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Autor: Sagawa, Yoshitane / Nakahara, Yasushi

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Robots for the Japanese Construction Industry

Robots dans l'industrie japonaise de la construction

Roboter für das japanische Bauwesen

Yoshitane SAGAWA
Civil Engineer
Kajima Corporation
Tokyo, Japan

Yasushi NAKAHARA
Civil Engineer
Kajima Corporation
Tokyo, Japan

Y. Sagawa, born 1929, obtained his civil engineering degree at Waseda Univ. Tokyo. Entering Kajima Corp., he spent 10 years in research in the field of soil mechanics followed by 17 years in the design of coastal structures. He is now responsible for the planning of technical development.

Y. Nakahara, born 1938, obtained his civil engineering degree at Kyushu Univ. Fukuoka. Entering Kajima Corp., he spent 20 years in research in the field of materials and execution methods for construction. He is now a section chief for the planning of technical development.

SUMMARY

In the Japanese construction industry, robotization of construction equipment is being advanced principally with respect to works such as tunnels, shield driven tunnels and coastal development structures. This article describes conditions in the Japanese construction industry which have made this automation and robotization necessary, goes on to describe the present state of development and application of automation and robotization in a big construction company and concludes by describing prospects for the future.

RÉSUMÉ

Dans l'industrie japonaise de la construction, la robotisation de l'équipement est à un stade avancé, principalement en ce qui concerne les tunnels, les tunnels percés selon la méthode du bouclier et les aménagements portuaires et côtiers. L'article décrit les conditions qui ont rendu cette automatisation et cette robotisation nécessaires de l'industrie japonaise de la construction, décrit les développements actuels dans une grande entreprise de construction et présente les développements futurs possibles.

ZUSAMMENFASSUNG

In der japanischen Bauindustrie wird die Automatisierung von Baumaschinen hauptsächlich beim Bau von Tunneln, Schildvortriebstunneln und Bauwerken für den Küstenausbau vorangetrieben. Dieser Bericht behandelt die Bedingungen in der japanischen Bauindustrie, welche die Automatisierung und Entwicklung von Robotern förderten, beschreibt weiterhin den gegenwärtigen Stand der Entwicklung und Anwendung von Automation und Roboter-Einsatz durch eine grosse Bauunternehmung und schliesst mit einem Ausblick auf zukünftige Entwicklungen.

1. INTRODUCTION

Spectacular advances have been made in the robotization of industry and Japan especially is attracting the attention of the world for the remarkable progress which has been made in the automation and robotization of Japanese manufacturing industries, even to the emergence of unmanned factories.

On the other hand, what is the state of utilization of robots in the construction industry?

Ever since the decade of the 1950s when large American construction equipment was introduced into Japan on large heavy construction works such as dams, diverse construction equipment has been employed on dams, tunnels, coastal development works and other types of works for the purpose of reducing costs and construction time and improving quality. Further, much labor saving, automated construction equipment was employed in the construction of expressways, the Shinkansen railway line and other works which were constructed in preparation for the Olympic Games held in Tokyo in 1964, but almost all of this equipment was of American or European manufacture or was manufactured using imported technology, almost none of it being developed and manufactured through original endeavors of the Japanese themselves.

However, together with the end of the period of rapid economic growth in Japan following the "oil shock" of 1973, a tendency arose in Japanese industry to break from copying American and European technology and to develop original technology of its own. Especially remarkable are the advances which have been made in technical development in the fields of electronics and electronics using equipment. In the construction industry too, there arose brisk technical development of an original nature utilizing electronic devices which had now become inexpensive and the automation and robotization of construction equipment is progressing at a rapid pace directed toward objectives such as improving quality and safety, maintaining the environment and reducing costs. This is believed to be due in great measure to the particular situation of the Japanese construction industry. This paper describes this particular situation which is stimulating development of automation and robotization in the Japanese construction industry, introduces the present state of progress in this field using Kajima Corporation as the principal example and concludes by giving a view of future directions.

2. FACTORS STIMULATING DEVELOPMENT IN AUTOMATION AND ROBOTIZATION

2.1 Aging of the Labor Force and Shortage of Skilled Labor

Together with the decrease in the rate of growth of its population, Japan is experiencing a remarkable advance in the general level of education of its people. However, in spite of this, the construction industry is lagging behind other industries in aspects such as work conditions, employment conditions and welfare conditions. Thus the young generation does not look upon the construction industry as an attractive occupation and it has become impossible to expect a new influx of young laborers.

According to statistics for 1983, 67.3% of Japanese construction laborers are 40 years of age or more and the average age is 44.6 years. This lack of young laborers and aging of the labor force has brought about a shortage of skilled labor and a lowering of labor skill in general and it is believed that this in turn is connected with the large number of accidents, stagnation in productivity growth and increasing cost described later. Thus much is expected of automation and robotization of construction equipment as a means of solution of this situation.

2.2 Poor Working Environment and High Rate of Labor Accidents

One of the characteristics of construction works such as dams, tunnels, bridges, coastal structures and underwater structures is the fact that with much of the work being performed under poor working conditions such as compressed air, high or low temperatures, dust, poisonous gas and water pressure, the working environment is much worse then that to be found in the factory facilities of industry in general. Because of this, the rate of labor accidents in the construction industry is greatly larger than in other industries. According to statistics for 1983, the construction industry accounted for 43.4% of all accidental deaths in all industries.

Thus automation and robotization are looked forward to as a means of liberating laborers from dangerous work under poor environmental conditions such as these.

2.3 Stagnation in Productivity Growth

Although productivity in manufacturing industry has approximately doubled during the past 10 years through automation and robotization, productivity in the construction industry has not increased at all since the time of the oil shock in 1973. Thus, together with the introduction of large construction equipment to increase productivity, much is also expected of automation and robotization.

2.4 Demand for Advanced Construction Techniques

Before 1973, the year of the oil shock, Japan successfully constructed diverse facilities such as heavy industrial facilities, urban transportation facilities, urban office buildings and urban and suburban housing. In the following years too, accompanying the expansion of the major cities, the development of the regional cities and the improvement of the people's standard of living, continuous demand arose for the construction of additional facilities such as new transportation facilities, energy storage facilities, housing, water supply and sewerage facilities and social welfare facilities. However, partly due to Japan's limited land area, the conditions of constructing these facilities vary greatly depending upon location and in many cases the work must be performed under extremely bad conditions.

Numerous advanced construction techniques are required. For example, in the construction of in-ground LNG storage tasks of 100,000 kl capacity or larger in soft reclaimed coastal land, technique is required for the precise construction of circular diaphragm walls to depths of as great as 100m. Other examples are techniques for constructing bridge foundations in water depth of 50m or more, techniques for excavating tunnels through ground which develops enormous ground pressures and techniques for constructing shield driven tunnels in urban areas for subways, sewers and electric power transmission tunnels without causing adverse effects on surface structures and street traffic.

Examples of such construction techniques required are various techniques for monitoring and control of execution; systems are required for analysing measured data such as earth pressure, water pressure and survey measurements and feeding the results back into the work, important are the automation of measurement, analysis by real time and reflection of the results of this analysis into the following action and automation and robotization technology are required for this series of operations to be performed continuously.

2.5 Intensification of Competition

During the past five years, the volume of construction work in Japan has remained about the same or has tended to decrease with a resulting intensification of competition for contract awards among the large general contractors. Each general contractor has seized upon automation and robotization of construction as a means to surpass its competitors in replying to its client's needs in price, quality, construction period and safety and is putting its full endeavors into technical development in this field.

Below is described what Kajima Corporation, one of Japan's large general contractors, has done in this field of developmental research and practical application of automation and robotization and the future directions of its activity in this field with focus on the field of civil engineering works.

3. PRESENT STATE OF AUTOMATION AND ROBOTIZATION

3.1 Tunnels

Because 80% of the land area of Japan is occupied by mountains, tunneling works are indispensable in the construction of expressways, Shinkansen railway lines and water conduits. On the Tohoku and Joetsu Shinkansen railway lines which were completed in 1983, tunnels account for 30% of their total length of approximately 800 km.

During the past several years, NATM (New Austrian Tunneling Method) is gradually coming to be employed as the ordinary method of work in tunnel construction. In adapting to this new method which is greatly different from the conventional method using steel arch supports and lagging, together with standardization of operations at each stage of the work, mechanization of work methods and automation and robotization of construction equipment are progressing at a rapid pace to accommodate the aging of the labor force and increase operating efficiency. Representative of this is the automation and robotization of the drilling operation in tunnel excavation and the application of shotcrete. Basically speaking, what is required for the efficient performance of tunnel construction is automation and robotization of the series of operations of drilling, charging, blasting, primary lining, mucking, rockbolting, monitoring and secondary lining, but at the present time, progress has not gone that far. Each of the large general contractors is performing technical development together with the related equipment manufacturers with this final objective in mind.

3.1.1 Automatic Drilling Machine

Automatic drilling machines were developed for the purpose of improving drilling speed and securing precision in drilling so as to obtain smooth excavation surfaces without being influenced by operator skill. In addition, they also liberate laborers from an inferior working environment.

In Japan, robot drilling machines of both playback type and numerical control type have been developed and put into practical use. Kajima Corporation has adopted the playback system and put into use machines with as many as five booms.

By setting this machine in the basic position for the face to be drilled and starting the automatic drilling device, the machine automatically drills the face in accordance with a previously memorized drilling pattern. The procedure for teaching the drilling pattern and the flow of the drilling operation are shown in Fig. 1 and Fig. 2 respectively.

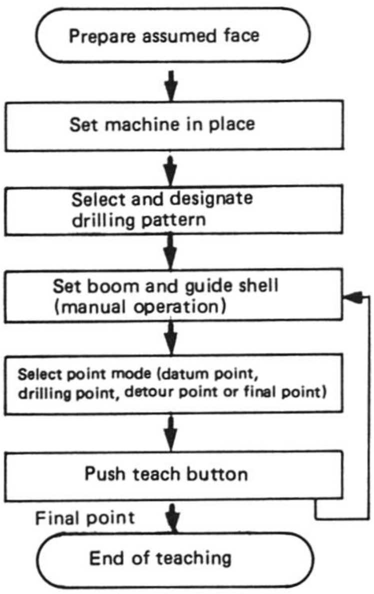


Fig. 1 Procedure for Teaching Drilling Pattern

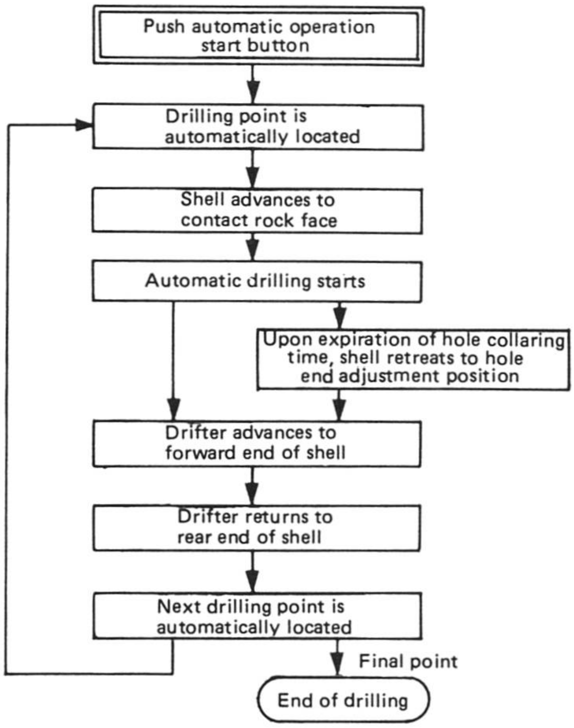


Fig. 2 Flow of Fully Automatic Drilling

Adopting an automatic drilling machine has the following advantages over previous methods:

– Skilled drillers are not required.

– One person can operate more than one machine.

– Drilling can continue even during the operator's rest period.

– A correct drilling pattern and depth of holes can be secured.

– The drilling time is shortened.

– Workers are liberated from an inferior environment.

An example of the reduction in overbreak obtained by use of an automatic drilling machine is shown in Table 1.

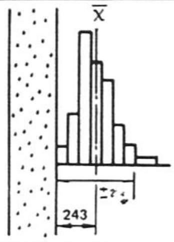
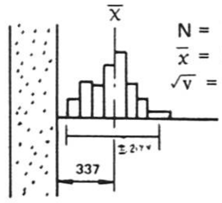
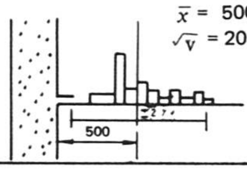
Depth of Overbreak (mm)	Method and Equipment Used
 N = 285, $\overline{x}$ = 243, $\sqrt{v}$ = 116	Method: Full face Equipment: System AD, 2 boom hydraulic jumbo
 N = 168, $\overline{x}$ = 337, $\sqrt{v}$ = 145	Method: Full face Equipment: 3 boom pneumatic jumbo
 N = 119, $\overline{x}$ = 500, $\sqrt{v}$ = 200	Method: Full face Equipment: 3 boom pneumatic jumbo

Table 1 Examples of Overbreak Ratios

3.1.2 Automation and Robotization of Shotcrete Application

In NATM, shotcrete application is an important operation. As shown in Fig. 3, shotcreting takes up as much as 30% of the total time in tunneling operations so that improving the efficiency of this operation is an important task. The principal problems in shotcrete application are improvement of the performance of the shotcrete applicator and mechanization of nozzle manipulation. Rapid progress has been made with both of these recently.

Shotcrete Applicator

There are two systems of shotcrete application, the dry mixed system and the wet mixed system. In tunneling work, the dry mixed system has been used almost exclusively up to now. However, with the rapid growth in use of NATM during the last two or three years, the wet mixed system is increasingly being used from the viewpoint of increasing work capacity, reducing rebound and securing quality. Numerous models of applicators have become available which can respond to this demand. Kajima Corporation has itself developed and put into practical use a computer controlled applicator by which high quality shotcrete work can be achieved. The special features of this system, shown in outline in Fig. 4, are as follows:

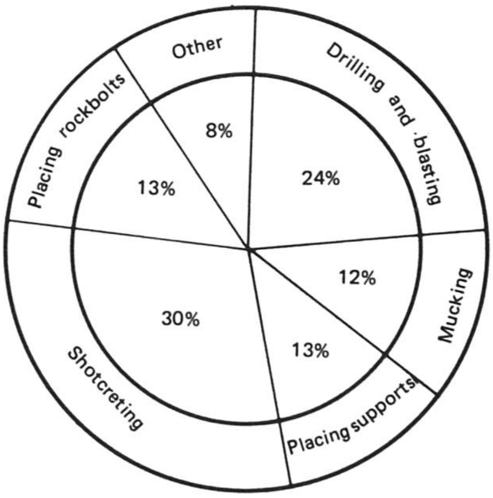


Fig. 3 Ratio of Operating Time

– The concrete is fed and jetted by compressed air.

– The accelerator, a dry powder, is mixed into the concrete at a point approximately 2 m before the mouth of the nozzle.

– The rate of shotcrete application is in the range of 4 to 6 m^3/h and varies with the consistency of the concrete.

– Because the quantity of air required and the air pressure vary with the consistency of the concrete, an appropirate rate of shotcrete application is determined based on the relationship between these factors and the rate of feed of accelerator is controlled by computer according to this rate of application.

Because the system has these properties, work can be performed without the presence of an engineer who is familiar with the characteristics of concrete and the applicator equipment.

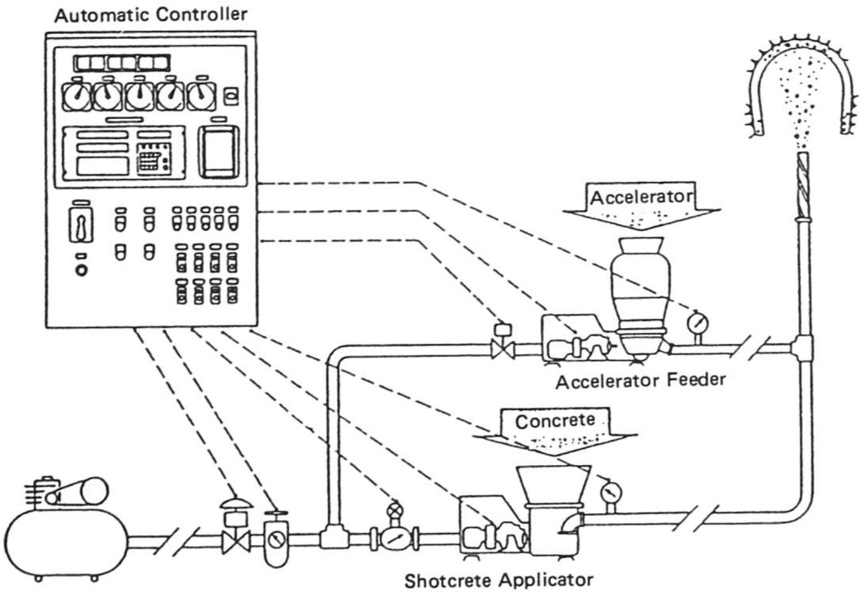


Fig. 4 New Wet Type Shotcrete (NWS) System

Shotcrete Applicator
A pneumatic concrete feeder made by modifying an applicator originally designed for use with both wet mixed and dry mixed shotcrete. The speed of operation (rate of concrete feeding) can be changed at will.

Accelerator Feeder
A device for adding the powder type accelerator to the concrete. The speed of operation (rate of accelerator feeding) can be changed at will.

Automatic Controller
A device to stabilize the state of concrete feeding and the condition of ejection. The speeds of operation of the shotcrete feeder and the accelerator feeder are controlled by microcomputer in correspondence with the concrete feed pressure.

Nozzle Manipulation

Up to the present time it has been said that skilled nozzlemen were absolutely necessary for shotcrete work. With the widespread use of NATM, problems arose due to a shortage of skilled nozzlemen, overwork of nozzlemen do to increased capacity of applicator equipment, danger to health due to rebound dust and danger from falling masses of shotcrete. As a solution, technical development is being performed at a rapid pace to automate and robotize nozzle manipulation and the results of this development are being put into practical use.

Three type are being employed in Japan at the present time:

a. Remote Control Type

b. Semiautomatic Remote Control Type

c. Robot Type (Playback Type)

Kajima Corporation has principally developed and put into use the semiautomatic remote control type. This is shown in outline in Fig. 5.

As a result of employing this type on the large cross section tunnels of an underground

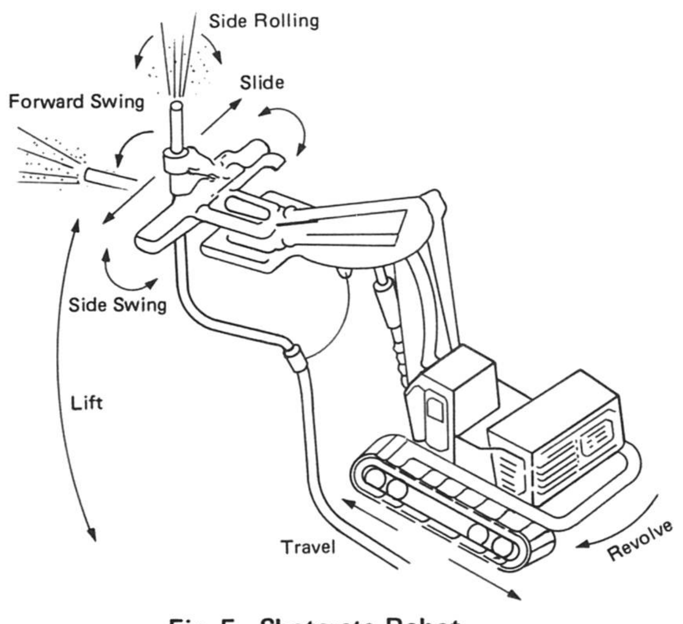


Fig. 5 Shotcrete Robot

power station, it is evaluated that even though all operations are performed by the operator of the base machine, the shotcrete was stable in quality, the work was easily performed and it was possible to keep rebound to a minimum. By this it became possible to liberate workmen from the dangers of dust and falling masses of shotcrete.

The playback type of robot was developed by Ohbayashi-Gumi, Ltd., one of Japan's large general contractors, and Kobe Steel, Ltd. The first unit of this type is now in use on construction work and the results have not been disclosed yet. If this type is satisfactory both functionally and economically, it will have attained the final objective of automation and robotization.

3.2 Shield Driven Tunnels

In the urban areas of Japan tunnel works are not allowed to be executed in such a way as would cause traffic congestion or otherwise adversely effect surface traffic. For this reason the shield driving method is employed in the construction of almost all subway tunnels, water and sewer tunnels and electric power transmission tunnels. Also, almost all of the shield machines being employed are of the mechanical excavation type.

In shield driving works there is a need for automation and robotization of operations at each step; driving control, removal of excavated material, shield attitude-position control, backfill grouting, segment erection and handling of materials. Shield equipment manufacturers and general contractors are all performing technical development on these subjects but progress has not been made to the extent that automation and robotization are possible at each step in the operations. Kajima Corporation is performing technical development aimed at a final objectives of automating and robotizing all steps of operations. Below are described the driving control and attitude-position control systems which Kajima has developed and put into use up to the present time.

3.2.1 Driving Control

In the operation of slurry shields, one type of mechanical excavation shield, driving control is performed by monitoring numerous measured data including the pressure within the face chamber, the revolving cutter torque, the volume of excavated material and the properties of the slurry. The procedure in use up to the present has been to measure these data items individually and separately and to devise corrective measures through the judgement of experienced engineers and skilled operators if any abnormal condition arose. However, in this, the relationships between the various items of data were not necessarily clear and although judgement was made on the basis of the principal data, much reliance was placed on intuition.

On the other hand, with the system recently developed and put into use, an overall judgement is made by gathering and immediately analysing the various data by real time and then applying this judgement to the following operations. An outline of the driving control system is shown in Fig. 6 and an example of the graphic display is shown in Fig. 7.

This system decides statistically what should be controlled in what way in order to perform good shield driving and determines the items for control and the control standards for shield operation. With this system it is possible to attain in a short time and thereafter maintain a constantly stable con-

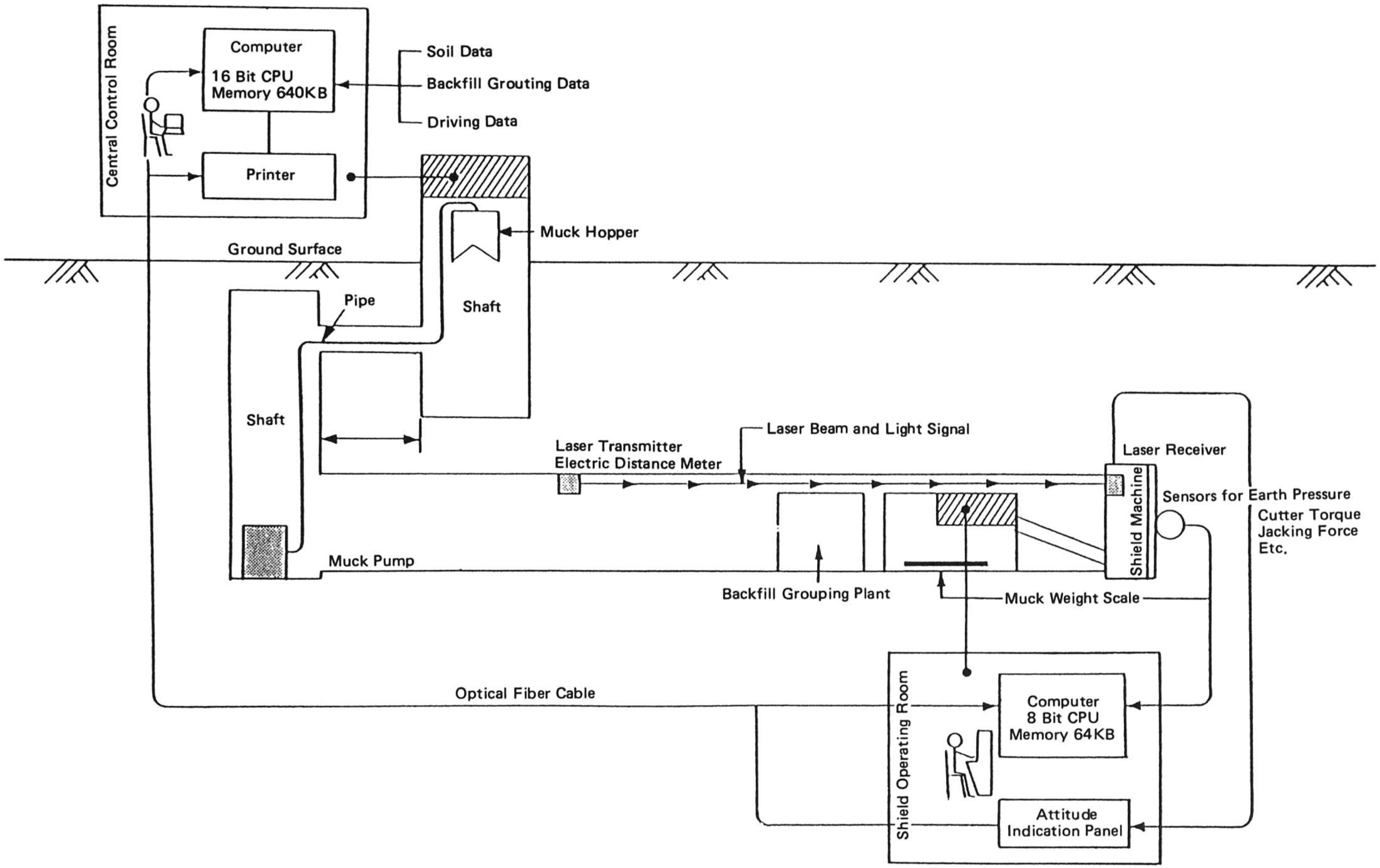


Fig. 6 Automatic Control System for Shield Driving

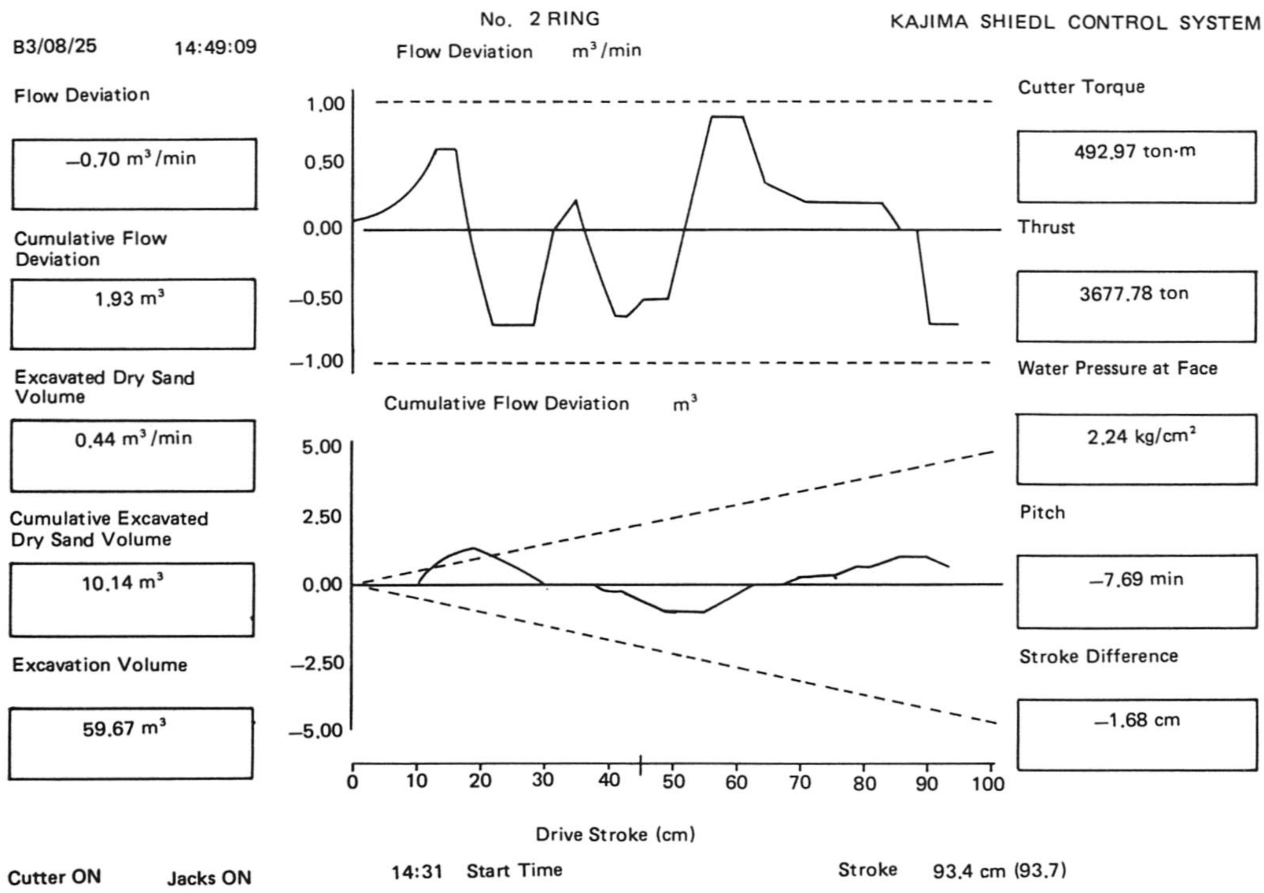


Fig. 7 Example of Graphic Display

dition of driving by statistically analysing the various data obtained in the initial stage of driving and repeatedly feeding this back into shield operation.

3.2.2 Attitude Control

In shield driving it is important to drive precisely along the planned line. Up to the present time, general practice has been to survey line and grade by hand at 5 to 10 m intervals and correct the direction of the shield in accordance with the results of analysis of this survey data. The problem with this procedure was that the shield was sometimes liable to go off line without being known, the construction period and cost were adversely affected by performing major directional corrections and weakening of the surrounding ground would bring about ground settlement. An outline of the attitude control system developed to solve this problems is shown in Fig. 6.

Through the use of this system it is possible to know continuously at all times the amount of deviation of the shield from the planned line by direction angle, lateral distance, vertical distance and pitch angle. Because the driving jacks can be controlled from the amount of deviation, the attitude and position of the shield can be controlled by real time and at the same time, because the survey operation is eliminated, major labor saving has become possible. At the present time, jack operation based on the measured data has not been automated, but technical development is in progress to link these completely in the near future.

3.3 Ultradeep Diaphragm Wall Excavator

In the construction of in-ground LNG storage tanks of 100,000 kl capacity or larger in soft reclaimed coastal land, an ultradeep diaphragm wall is constructed down to the impermeable layer located approximately 100 m below the ground surface to surround the tank and prevent the inflow of groundwater. (Fig. 8) In order to make this diaphragm wall effective in shutting out the goundwater, an important problem is to secure precision in vertical excavation by the diaphragm wall excavator. To solve this problem, Kajima Corporation developed the automatic excavation system shown in Fig. 9. By controlling the attitude of the machine during excavation and the size of load applied in accordance with the physical properties of the soil being excavated, it has been possible to secure an excavation precision of over 1/1000.

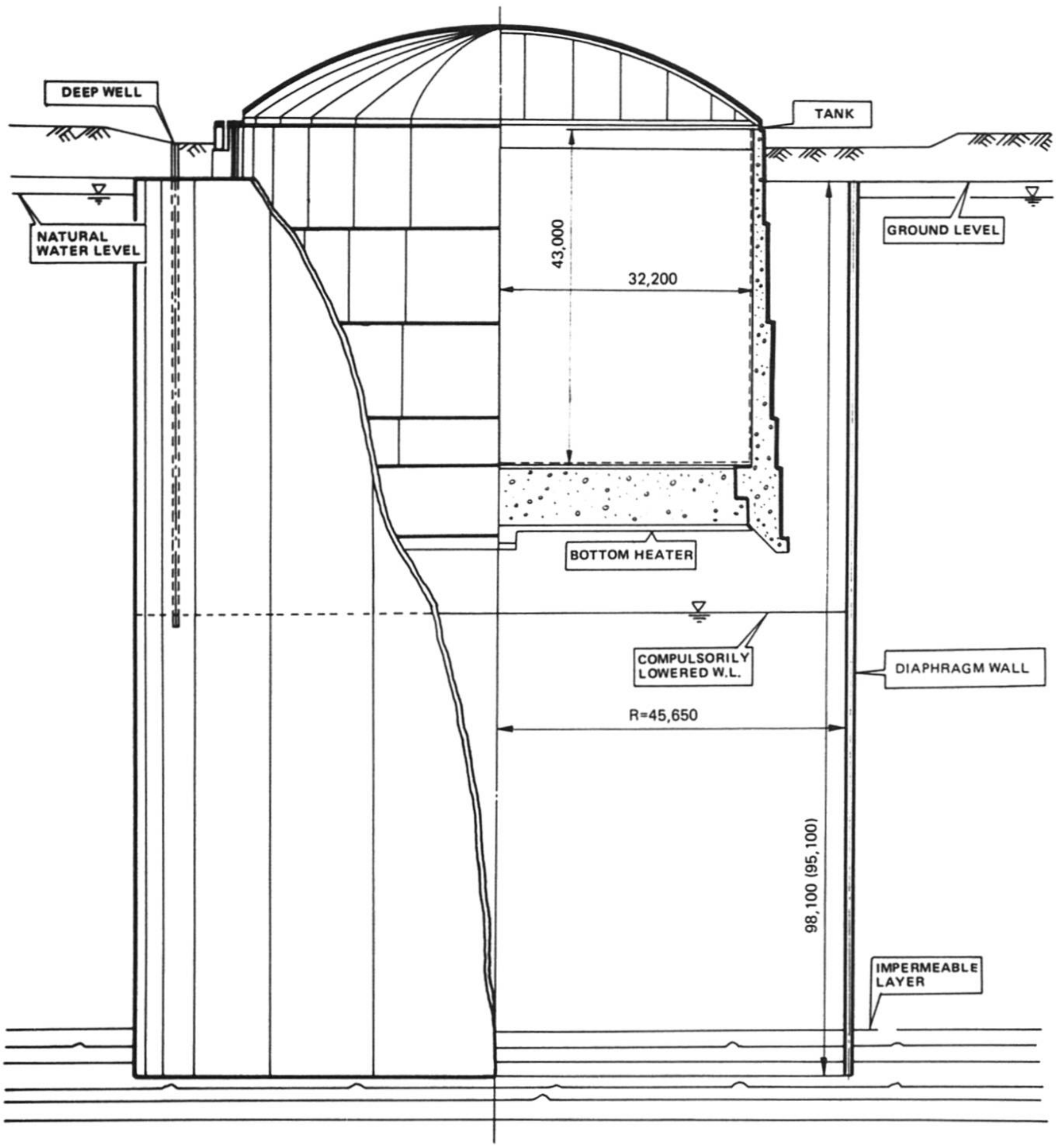


Fig. 8 LNG In-ground Storage Tank (130,000 kl)

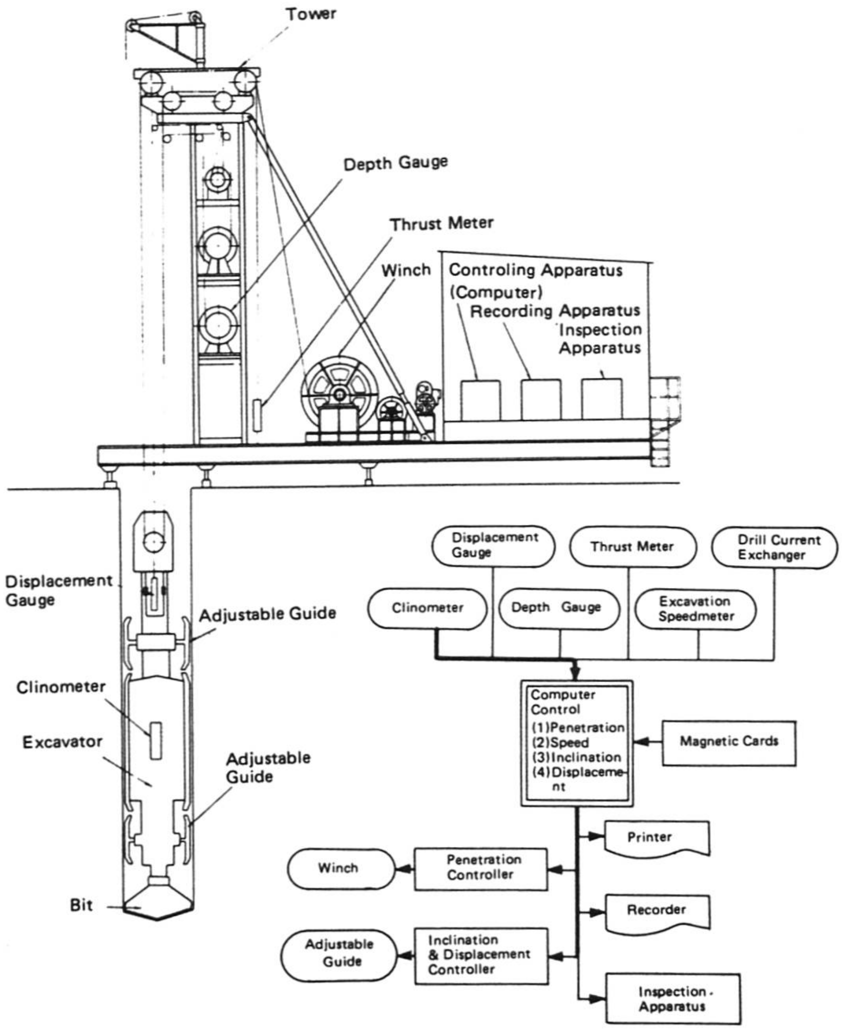


Fig. 9 Kajima Ultradeep Diaphragm Wall Automatic Excavator

3.4 Dam Concrete Transfer Car

This is a completely unmanned automated system for transporting concrete from the concrete plant to the point of transfer of the concrete into the cable crane bucket in dam construction. (Fig. 10)

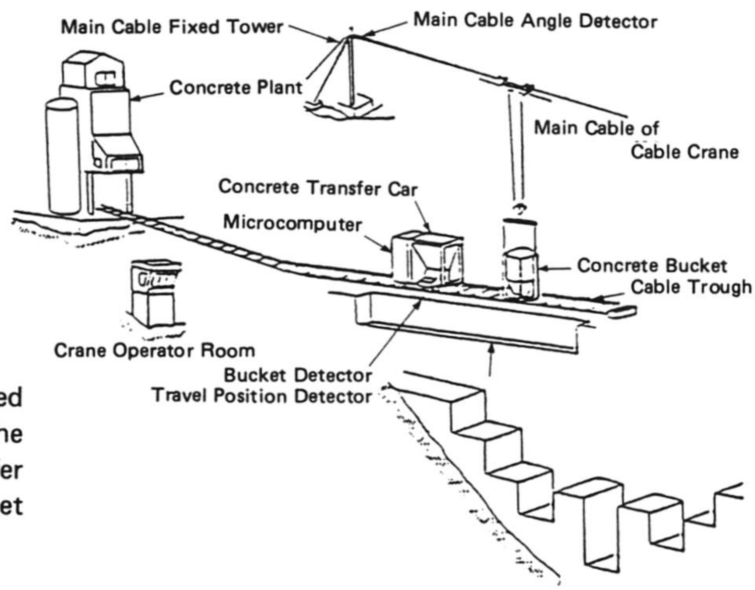


Fig. 10 Automatic Control System for Concrete Transfer Car

4. EXAMPLES OF TECHNICAL DEVELOPMENT IN PROGRESS AND FUTURE PROSPECTS

Above has been described examples of equipment and systems already developed and put into practical use. In this chapter examples are given of technical development which Kajima Corporation is presently undertaking and a look is taken at fields of technical development which should be taken up in the future.

4.1 Cutting Device for Rock and Concrete Structures Utilizing an Ultrahigh-Pressure Water Jet

In construction work there is often a need to perform demolition and removal of old structures and excavation of rock without causing vibration and noise. Especially in Japan, there is a strong demand for not causing any adverse effects on the living environment of the people living near a construction site and general contractors are energetically working on the development of techniques and methods required for this.

As one method for responding to this demand, Kajima Corporation is developing a method of cutting by abrasive jet. In Fig. 11 an example is shown in which the nozzle movement device has been automated and robotized in order to apply this method to the cutting of the 70 cm thick concrete lining and steel arch supports of a tunnel. In order to cut concrete in a widely set range of positions, a "manipulator" has been employed which is widely utilized as the arm in industrial robots. The manipulator is mounted on a rail mounted car together with the other equipment.

It is expected that there will be increasing demand in the future for the demolition, repair, strengthening and addition of new functions to structures constructed in the past during the period of high rate economic growth or earlier and in order to fulfill this demand, there will surely be need for a method such as abrasive jet. It is believed that in order to apply this method effectively the nozzle movement device needs to be robotized so as to be able to deal with various differing object structures.

4.2 Concrete Slab Finishing Robot

The surfaces of concrete structures with large slab areas are finished by the concrete finishers several hours after the concrete is placed. The precision of finishing required differs according to the type of structure, but levelness of especially high precision is required in the finishing of building floors. Several problems are associated with this operation. Among these are the fact that this work is heavy labor performed in an unnatural position, the fact that the time for starting this operation after the concrete is placed differs with the season so that in the wintertime this operation is performed late in the night even though concrete placing was completed during the daylight hours, and the fact that highly skilled workmen are required.

In order to solve these problems, a "floor finishing robot" was developed. This is an automation which travels automatically without a track by means of an autopilot device using a gyrocompass and travel distance sensors. The robot travels a set course, perceiving its own position and automatically correcting deviations from the planned course of travel as it moves. As the robot travels it finishes the concrete surface by swinging from side to side a revolving trowel which is mounted on a horizontally

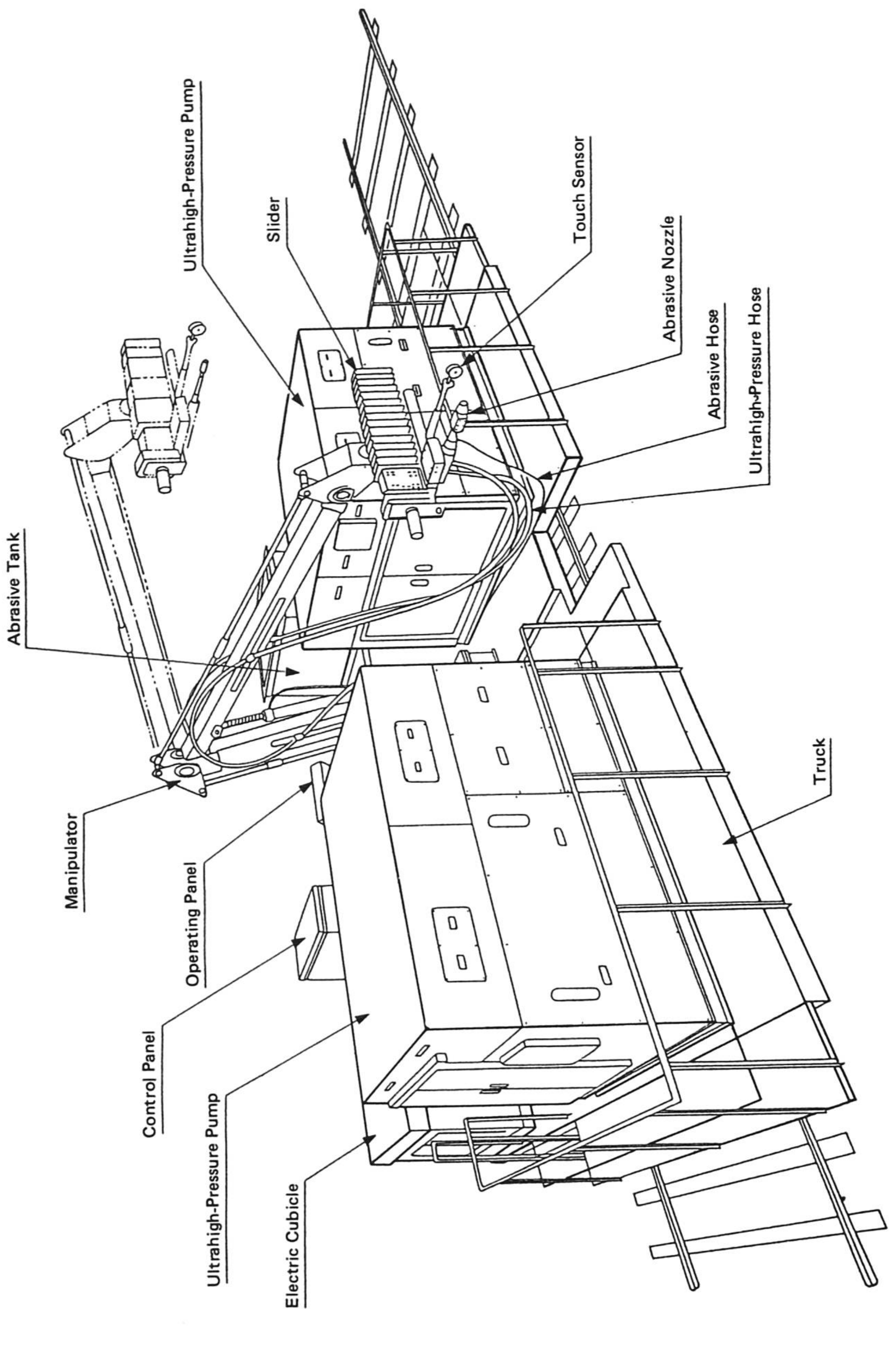


Fig. 11 Ultrahigh-Pressure Water Jet Cutter

articulated arm. A pilot model of this robot is shwon in operation in Photo 1.

It is believed that there is a wide scope for application of this traveling device in construction in the future. For example, future development is anticipated in operations such as concrete pavement finishing, removal of laitance from dam concrete and quality checking of slab concrete.

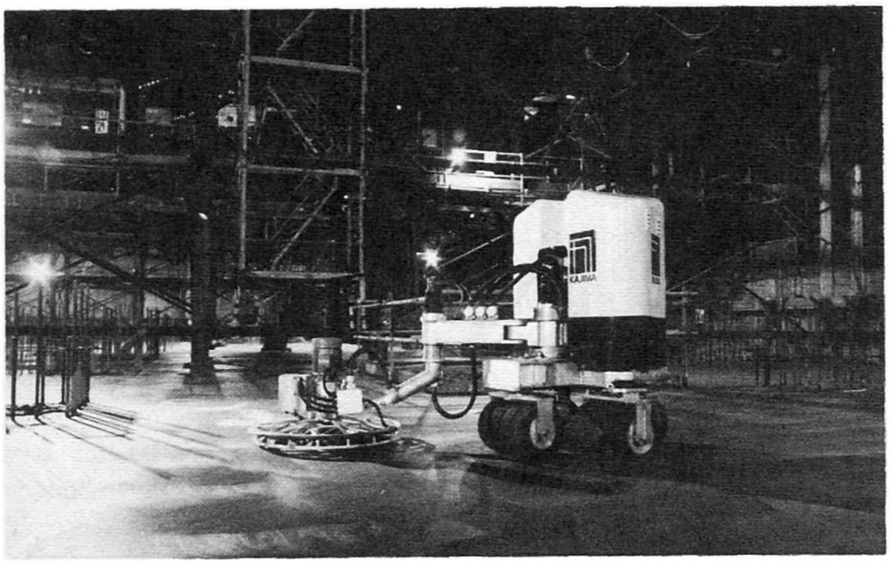


Photo 1 Concrete Slab Finishing Robot in Operation

4.3 Future Prospects

In order to save labor, enhance precision and reduce time and costs in construction work, studies are being made regarding intensified utilization of electronics in construction techniques and equipment in all fields of construction and it can be easily imagined that this will steadily progress into automation and robotization in the future.

However, in order to truly enjoy the benefits of automation and robotization, development must go beyond mere application to partial operations as at present to complete automation and robotization of the whole series of construction operations as a system. Especially on works such as tunnel works where a series of operations is performed by a fixed working group, true labor saving can not be expected with only partial automation and robotization. For this reason hope is being placed on technical development of automation and robotization as a total system.

In addition to further development and total systemization in the fields referred to above, automation and robotization are hoped for in the future in the following two fields not mentioned above.

4.3.1 Sea Bed Operations Robot

In Japan with its small land area surrounded on all sides by the sea, new projects such as breakwaters, sea walls and artificial offshore islands can be expected, but with water depths inevitably much greater than in works performed in the past, it is recognized that manual operations will be impossible and automation and robotization are the natural course. However, equipment for sea bed operations will face adverse conditions of high water pressure and a steel corrosive environment so that it is imagined that a wide range of technical capacities including the development of new materials will be needed before these can be realized.

4.3.2 Robot for Nondestructive Testing and Repair of Concrete Structures

The problem of deterioration of reinforced concrete structures has been taken up in Japan in the last year or two and what to do about it is the subject of much discussion. This is the problem of decreased durability of reinforced concrete structures due to corrosion of the reinforcing steel in coastal structures and decreased durability of concrete structures due to alkaline reaction of aggregate which in the past had not been viewed as a problem in Japan. Under present conditions where 60 to 80 million tons of cement are used annually in Japan, it is close to impossible to execute investigations, tests and remedial works on this problem by human labor, even if this were restricted to important structures only. Concrete structures have a wide scope of application, deep below than high above the ground surface and also in the sea. It is necessary to investigate these structures by some method and repair them if any problem is discovered. Is it not possible to automate and robotize this series of operations? There is a need to arouse the interest of the engineers concerned and obtain their cooperation.

5. IN CONCLUSION

Above has been described the present state of automation and robotization in the Japanese construction industry, but contrary to the case of general manufacturing industry, automation and robotization in the costruction industry has not necessarily brought economic benefit and there are numerous problems which require future study. However, as we progress twoard the 21st Century, development is inevitable in the several items discussed above and as a person in the position of being a participant in the development of construction technology, I wish to watch future developments in this field.

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