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Development of a fully automatic robotic system for small diameter tunnel construction: "development of the ACE MOLE 1200-M2 construction method"

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Abstract

The ACE MOLE 1200-M2 is a robot system for constructing small-diameter long distance tunnels with one man control. This is achieved by automating all the construction works from tunnel excavation to lining finish. All aspects of mechatronics utilised in this. This robot system can select free alignment, over a curvature radius of 80m,. according to the road alignment and the condition of the underground installations, and realises long distance constructions of 1 km, with superior capabilities than previous systems.The maximum driving length of the previous system was 500 meters.

The robot system features the following:

(1) The system is provided with a compound oil-pressure mechanism which can control the up and down, and right and left directions of the long and narrow shield machine with a high accuracy using six jacks. A shield machine consisting of four-sections is effectively driven with a compound driving mechanism.

(2) Instead of assembling pre-fabricated segments, the system adopts a cast-in-place automatic lining system using resin mortar lining material. This provides high early-strength in its lining material and allows lining work underwater.

(3) The system transports excavated earth and lining material using an unmanned control system, which incorporates a trackless transport vehicle.

We have established the full automatic tunnel robot technology through this system, utilising an information-oriented construction method. The method represents unprecedented, epoch-making, tunnel robot technology. The paper outlines the development of fully automatic unmanned tunnel robot technology which has been realised in the ACE Mole 1200 -M2 method.

1. INTRODUCTION

Little technology for shield tunnel construction method has been established for the construction of 1.0 meter inner-diameter tunnels, because it is difficult for construction workers to work in such tunnels and also to secure sufficient space within the shield machine for implementing automatic operation.

Thus, NTT worked on the development of an automated method for lining small-diameter shield tunnel with cast-in-place resin mortar whose strength is developed soon after placement, instead of prefabricated segments. Construction under water can also be carried out by this method. In an experiment it has been used to build a 170 meter long

small-diameter tunnel with a radius of curvature of 200 m. This has lead to the successful development of the automated tunnelling system, the "ACE MOLE 1200-M2 Method".
A method by which a tunnel of 1m inner radius or so can be excavated for distances of one km or so, whilst following the course of existing main roads or street, has been made possible. Furthermore, this has been achieved with proper control of the alignment, for example, avoiding underground installations which might be buried. These are important achievements in the context of the environmental conditions of urban construction.
The following technical requirements had to be met to implement the construction method for a 1 km driving length and high-speed operation:

(1) Improved shield machine system reliability
(2) Higher speed vehicle transport for the resin mortar lining material and the excavated earth and improved stable machine angle capabilities
(3) To implement construction workability at 80-meter radius curvature (including improved shield machine direction control at curved sections)
(4) Improved long-distance traction capabilities for control cables

Various improvements and developments were made for the new tunnel robot system on the basis of the above requirements.
The new ACE MOLE 1200-M2 method uses high-performance lining material for strength and anti-separation, functionally-enhanced units including a highly accurate directional control system, an automated lining unit with improved reliability of mixing ratio control and form function, and a trackless transport vehicle with significantly improved running function. Improvements have also been made in the method of overall system control. Testing at the sewerage system construction project in Yokohama City (1.2-meter inner-diameter, 674-meter driving length, and 100-meter radius curvature at three locations) revealed that the tunnel robot realised its technical capability by installing a 1.0-meter small diameter shield tunnel extending over a distance of 1 km.

2. SYSTEM OUTLINE

2.1 System composition

Figure-1 is the system diagram for the machine and Table-1 gives the shield machine specifications. The system has a shield machine consisting of four sections: excavation apparatus, local electrical control apparatus, power supply apparatus and lining apparatus.
The latter comprises unmanned transport vehicle that transports excavated earth and lining material, a one-man controlled operation house that monitors and controls the entire system,

Table-1 Shield machine specification

Outside diameter	ϕ1,480mm
Machie length	12,145mm
Shield jacks	30tf×750mm×6pcs.
Thrust jacks	30tf×750mm×6pcs.
Type	Earth pressure type
Other	Four-divided machine

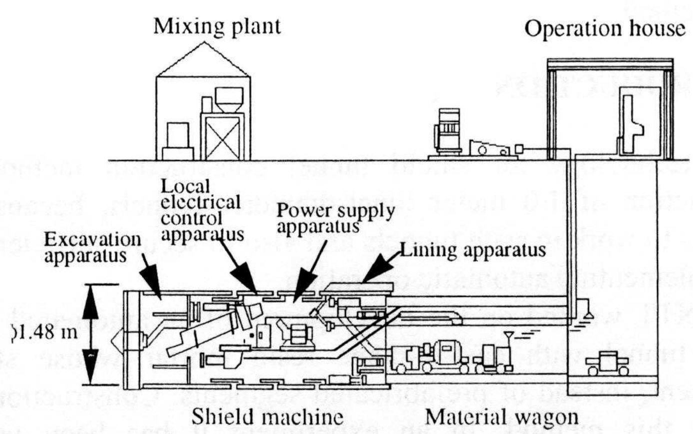


Figure-1 System diagram

and a mixing plant that kneads the lining material.

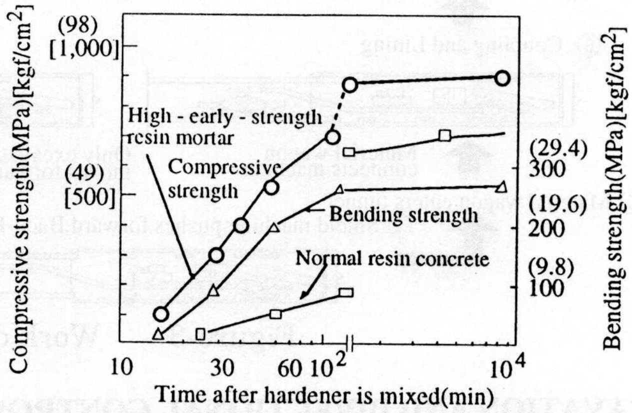


Figure-2 Lining material strength propeties

2.2 Tunnel lining material

The target of the M2 construction method is to enable unmanned lining work in narrow tunnels. It features automatic building of a unreinforced lining wall by simply feeding lining material. For this purpose, resin mortar was developed and implemented as this lining material that assures high early-strength.

The general features of the lining material are as follows:

(1) Advantages: high-strength, quick setting, excellent chemical resistibility and abrasion resistibility

(2) Disadvantages: large shrinkage when hardening, and high cost tendency.

To develop new resin mortar with features of extremely low shrinkage and quick-setting, which permits adhesion-in-water. New improvements on the resin mortar mix combination for the lining materials were made on the following basis:

(1) Before the improvement the strength deceased by about 30% when soaked in water. However, after increasing the special surface processing density with silane coupling agents applied to the sand aggregate, the strength loss ratio was significantly improved.

(2) More additives were applied to the anti-segregating agent which helps achieving a mix combination that does not segregate the materials for three days after kneading. Figure-2 indicates the strength properties of the lining material and Table-2 shows the mix combination of the resin mortar.

2.3 Work cycle

It takes about two hours to complete a single work cycle. As shown in figure-3, the work cycle comprises earth excavation, lining form removing, pushing forward, back-filling, lining form setting and lining work. As can be seen in the cross-section of the shield machine shown in figure-4, a shield jack is provided at the excavation apparatus section, while a driving jack is provided at the lining apparatus section. A compound driving mechanism that operates these jacks in turn has been adopted. Each work cycle completes a 70 cm length of lining wall.

Table-2 Mix combination of lining material

Item	Material
Resin	Unsaturated polymer
Aggregate	Sand
	Calcium carbonate powder
Anti-segregating agent	Fine powder of silica
Hardener	Methyl ethyl keton peroxide

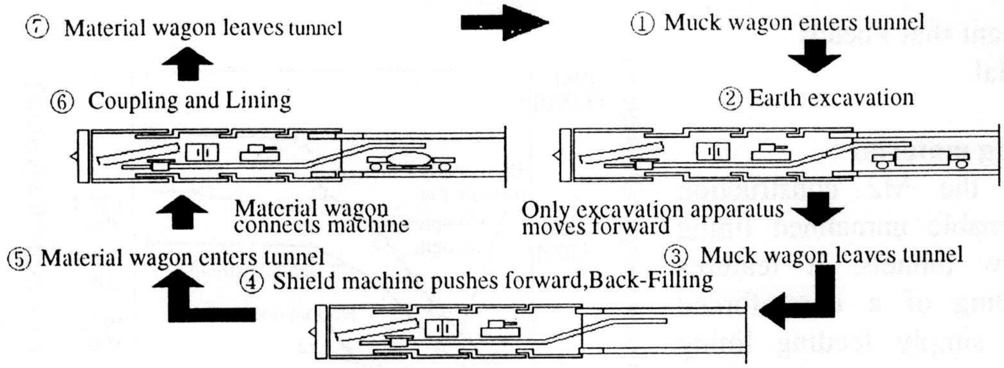


Figure-3 Work cycle

3. EXCAVATION AND DIRECTIONAL CONTROL MECHANISM

The excavation apparatus moves forward alone while excavating earth by rotating the cutter wing and extending the six shield jacks forward. The screw-conveyer hauls the proper amount of the excavated earth into the machine. A pressure pump then sends the earth into the soil packet on the muck wagon waiting at the rear end of the machine. This radio controlled muck wagon starts running and transports the earth to the shaft.

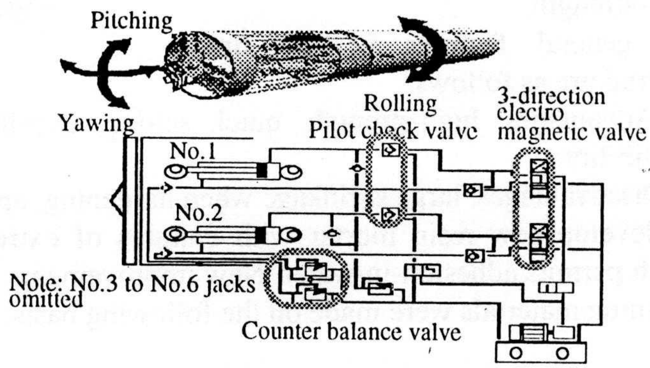


Figure-4 Oil pressure mechanism of shield jacks

Compared with the previous system, the running function of the tunnel vehicle has been significantly improved by mounting an inclinometer for correcting rolling and by adopting a right angle wheel. The shield machine is equipped with a gyro compass, rolling meter, pitching meter and stroke-angle meter to control the machine position with tolerable values according to the planned alignment. It is extremely difficult to precisely control the shield machine direction by simply relying on the thrust of six jacks. Therefore, in this system, a compound oil-pressure control mechanism, that provides tension and fixed capabilities, was newly added to each shield jack (Figure-4). Furthermore, in sections with high cohesion in the excavation soil layers, a dispersant was additionally injected. As a result, these sections were excavated without increased cutter torque and thrust.

4. AUTOMATIC LINING MECHANISM

4.1 Composition of automatic lining system

Radio-control is used in the lining system. The material wagon loaded with resin mortar is connected to the rear of the machine and resin mortar is sent under pressure to the mixing unit

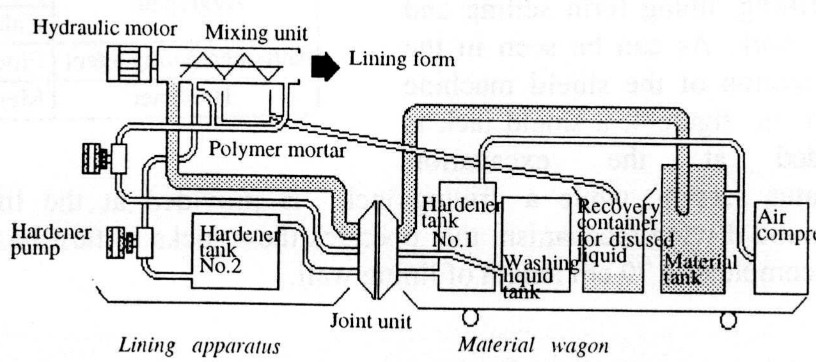


Figure-5 Lining system outline

for lining inside the lining form. As shown in figure-6, the lining system consists of a joint unit, feeding unit, mixing unit and lining forming unit.

4.2 Automatic lining function

It is important that a proper amount of hardener is mixed with the resin mortar, the material. The automatic lining system, for which the processes consisting of preparation, lining and washing, controls the whole operations from start to end automatically. This automatic operation is done by pushing the operation button. The flow of the automatic lining system is shown in Figure-6.

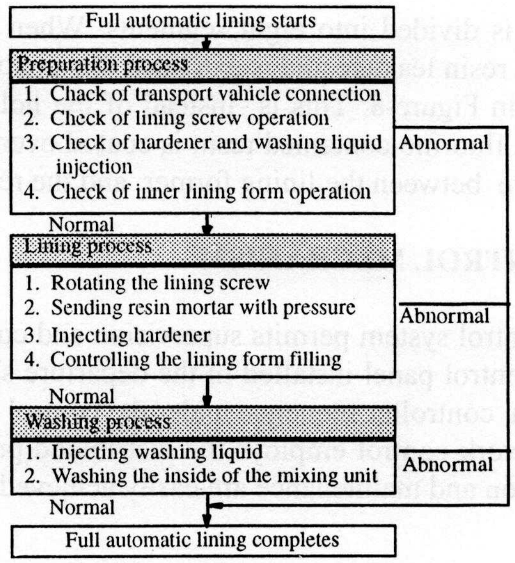


Figure-6 Flow of automatic lining

4.3 Mixing unit function

Lining work is performed continuously. At the mixing unit, resin mortar and hardener are mixed in equal proportions with the aid of a screw operating at 700 rpm. Because it is wagon informs (by wireless communications) the machine controller of the necessary weight to be delivered in a specified time. The machine controller automatically adjusts the amount of hardener for mixing, using an on board sequencer. For quality control purposes in the wall lining activity, the optimum mixing rate of resin mortar and hardener is within the range of 2.- 3.5 phr (phr: parts per hundred resin). In this system, the harder mixing rate control flow, as known in Figure-7, provides the optimum mixing rate, according to a mortar feeding amount at the previous spot. When lining is completed, the resin mortar remaining in the mixing unit is washed and recovered.

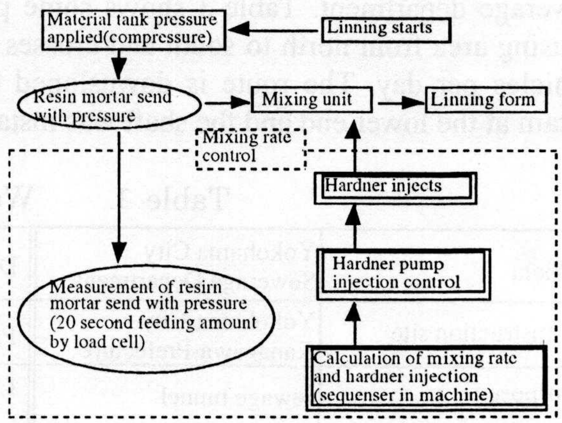


Figure-7 Mixing rate control

4.4 Lining former unit function

The lining former unit is composed of outer-lining formers, inner-lining formers, an end lining former, removable jacks and thrust jacks. The inner lining

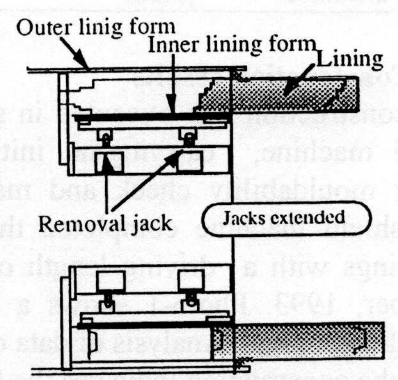


Figure-8 Lining form unit

former is divided into eight segments. When lining, the lining former is completely closed to prevent resin leakage and is extended and contracted by the two jacks equipped on each piece, as shown in Figure-8. This is instead of the holding ring method of the previous system. A very durable fluorine-contained resin is coated over the lining former surface to avoid the problem of adhesive between the lining former and the resin mortar

5. CONTROL MECHANISM

The control system permits supervision and control of the shield machine and transport vehicle via a control panel installed in the departure shaft. All operations are carried out automatically by each controller sequence under the control of a FA controller.
Since work control employs the distributed processing system using the FA controller, system extension and maintenance are easily achieved.

6. IMPLEMENTATION AND EVALUATION

6.1. Outline of the construction

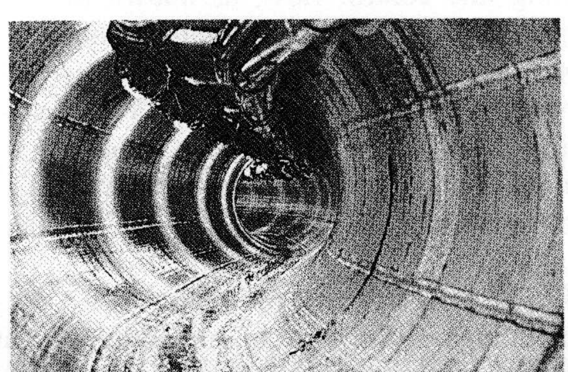
The M2 method was utilised for a sewerage construction project in Yokohama city. The construction is a sewage main trunk rehabilitation work ordered by Yokohama municipal sewerage department. Table-3 shows some project statistics. The construction route passes a housing area from north to south and crosses a national highway bypass which carries 100,000 vehicles per day. The route is downsloped because the departure shaft site was difficult to obtain at the lower end and the shaft was installed at the upper end of the route.

Table-3. Work outline

Client	Yokohama City Sewerage Department	Driving length	674m
Construction site	Yokohama-City Kanagawa-Prefecture	Planimetric alignment	R=100m:three, R=200m:four
Purpose	sewage tunnel	Longitudinal alignment	-0.29% slope
Construction period	1991.10~1994.3	Earth covering	GL-6~-15m, Water pressure:4.9KPa
Inner tunnel diameter Wall thickness	1.2m 10cm	Soil conditions	Silty Clay(Value N=2~30)

6.2. Construction results

The construction was executed in sequence of shield machine, carrying-in, initial driving, lining mouldability check and main driving. The shield machine completed the lining of 962 rings with a driving length of 674 m in October, 1993. Photo-1 shows a part of the completed tunnel. Analysis of data obtained from the construction indicates the following:


Photograph-1 Completion

(i) Finishing of the lining walls

No cracks were found on the completed wall lining and the walls were uniformly structured. It is confirmed that the mixing ratios for resin mortar to hardener are controlled within a range of 3.0 phr +0.5 phr (see Figure-9), which satisfies the required quality level. On the other hand, further study is required for improving the adhesive property of the in-water lining materials and limiting material leakage from form the former.

(ii) Directional control

The construction accuracy, which is important particularly for sewerage tunnelling, is within +35 mm apart from the baseline as shown in Figure-10, this sufficiently meeting the management criteria of +50 mm. This accuracy is high rated, considering that secondary lining for meandering adjustment is not performed in this M2 method. Also, we confirmed that a required accuracy for curvature lining is fully controllable with six jacks.

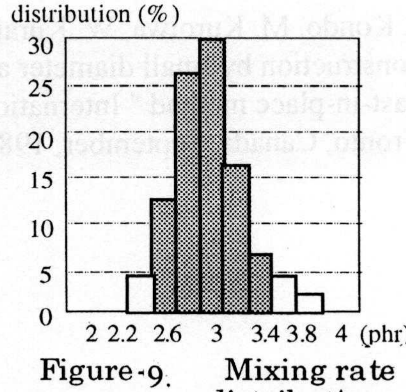


Figure-9. Mixing rate distribution

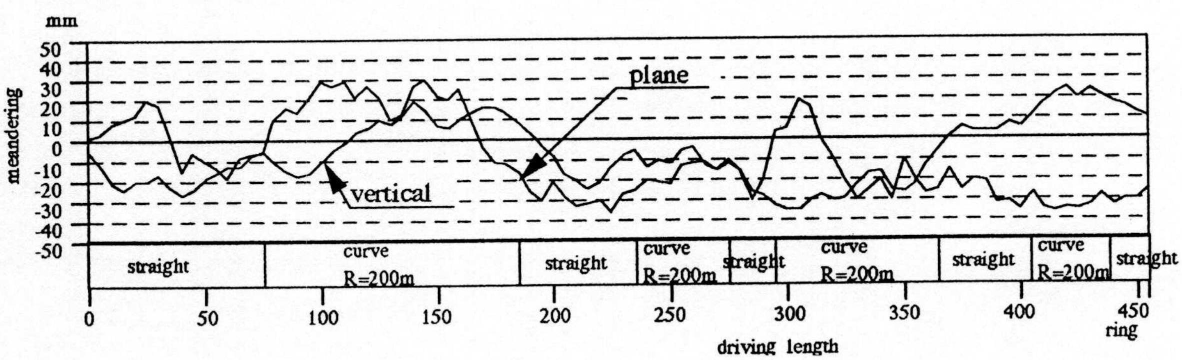


Figure10.Construction accuracy (plane, vertical section)

(iii) Work efficiency

The average driving length per day was 3m, which was below the target of the average driving length. After proving the machine, the maximum driving length was extended to 4.6m per day in several operations.

With the present system, 5.6m per day is the limit due to the cycle time. We must now achieve higher speed operations by shortening the curing time for lining.

CONCLUSIONS

Hitherto, the M2 construction method was improved to realise a 1.2m diameter, long distance (1 km), curved (R=80m) tunnel construction. The practicality of the method was then applied to a 1.2m inner-diameter, 674m long sewerage tunnel construction work. As a result, the M2 method is now to become a recognised ECL construction method, proving that it possesses the basic capabilities of an automatic tunnelling system using resin lining material, and without reinforcement. We must also concentrate on enhancing the functions while positively applying the construction method to long-distance, sharp-curved construction work.

We are very indebted to the personnel of the Yokohama City Sewerage Department and to those concerned in sewerage construction work, for their co-operation in preparing this paper.

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