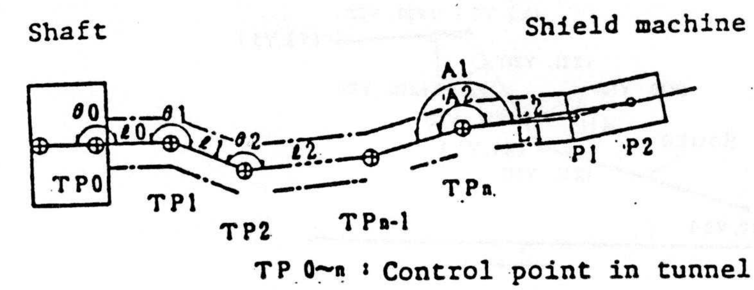


Chart 6. Survey in plane direction

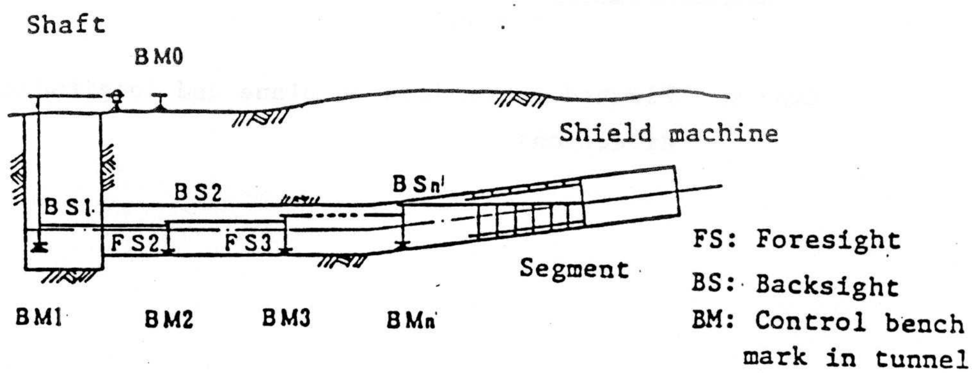


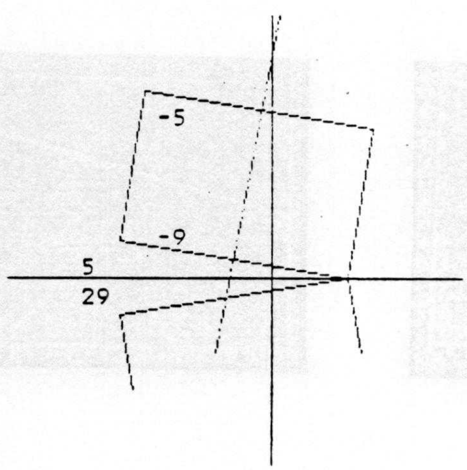
Chart 7. Survey in longitudinal section direction

SDACS　　シールド掘進記録

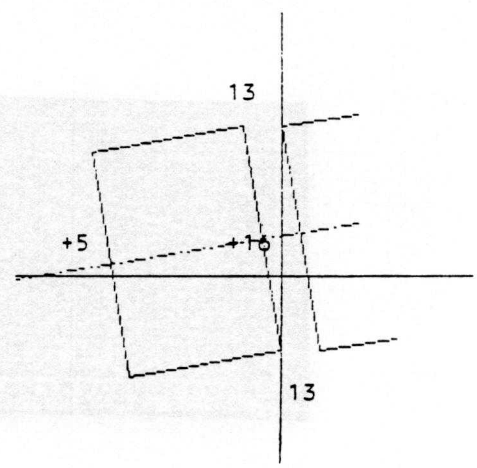
基準点データ		測量データ		マシンデータ		
基準点No.	1	距　離　m	65.558	ピッチング		+1
X 座標	-33298.700	移動距離　m	1.875	ローリング		-7
Y 座標	+6508.860	水平角　1	180　58　45	ストローク	NO. 1	988
方位角	189 15 39	高度角　1	90　24　45		NO. 7	971
BM. EL	-5.824	水平角　2	180　58　25		NO.13	988
掘進延長距離	267.133	高度角　2	90　25　10	mm	NO.19	1005

	X 座標	Y 座標	△H	方位角	計画高	測定高	△V
切羽	-33367.300	-33361.000	-5	190　3　1	-10.840	-10.835	+5
テール	+6496.480	+6497.590	-9		-10.853	-10.837	+16

水平蛇行



鉛直蛇行



The results of the analysis are shown in Chart 8.

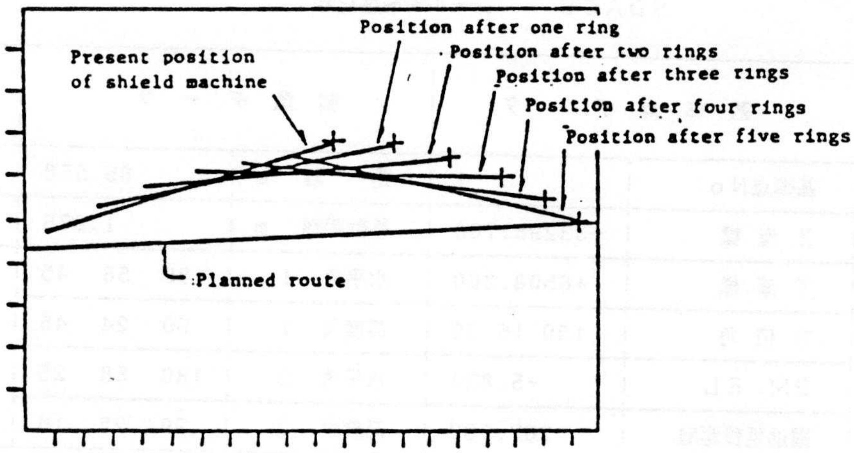


Chart 9. Simulation of jack operation

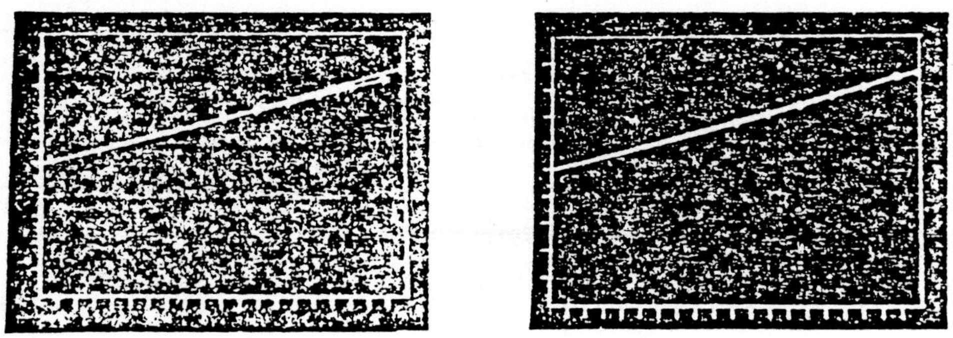


Chart 10.

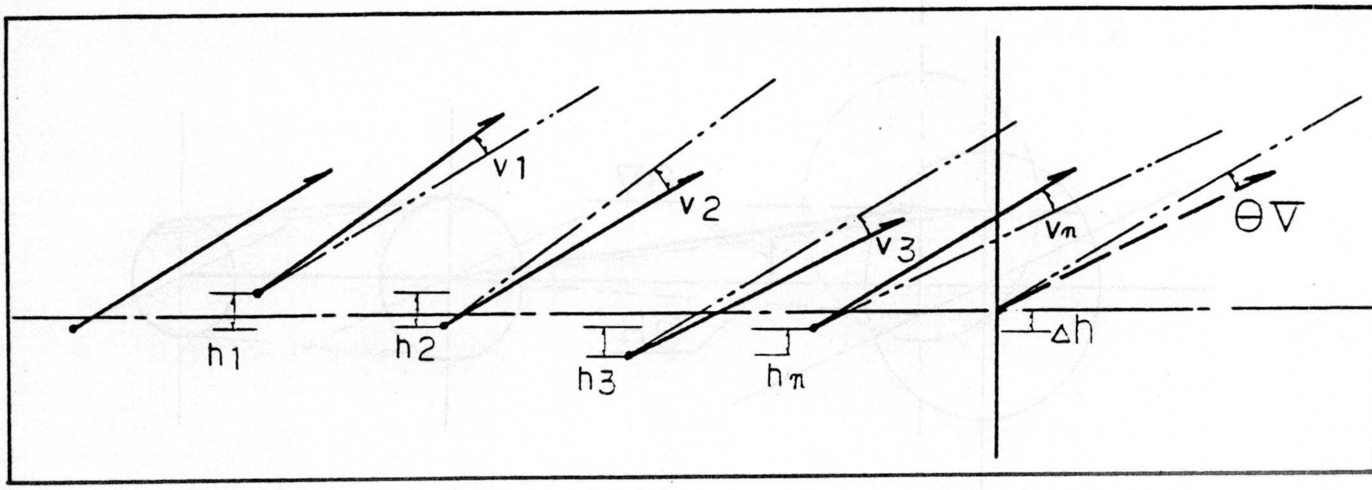


Chart 11. shows a model of the analysis.

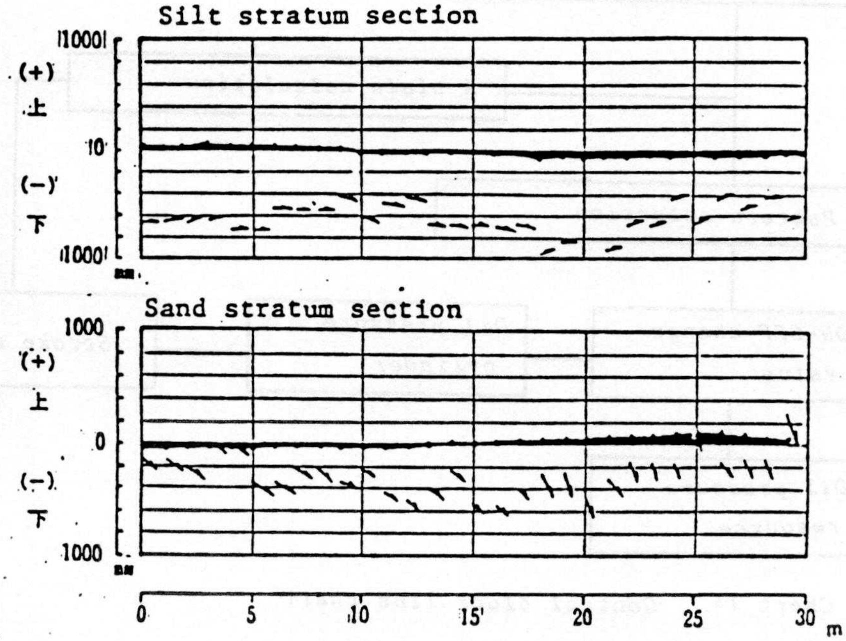


Chart 12. Comparison of driving tendency due to earth quality

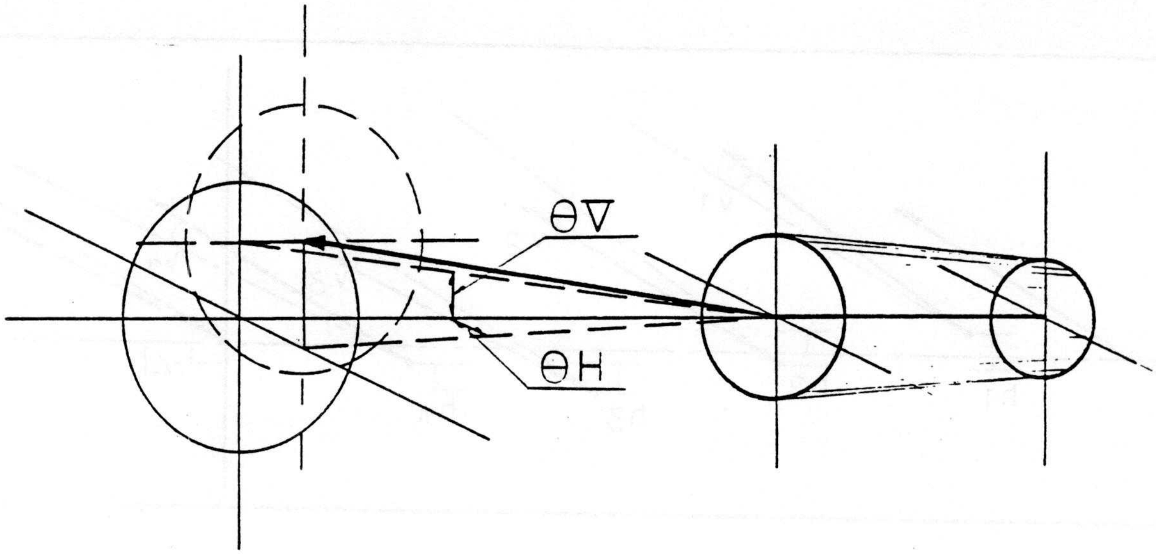


Chart 13. Shield direction control model.

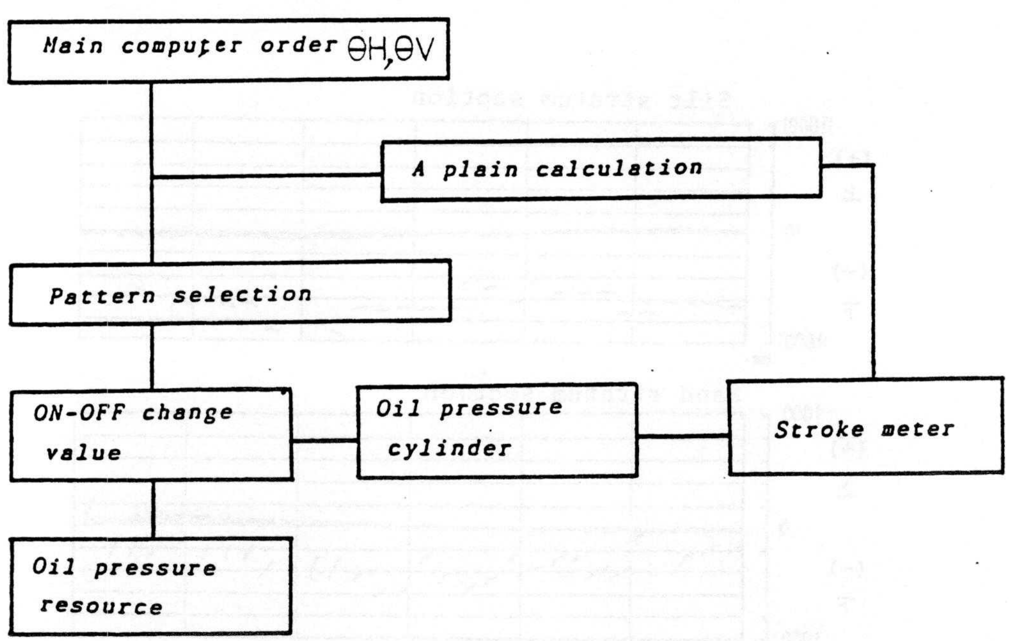


Chart 14. Control block line chart

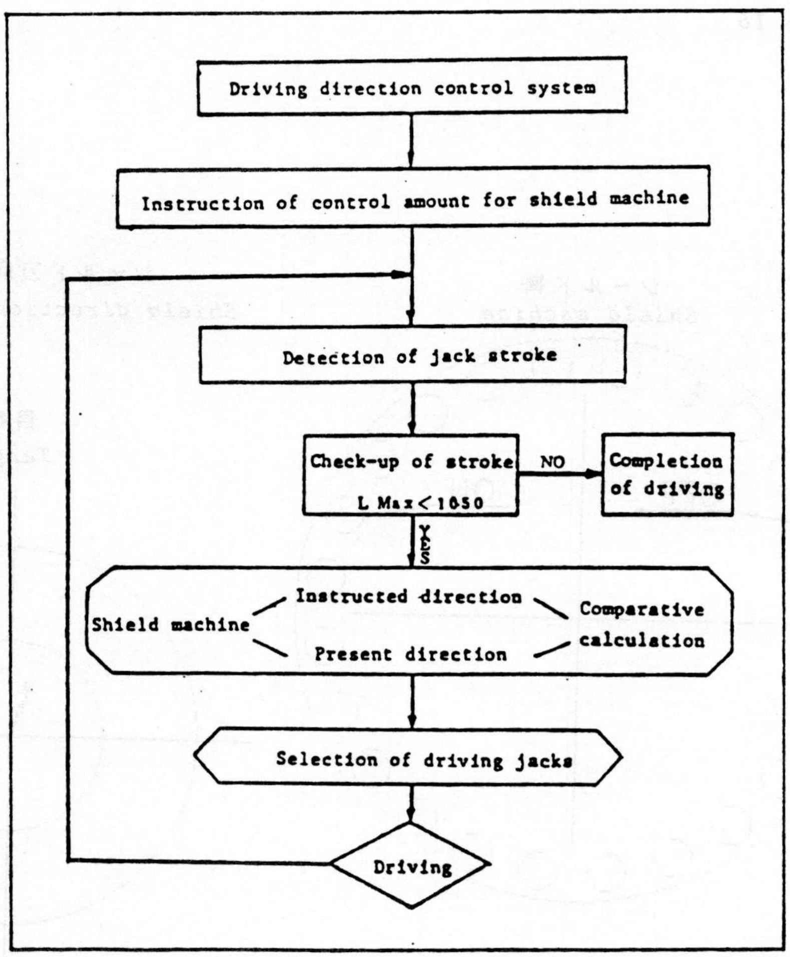


Chart 15. Driving direction control system

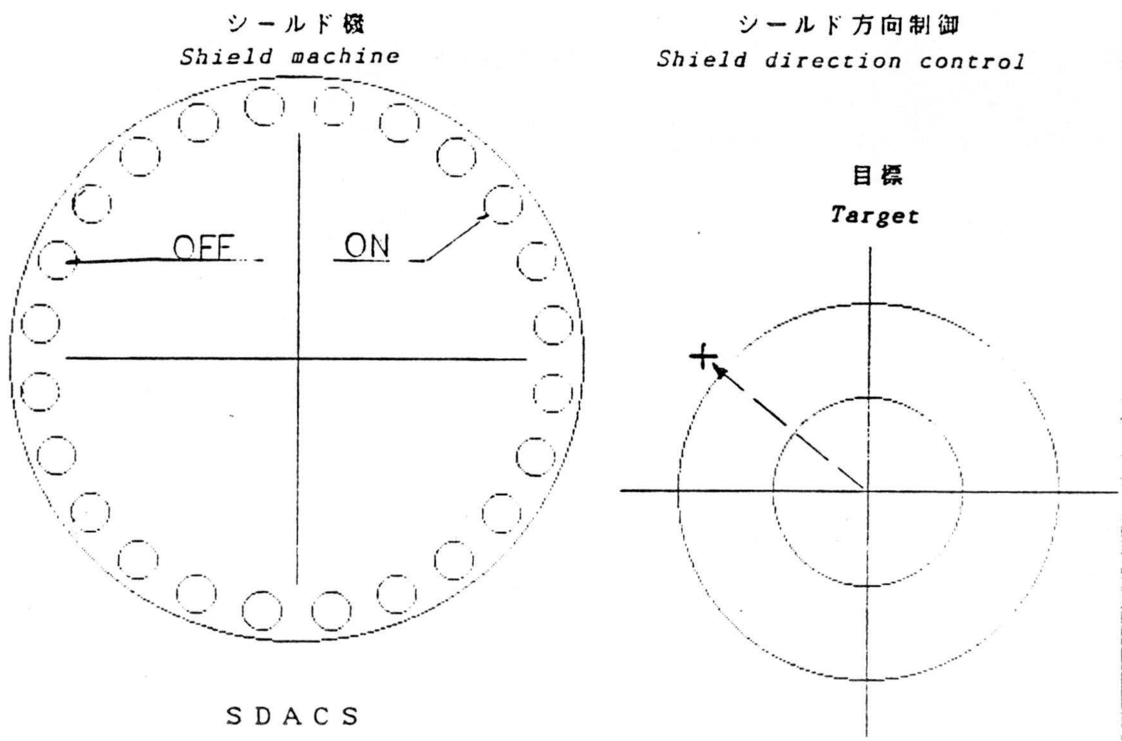


Chart 16

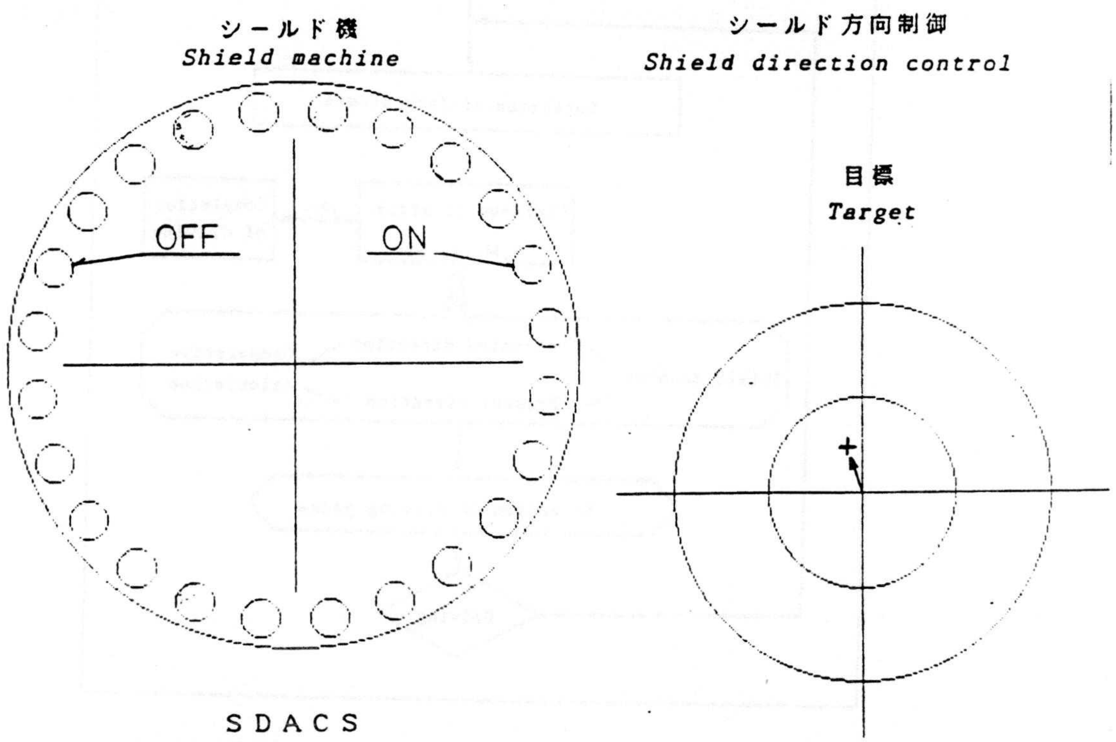


Chart 17

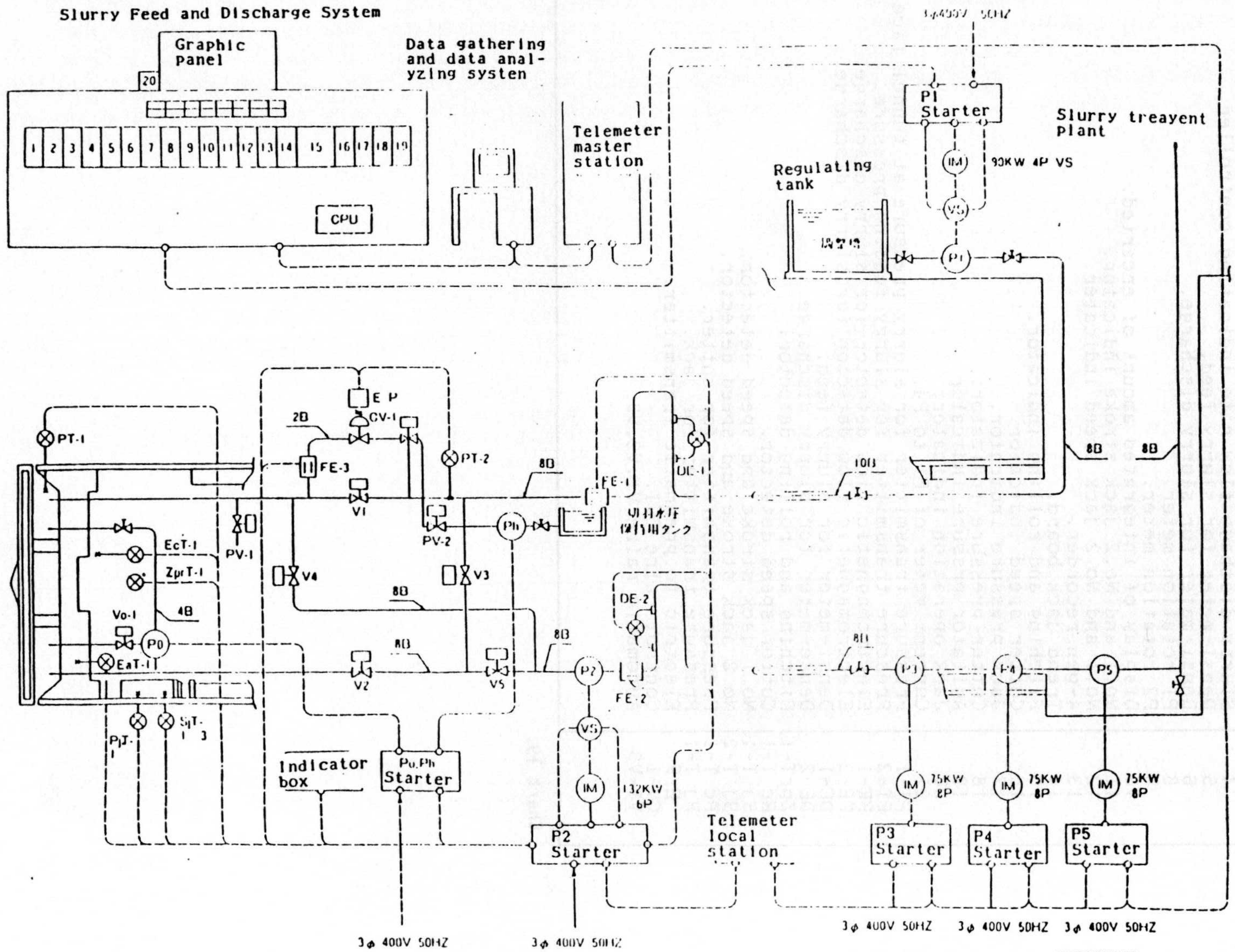
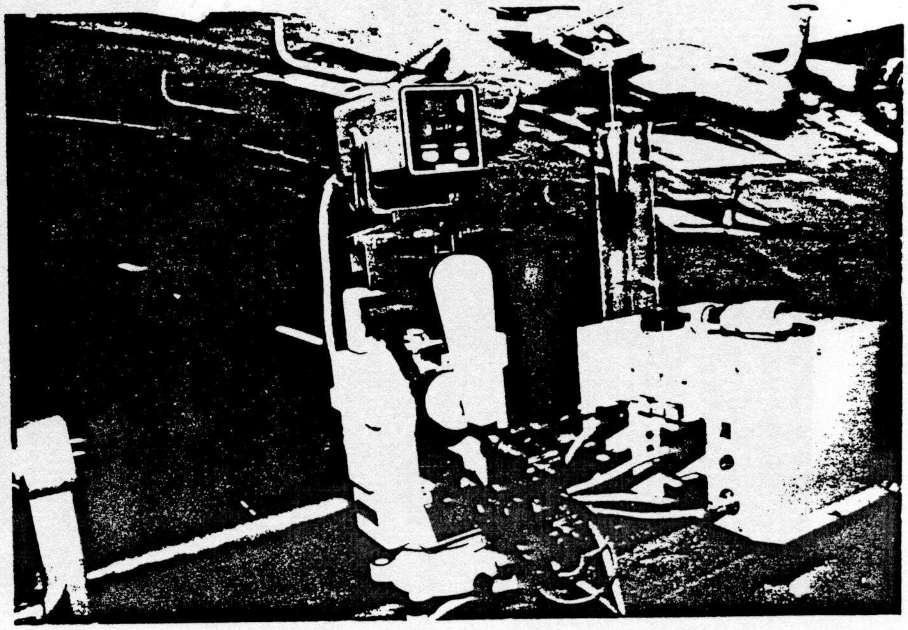


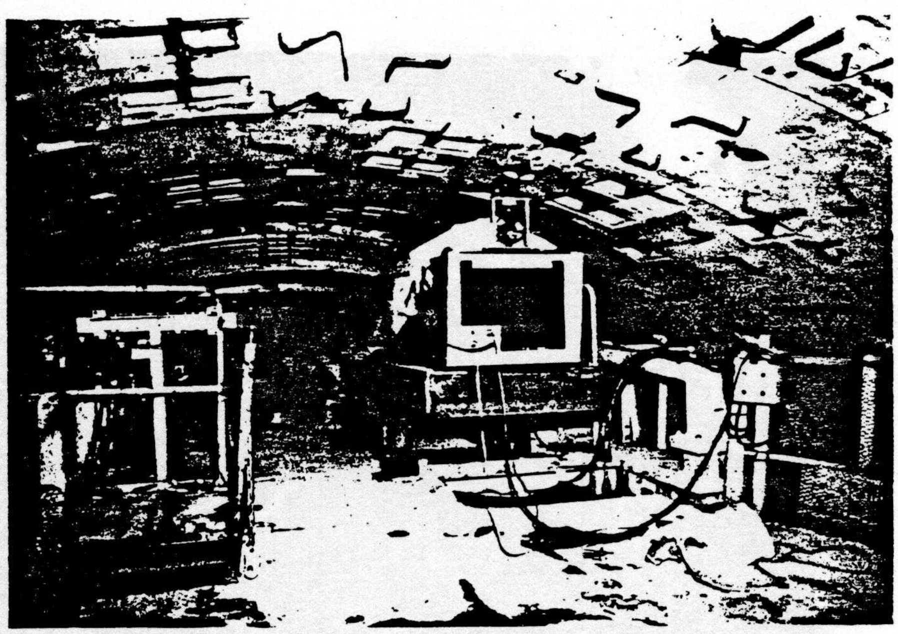
Chart 18. Slurry Feed and Discharge System

N O	Name of instrument
1	Indicating controller for water pressure at tunnel face.
2	Indicating controller for slurry feed pressure.
3	Slurry flow rate indicator.
4	Slurry dischage flow rate indicating controller.
5	Densi-meter for slurry feed.
6	Densi-mater for slurry discharge.
8	Pl rotation meter.
9	P2 rotation meter.
10	Display of integrated amount of ercarted.
11	No.1 and No.2 jack stroke indicator.
12	No.1 and No.2 jack speed indicater.
13	4-pen recorder.
14	Trend jack board.
15	Pitching and rolling indicator.
16	Cutter speed indicator.
17	Jack pressure indicator.
18	Cutter pressure indicator.
19	Agitator prssure indicator.
20	Jack operation indicator.
21	Current meter of Pl to P4.
PT-1	Pressure transmitter for slurry pressure at tunnel face.
PT-2	Pressure transmitter for slurry feeding pressure.
FE-1	Electromagnetic flow detector for slurry discharge.
FE-2	Electromagnetic flow detector for slurry discharge.
DE-1	Densi-meter for slurry feed.
DE-2	Dense-meter for slurry discharge.
ZprT-1	Pitching and rolling detector.
Rc T-1	Cutter speed detector.
Sj T-1	No.1 jack stroke and speed detector.
Sj T-2	No.2 jack stroke and speed detector.
Pc T-1	Pressure transmitter for cutter.
Pj T-1	Pressure transmitter for jack.
E/P	Electric to pneumatic transmitter.
CV-1	Control ralre CV1.
V1-V3	Automatic ralre V1,V2,V3.

Chart 19.



Photos 2.



Photos 3.

Photos 4. Shield Machine viewed from its back

Photos 5. The completed tunnel