Development of "SPL Robots" for Construction of Tunnel Linings

Shigetoshi Koga,
Director, First Research Division,
Technical Research Institute of Fujita Corporation

Akimasa Waku,
Head of Civil Engineering Laboratory,
Technical Research Institute of Fujita Corporation

74 Ohdana-cho Kohoku-ku Yokohama-City
Kanagawa JAPAN 223

ABSTRACT

The traditional methods used in the construction of primary linings in tunnels have the disadvantage that, because the lining materials are sprayed directly on to the excavated rock face, concrete materials rebound and dust is generated, leading to deterioration of the working conditions, as well as rendering the process uneconomic because of the loss of the materials. The robotised Sliding Press Lining (SPL) Method aims at solving these problems.

The present paper deals with the development of the SPL robot and experiments carried out using the SPL robot in a test tunnel.

1. Introduction

Under the SPL method, ready-mixed concrete provided from the agitator car is fed through squeeze pumps and mixed with the set accelerator near the end of the nozzle before being poured into the press form and pressed on to the rock face.

When the concrete placed hardens, the press form is moved along a circular path into the next position and the construction of the lining is carried out continuously through repetition of this process.

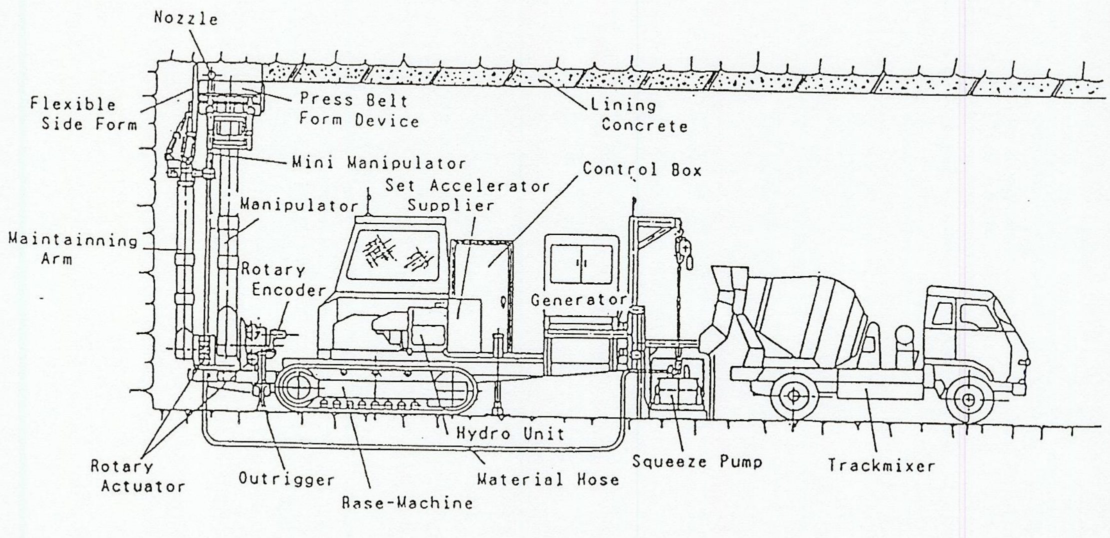


Figure 1 Construction of Lining in Progress under Sliding Press Lining (SPL) Method

2. Special Features of SPL Method

1) Use of SPL robots allows one to avoid dangerous and unpleasant working conditions and to reduce labour.
2) Because the concrete is poured into the space between the from and the rock face, materials do not rebound and dust is not generated.
3) Use of circular travelling forms allow one to create thin supporting structures with smooth surfaces.
4) Press lining raises the quality of the lining concrete.

3. SPL Machinery

3.1 Composition of SPL Robot

The SPL robot consists of the sliding press lining form device, a manipulator, devices for supplying materials including a concrete pump and a supply pump for the set accelerator, a lateral form, a plate to prevent overflow of concrete materials, a crown form, a minimanipulator, a monitoring device and three automatic control systems. The three automatic control systems are the automatic positioning device for the machine, the automatic control system for the manipulator and the automatic control system for material supply. All these machines and devices are mounted on a crawler-type base machine to enable them to be transported together and so raise their mobility.

3.2 Sliding Press Lining Form Device

This device consists of an endless belt form with a lining width of 1.0 m and length of 1.2 m.

The form device is equipped with a lining form with a press mechanism. Fast-hardening, flowing concrete is poured into the pressurising part consisting of the top 50 cm of the form and the lining materials are pressed on to the rock face.

As the concrete hardens, the form is moved up into the next position along a circular path and this procedure is repeated to create the tunnel lining. The principle of press lining is depicted in Figure 2.

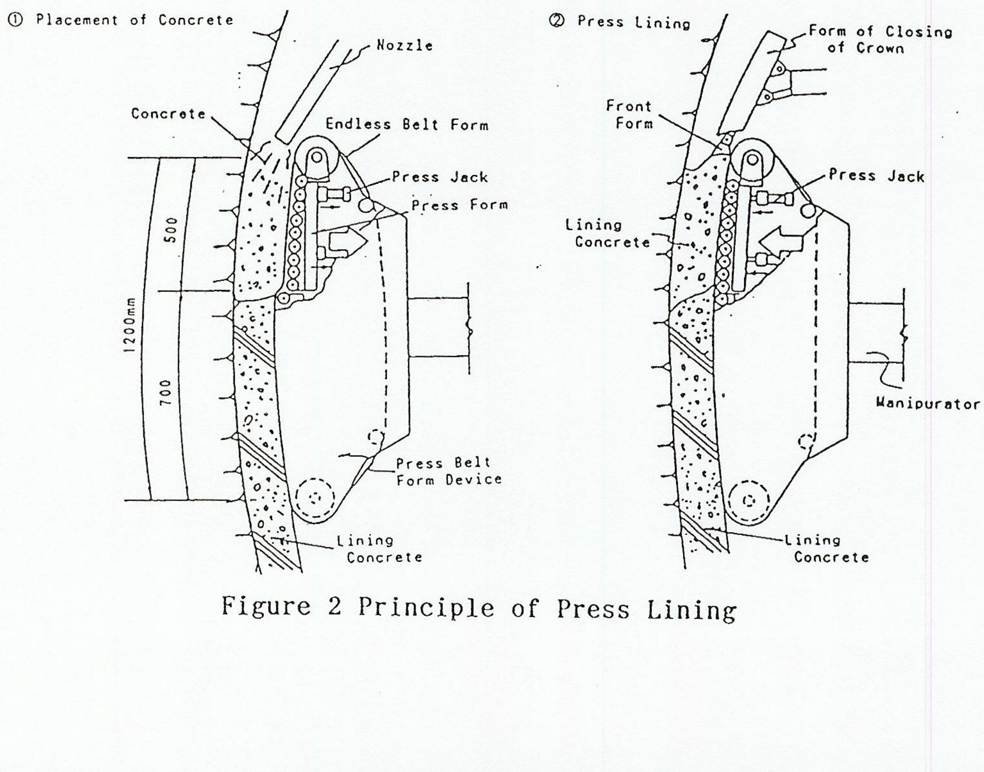


Figure 2 Principle of Press Lining

3.3 Manipulator

The manipulator is automatised and robotised using the automatic control system shown in Figure 3. The automatic survey system measures the distances ΔX and ΔY which express the positional relationship between the axis of the manipulator and the intersection of the tunnel centre and the spring line and provides the numerical data for controlling the movement of the manipulator by processing the position of the manipulator in relation to the design construction line.

The manipulator is operated through the combinations of a rotary encoder and a rotary actuator and of a linear encoder and a hydraulic jack and automatically controls the movement of the press lining form along the circular control path. The range of the lining radii is between 4.0 and 5.6 m and the lining thickness between 10 and 50 cm.

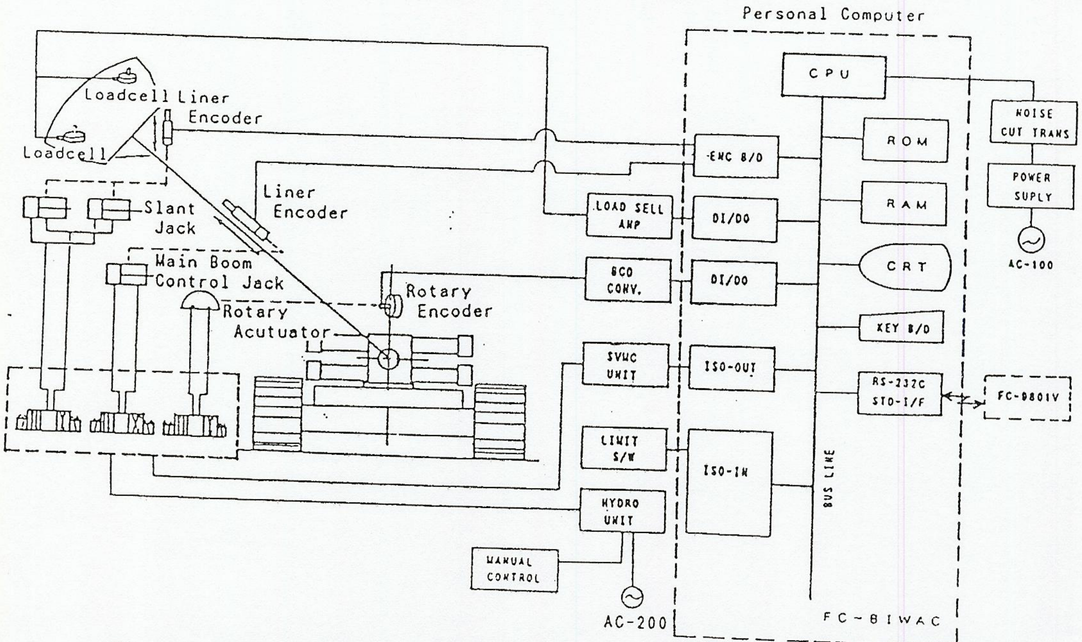


Figure 3 System for Automatic Control of Manipulator

3.4 Material Supply Device

The device consists of a concrete pump (squeeze type, maximum discharge: 7.0 m³/h), a supply pump for the set accelerator (diaphragm type, maximum discharge: 5.0 ℓ/min.), a compressor, a mixing device for materials, a nozzle and a material hose.

These devices are systematised to allow automatic supply of the concrete materials and the set accelerator. The quantity of the concrete being supplied is measured with a sensor and the supply of the set accelerator in the mix is adjusted accordingly.

The quantity of the concrete supply is calculated from the rotation of the propeller shaft in the squeeze pump, while that of the set accelerating agent is measured with an electromagnetic meter attached to the supply pipe and the discharge regulated by inverter control. The mixing device for the materials is attached near the end of the material hose.

The concrete is fed through the squeeze pump and stirred with low-pressure air. The set accelerator is then blown in the form of a spray and mixed with the concrete materials. After being mixed with the set accelerator, the concrete is placed by being poured into the space between the press lining form and the rock face.

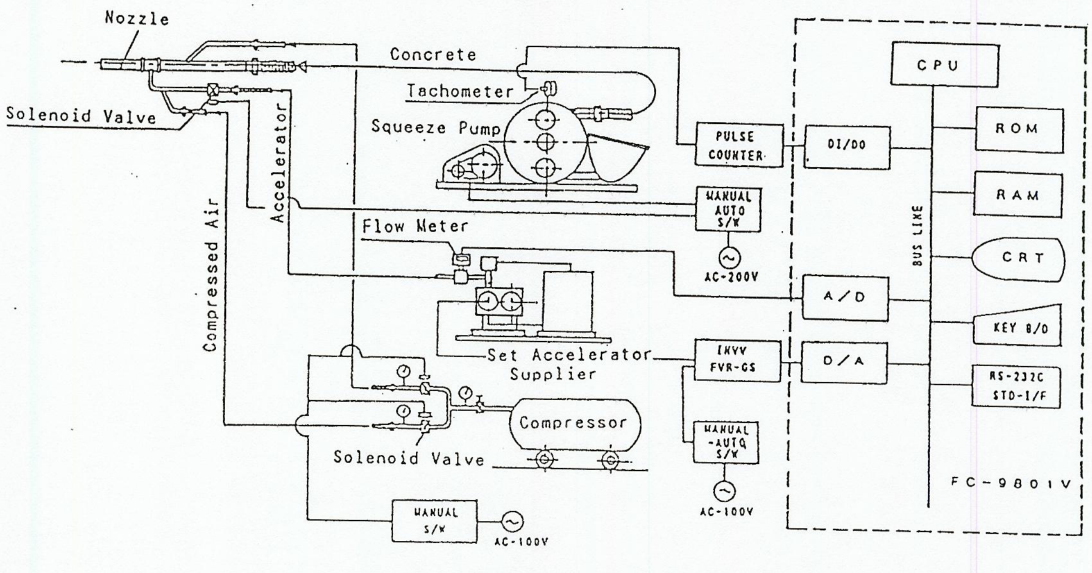


Figure 4 System for Automatic Control of Material Supply

3.5 Positioning Device for Machine

The device consists of an automatic measurement device and a detector and a control device for the position and the orientation of the machine. The automatic measurement device is made up of measuring instruments including a laser positioner, an optical meter, a propulsion device and a personal computer and a prism reflector for the optical meter.

The position detector is made up of a tiltmeter, a linear displacement gauge and an angle gauge and is controlled by the personal computer through an amplifier. The detector works out the three-dimensional coordinates for the position of the lining machine by following the prism attached to the machine while communicating with the automatic control system on radio, and automatically controls the coordinates of the rotary axis of the manipulator in relation to the tunnel centre and the spring line.

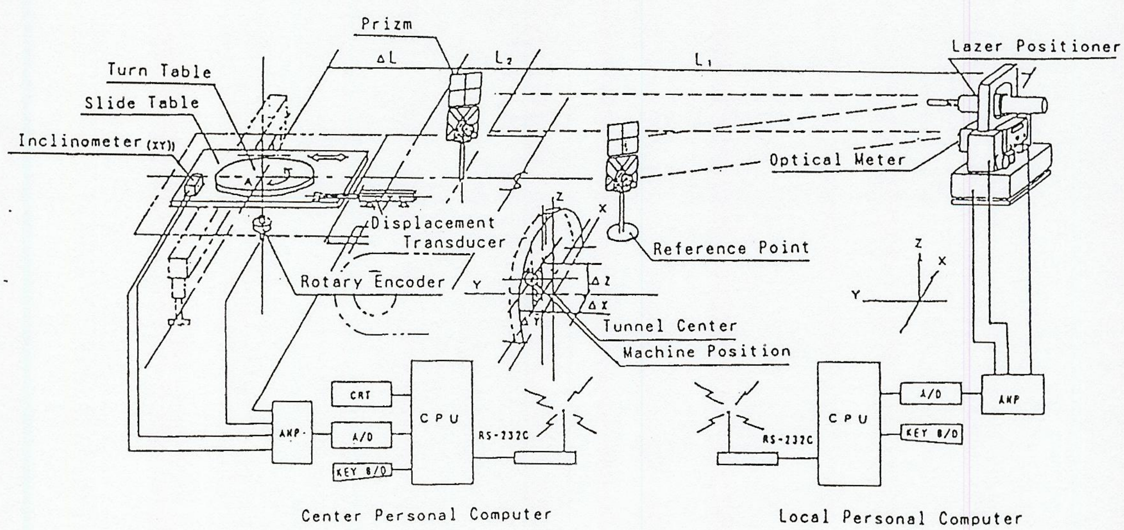


Figure 5 Model of Positioning System

4. Properties of Concrete

4.1 Concrete Mix

There must be no separation of materials in the unhardened concrete before addition of the set accelerator and the concrete must maintain its fluidity. After hardening, the concrete must satisfy the required strengths, durability and watertightness. The concrete mix is given in Table 1.

Table 1 Mix Proportion

Max size of coarse aggregate (mm)	Range of slump (cm)	Range of air cont. (%)	w/c (%)	s/a (%)	Unit content (kg/m³)				Admixture (kg/m³)	
					W	C	S	G	AE agent	High-range water-reducing agent
15	22 ~ 24	3.5	48.7	54	185	380	929	815	0.114 (C ×%)	6.460 (C ×%)

In this mix, the concrete shows an increase of 2 to 3 cm in the slump after addition of the set accelerator, meaning that the slump in reality is approximately 20 cm.

4.2 Concrete after Addition of Set Accelerator

The concrete after addition of the set accelerator and before hardening must have the following properties.

1) The concrete after addition of the set accelerator must have the properties needed for application to uneven surfaces in the required layer thicknesses.

2) The concrete must maintain the required level of fluidity until the required amount of concrete has been placed in the form and operation of the form has been completed. It must then harden rapidly to allow the form to be moved upwards into the next position.

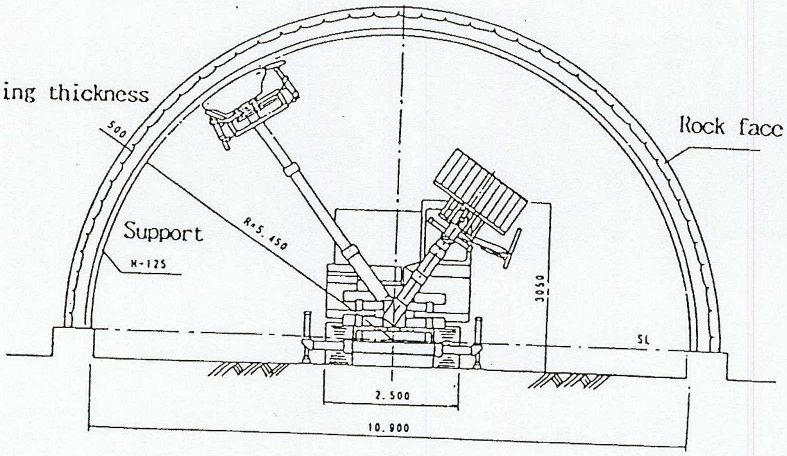


Figure 6 Structure of a Mock-up Tunnel

5. Results of Experiment in a Mock-up Tunnel

A test tunnel was constructed and a press lining test was implemented using the SPL Method. The results obtained are given below.

5.1 Scale of a Mock-up Tunnel

1) Tunnel Radius: 5.45 m
2) Intervals between Supporting Members: 1.15 m (H-shaped steel supporting members, 125 mm x 125 mm)
3) Thickness of Concrete Lining: 40 cm to 50 cm
4) Test Bedrock: Rocks approximately 300 mm by 200 mm were buried into the bedrock to create an uneven surface.

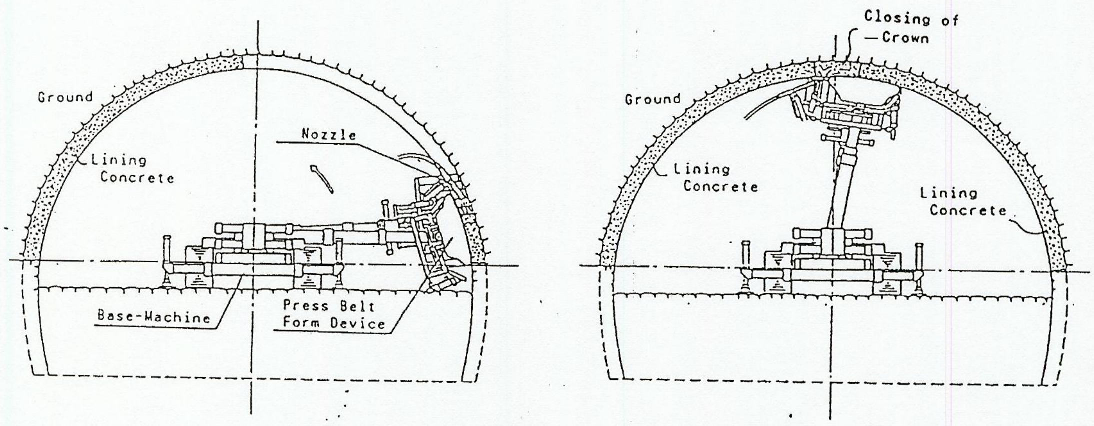


Figure 7 Lining Procedure

5.2 Generation of Dust

There was no rebound of materials and generation dust during the lining work, allowing work to progress under satisfactory conditions.

5.3 Strength Characteristics of Lining Concrete

1) Strength after 28 Days

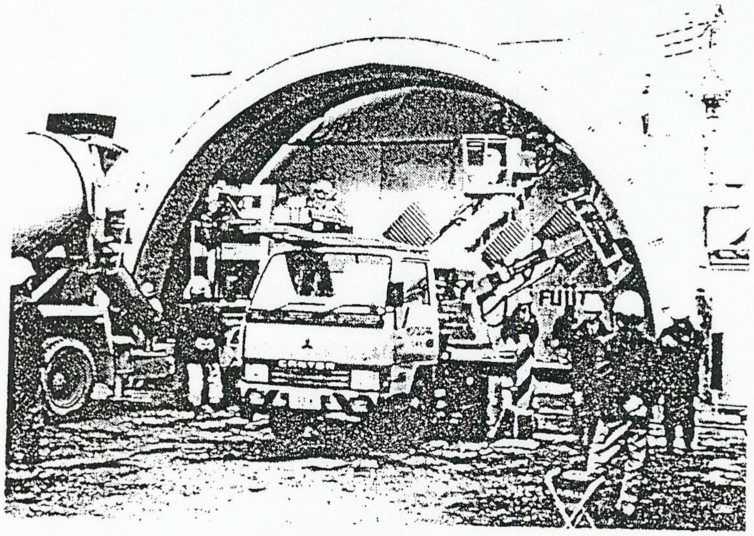
The compressive strength of the core sample taken after 28 days and tested upon was 205 to 289 kgf/cm^2, satisfying the design strength of 180 kgf/cm^2.

2) Strength at Young Age

Because of the effect of the set accelerator, the strength had reached 2.0 kgf/cm^2 after approximately 15 minutes and there was no peeling off of concrete after removal of the form.

6. Conclusion

The work for the development of the SPL Method for primary lining of tunnels is at present in the stage of lining tests in test tunnels. We hope, in the future, to deal with the following problems in order to develop the method further and to promote the use of the method in actual construction of tunnels.



Photograph 1 Experimental SPL Method of Lining in a Mock-up Tunnel

1) Capacity

The time required for construction needs to be reduced further to allow SPL robots to be used in real construction works. There is a need to raise the capacity of the robots to fulfil this requirement.

2) Lining of Crown

Investigations are being made on a twin-armed robot, which has a form on either side, in order to allow stable construction of the crown part of the lining. Use of twin-armed SPL robots will naturally also reduce the amount of time required in construction.

3) Tests at Real Construction Sites

Test construction must be carried out at real construction sites and investigations made on reduction of the time required in real construction work and on the durability and safety of the machine under such conditions.

Finally, we should like to take the opportunity to express my gratitude to the members of Gifu Kogyo K.K. for their help in the development of the SPL robot.

References

1) Koga, S., Hosokawa, Y. et al., "Proceedings of 43rd Annual Meeting of Japan Society of Civil Engineers (Section 6)", Oct. 1988

2) Koga, S., "Texts of 39th Meeting on Industrial Robot Technology", Japan Industrial Robot Association, July 1989