DEVELOPMENT OF AN AUTOMATIC LAITANCE CLEANING MACHINE

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ABSTRACT

To the rationalization of entire process of construction joint treatment, we developed Automatic Laitance Cleaning Machine. The system consists of travelling green cutting unit, a support unit composed of high pressure pump, and a vacuum pump, and a path guidance system. The travelling unit washes out laitance using a high pressure water jet(maximum 1,000kg/cm^2) and removes the dust by suction while travelling automatically under control of an optical communication path guidance system. This paper reports its development process, system outline, result of field tests in an actual dam sites.

1. INTRODUCTION

The removal of laitance is an important step in the treatment of concrete joints to ensure the structural integrity and watertightness of concrete. In the field of concrete dam construction, this is called green cutting. Green cutting is important, both qualitatively and quantitatively, because of high watertightness requirements and extremely large joint surfaces of dams. In a typical conventional green cutting, workmen removed laitance with low-pressure water jet and carried the dust out of the dam body using, for example, cranes while the strength of concrete was within a certain range. It has been pointed out, however, that this method poses the following problems:

1) Working environment is not favorable.
2) Skilled workmen are needed if good finish is to be achieved.

In applying the RCD (roller compacted dam) construction method, which has come to be used widely, it is necessary to perform construction at a very high rate of progress because a large joint surface is created at a time and a placement cycle of concrete is short. In addition, since lifts used in the RCD construction method are only 1/2 to 1/3 of those used in the block construction method, the total area of joint surfaces becomes large. For these reasons, the need for rationalization by use of machinery is great, especially in the RCD construction method. In view of the situation, the authors set out to work on the development of automation machinery in order to rationalize the work of green cutting. The ultimate goal was to contribute, through this research and development effort, to the rationalization of the entire process of joint treatment. This paper outlines results of the research and development.

2. DEVELOPMENT SCHEME

Prior to the establishment of the development scheme, the significance of green cutting was considered from the viewpoint of the rationalization of joint treatment.

(1) Green Cutting as a Step of Joint Treatment

Fig. 1(a) outlines the flow of construction joint treatment. The figure indicates that "green cutting" and "preplacement cleanup" bear similarities in purpose and significance, though there are differences in how and when they are performed. The time for typical green cutting is affected by the hardening rate of concrete. Hence, green cutting is performed at an early stage of hardening between about 10 to 40 hours after placement. Because of this, however, it has the following disadvantages:

1) Since the strength of concrete is not yet strong enough, a considerable amount of not only laitance, but also mortar is removed.
2) Since green cutting is conducted at an early stage of hardening, secondary laitance is generated after it is done.
3) Improper operation on the part of workmen could loosen coarse aggregate.

From above, it is expected that if green cutting can be performed at a desired time, the problem of overlapping work and other problems as listed above can be solved, and the treatment of construction joints can be rationalized. For example, performing green cutting for an additional purpose of "preplacement cleanup" is expected to offer the following advantages:

1) There is no need to perform the removal of laitance more than one time.
2) Excessive removal of mortar is reduced. (The amount of dust removed decreases, resulting in a saving of mortar.)

Flow of Joint Treatment	Description	Objectives
Placement of the (N)th lift concrete		
Water/spray curing	Water curing, or spray or fog curing by use of sprinklers	Creating a buffer on the surface to reduce the influence of air temperature
Green cutting	Removing laitance by use of low pressure water jet or brushes, collecting dust and carrying it out by a crane	Separating impurities; maintaining proper roughness; removing dust
Water/spray curing	Water curing, or spray or fog curing by use of sprinklers	Creating a buffer on the surface to reduce the influence of air temperature
Cleanup before placement	Cleanup by use of low pressure water jet, and removal of impurities by use of vacuumer	Separating impurities; removing dust
Spreading of mortar	Manual spreading of mortar over the work surface by use of hoes	Achieving close contact between mortar and the work surface
Placement of the (N+1)th lift concrete		

Fig. 1(a) Flow of Construction Joint Treatment

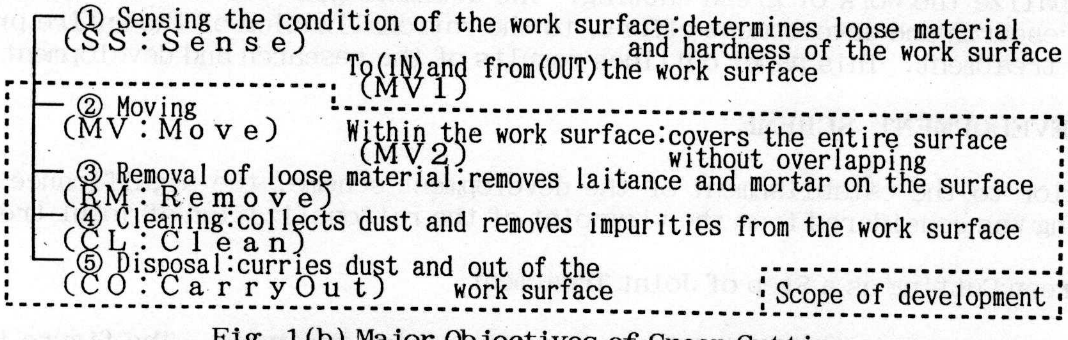


Fig. 1(b) Major Objectives of Green Cutting

(2) Definition of the Goal and Conditions

The scope of automation was limited to the green cutting operation after the system has been set up. Major tasks of the green cutting operation are listed in Fig. 1(b), of which the portion enclosed with a dotted line represents the scope of research and development defined at the outset.

(a) Scope of Application

As a first step, the R & D effort is aimed at developing an operational system in an environment where the block construction method is used. After that, the developed system is to be applied to the RCD construction method.

(b) Conditions

1) The developed system must be capable of following uneven surfaces (datum level ±2cm).
2) The system must be designed so that it can be carried by a 4.5t crane.
3) The removal of laitance, and the collection and disposal of dust must be performed at the same time automatically.
4) The system must be capable of adapting itself to varying degrees of hardening in ordinary placement cycles.

3. Outline of Automatic Green Cutting Machine

(1) Configuration

This system can roughly be divided into three sections (see Fig. 2(a) for a general view):

1) Traveling Section
While moving around on the work surface, the traveling unit performs the removal of laitance and the collection and disposal of dust. The movement of the unit consists of a repetition of forward/backward travel and transverse travel.

Forward/backward travel:
A nozzle gun head provided on the front of the traveling unit performs operation, repeating traverse motion.

Transverse travel:
At the end of a forward/backward travel, the unit moves parallel to a next lane (operation is halted).

2) Support Equipment Section
This section consists of a mobile pump to supply very high pressure water to the traveling unit, a vacuum pump unit to supply suction under negative pressure, and a tank to store dust sent from the traveling unit.

3) Guiding System Section
By issuing path commands, the guiding system controls the routing of the traveling unit. The guiding system consists of a bidirectional, automatic-tracking optical communication units, which are set up on and off the traveling unit, and a small computers.

Fig. 2(b) shows a system block diagram of this system. The following sections describe how major functions of the system were designed.

(2) Laitance Removal Function

Requirements for the laitance removal function based on the development scheme are as follows:

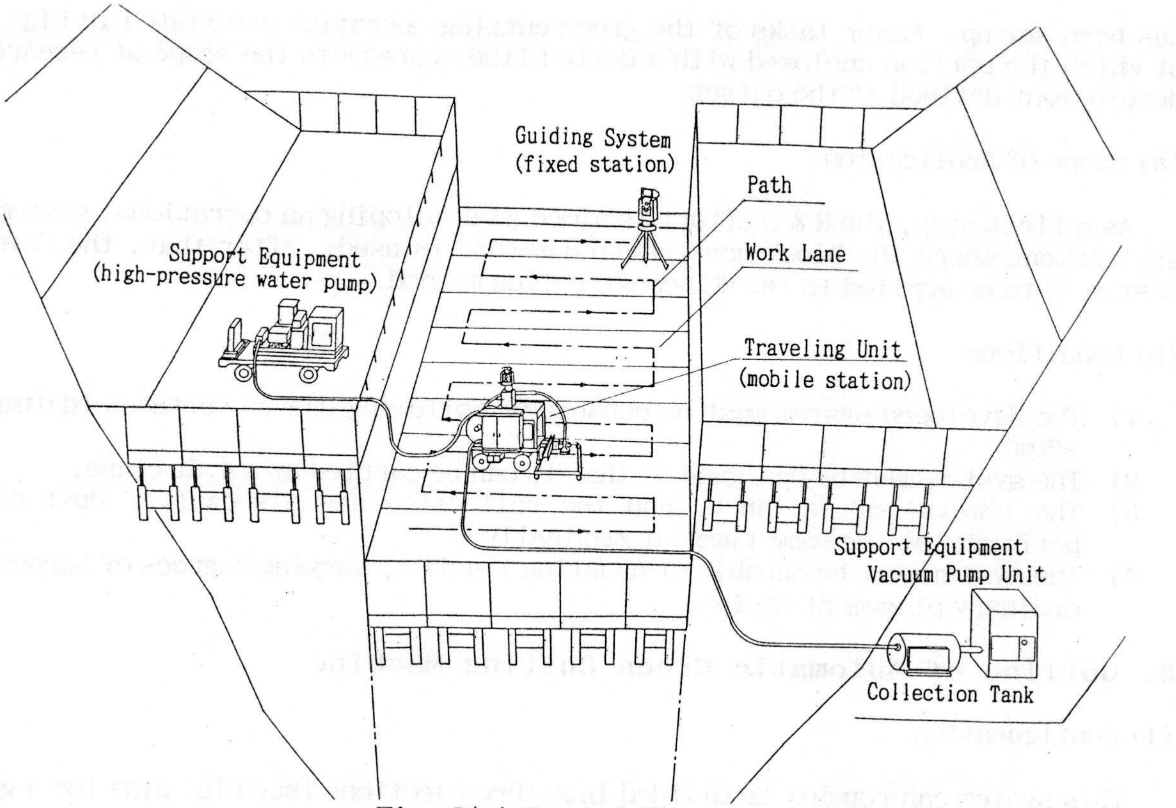


Fig. 2(a) General View

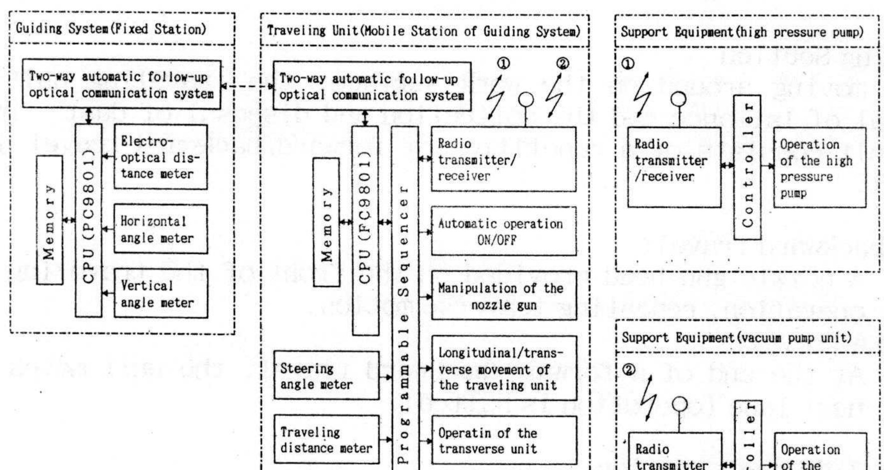


Fig. 2(b) System Block Diagram

1) The intensity of operation must be optimized depending on the hardening level of concrete.
2) Unevenness must be offset.
3) Coarse aggregate should not be loosened.

Applicable methods include (a) very high pressure water jet method, (b) brushing method, (c) blasting method, and (d) hammering method. Judging from the requirements, method (a) was adopted. This method uses very high pressure water fed from a very high pressure pump, where laitance is separated, more like cut away, by a water jet spouted from a thin nozzle (ϕ0.1mm-ϕ0.2mm). The movement of many such nozzles, each of which can only cover a point or a line, are coordinated so that they sweep a plane. In applying this principle, major operational elements to be considered are as follows:

1) Sizes of jet nozzles (diameters)
2) Water pressure
3) Feedrate of nozzles
4) Distance between jet nozzles and work surfaces (standoff distance)
5) Arrangement and movement of jet nozzles

Of these, 1) through 4) were determined through a basic experiment. Values for 5) were evaluated through simulation.

(a) Basic Experiment

Table 1 summarizes data on the basic experiment. Very high pressure water jet was generated from a nozzle head, whose specifications are shown in the table 1. This method utilizes the circular movement of the nozzles. Each nozzle follows an 8mm diameter circle path, which continuously shifts to cover a plane.

Results of the experiment are summarized as follows:

1) The ratio of the width of an eroded groove to the diameter of the nozzle tended to be higher with the diameter of 0.15mm than with 0.20mm. On the work surfaces used in the experiment, laitance removal by 0.20mm water jet looked like "washing away," while one by 0.15mm water jet was more like "cutting in." Finish by the former was better.
2) At water pressures higher than a certain level, increases in the depths of grooves were greater than those in their widths. That is, too high water pressure only dug around coarse aggregate, and was not very effective in plane formation. From this, it was thought that about the water pressure of 1,000kg/cm² was enough.
3) Longer standoff distances turned out to be preferable in terms of the widths of grooves obtainable to the extent that necessary groove depths could be maintained. Allowable unevenness, which should be determined according to effective standoff distances, was for each age of concrete as follows:

$\sigma c=30kg/cm^2$: 5cm-10cm $\quad$ $\sigma c=50kg/cm^2$: 4cm-8cm

4) At the nozzle revolution speed of 1,500rpm, water pressure of 800kg/cm², standoff distance of 5cm, and σc=50kg/cm², the upper limit of the nozzle's feedrate (traversing speed) for favorable laitance removal was 9m/min.

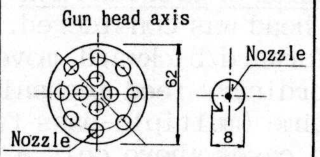
Table 1. Outline of Basic Experiment

Concrete Used	Gmax (mm)	σ_{28} (kg/cm²)	Slump (cm)	Air content (%)	Cement	Surface
	40	210	8	4.0	Class B, Portrand blast-furnace slag cement	10m×2m t=20cm

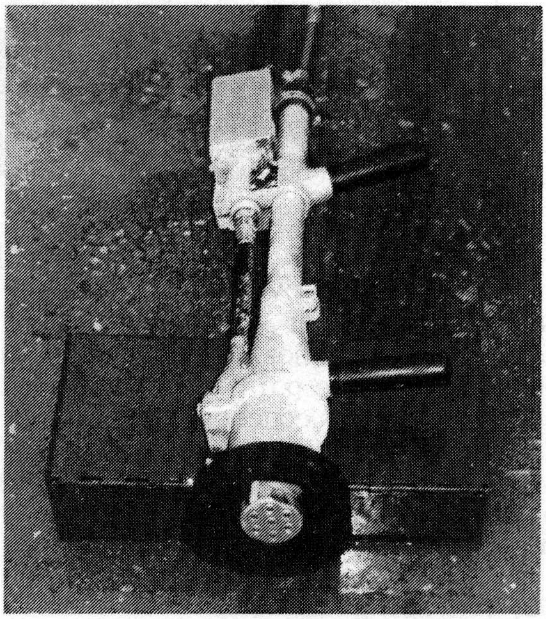
Concrete Used	W/C (%)	S/a (%)	Unit Content (kg/m³) W	C	S	G	AE	Time
	59.0	40.2	150	254	762	1154	0.096	90.1

Nozzle gun		
Nozzle diameter	(mm)	0.15 0.20
No. of nozzles		12
Diameter of nozzle gun head	(mm)	62
Revolution diameter of nozzle gun head	(mm)	8
Revolution speed of nozzle gun head	(rpm)	1500

Nozzle gun head



Conditions		
Surface strength σ_c	(kg/cm²)	30 (72h after placement) 50 (120h after placement)
Nozzle diameter	(mm)	0.15, 0.20
Water jet pressure	(kg/cm²)	600, 800, 1000, 1200, 1600
Feedrate of nozzles	(m/min)	5.0, 7.5, 10.0, 12.5, 15.0
Standoff distance	(cm)	4, 5, 6, 7, 8, 9, 10



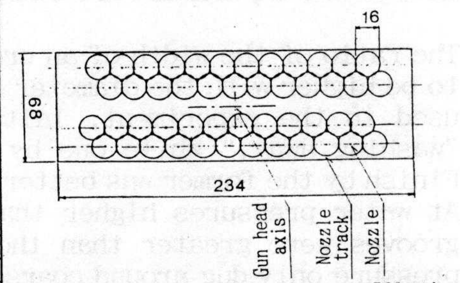
Phot 1. Handy Gun

(b) Nozzle Movement

This type of laitance removal requires a considerable number of nozzles in order to meet performance requirement. In view of the maximum discharge of a mobile pump (40ℓ/min or so under the pressure of 1,000kg/cm²), a rectangular nozzle unit holding 48 0.2mm nozzles was adopted. From results of the experiment, desirable nozzle arrangement and gun head movement were estimated through a simple simulation. In the simulation, given cutting widths determined from the results of the experiment, such parameters as nozzle arrangement, diameters of revolving motion, revolving speeds, and feedrates were manipulated. The resultant paths were drawn on a personal computer display, and the quality of planes obtainable was judged visually. Results thus obtained are shown in Fig. 3. With the speed limit of the revolution mechanism taken into consideration, the revolving speed of 2,500rpm, the revolution diameter of 16mm, and the 12 nozzles x 4 rows arrangement were adopted.

Conditions for Simulation			Results	
No. of rows	Dia. of Revolving circle(mm)	Revolving Speed (rpm)	Maximum Gun Head Traverse Feed (m/min)	Maximum Cutting Capacity (m²/h)
4	16	1500	9.0	104
		2000	11.0	127
		2500	15.0	173
		3000	17.0	196
3	15	1500	5.0	72
		2000	7.0	101
		2500	9.0	130
		3000	11.0	158
	18	1500	6.0	104
		2000	7.0	121
		2500	8.0	138
		3000	10.0	173
2	16	1500	4.0	92
		2000	5.0	115
		2500	7.0	161
		3000	8.0	184

Arrangement of Rectangular Gun Head Nozzle



No. of rows		No. of nozzles		Dia. of Revolving circle		Effective gun head length
4	x	12	x	16 mm	:	192 mm
3	x	16	x	15 mm	:	240 mm
3	x	16	x	18 mm	:	288 mm
2	x	24	x	16 mm	:	384 mm

Examples of Outputs from Simulation (hard copy of monitor screen)

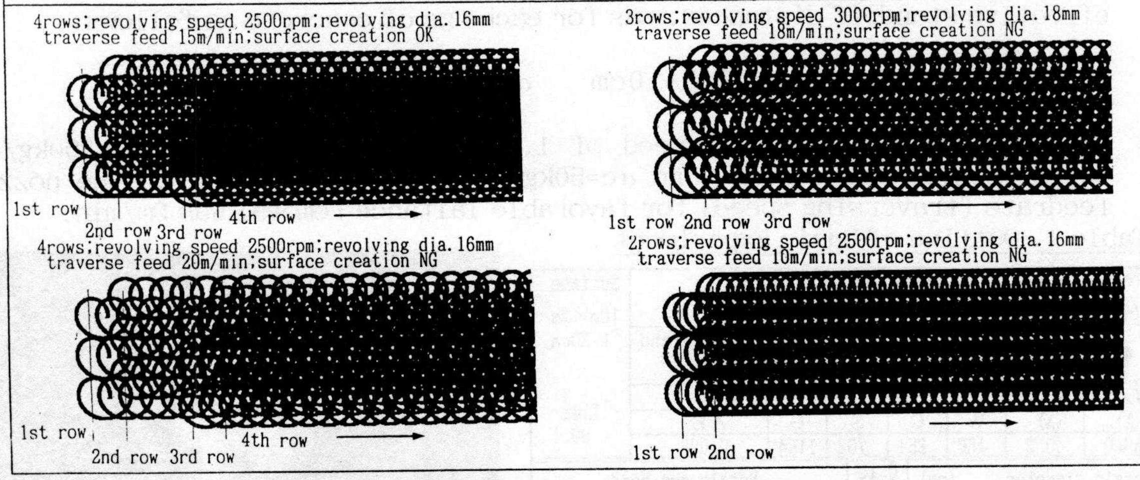


Fig. 3 Simulation of Erosion Path

Finally, the movement of the nozzle head was considered. Traversing movement was adopted. However, as long as the forward/backward movement of the machine is continuous, the nozzle head, with an ordinary feed mechanism, must inevitably pass through the same points more than one time (multiple-pass finish). Nevertheless, at earlier ages of concrete, there may be cases where only a single pass (single-pass finish) is preferable so as not to overcut concrete surface. For this reason, a swing traverse method using a slanted traverse rail was adopted, so that the paths of the gun head were kept perpendicular to the direction of forward/backward (longitudinal) movement of the machine.

(3) Traveling Function

In order to perform automatic operation on work surfaces at early ages, the following requirements have to be met:

1) Construction joints must not be damaged.
2) As large an area as possible should be covered.
3) Traveling patterns suited for automatic operation must be developed.

Another important consideration was changeover to a next lane. Steering equipment which was commonly found in conventional mobile units could hardly meet the above requirements. Therefore, although the front wheels did have a steering device for the correction of snaking motion, a set of wheels for transverse movement between lanes, which was independent of the longitudinal feed wheels, was built in the feed mechanism (see Fig. 4).

(4) Dust Collection/Disposal Function

The following requirements were defined:

1) Unevennesses, such as footprints and wheel tracks, must be offset.
2) Dust consisting of removed laitance, sand and coarse aggregate with diameters of up to 5mm or so must be collected and disposed.

To meet these requirements, a method using a suction system, which had already been proven in the use for preplacement cleanup, was adopted. Due to the need for the compactness of the traveling unit, the suction unit was installed separately. The suction mouth were arranged so that they encircled the nozzle gun head. This is because collecting dust as it was produced was considered to be more efficient than letting it be scattered for later collection. A task yet to be done is to find out a method of directing dust toward the suction spots efficiently during traversing. Fig. 5 outlines this system.

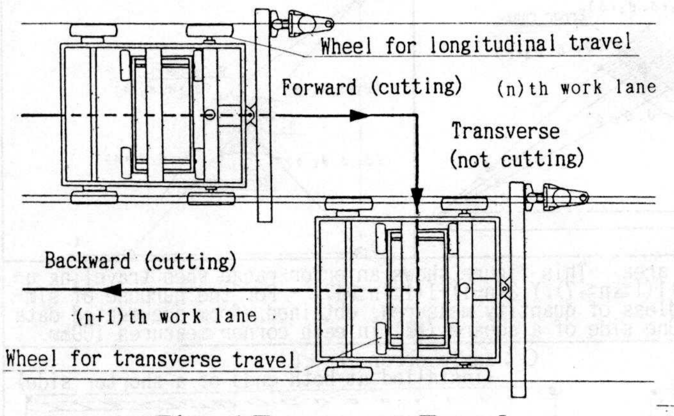


Fig. 4 Transverse Travel

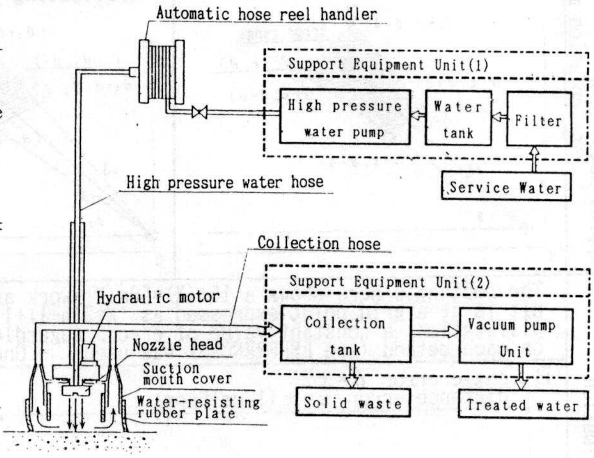


Fig. 5 Collecting Function

(5) Automatic Traveling Function (Guiding Function)

Considerations concerning this function were as follows:

1) Preparatory work should be simple.
2) Guiding accuracy for the longitudinal and transverse movement should be within 5cm.
3) The guiding system should be operational even in not so heavy rain or at night.

The following characteristics of the machine are also important considerations:

1) Feedrates are low. (The maximum values are about 2m/min for longitudinal feed and 10m/min for transverse feed.)
2) The traveling patterns consist only of linear paths.

3) Gradients of roll and pitch of the machine are small.

From above, the following methods were considered to be applicable:

A. Dead Reckoning Method
The current position of the machine is estimated from distances traveled in the longitudinal and transverse directions measured by encoders provided on axles, and the orientation of the machine measured by an orientation sensor (gyro, for example).

B. Automatic Follow-up, Distance & Angle Measurement Method
The current position is recognized by automatically tracking the position (r, θ) of a certain point on the machine in relation to a fixed external reference point.

C. Automatic Follow-up, Angle Measurement Method
On the basis of the principle of triangulation, the current position is recognized by automatically tracking the angle between a reference line and the direction in which the machine is oriented.

D. Optical Rotary Angulation Method
The current position is recognized by measuring angles between lines connecting three or more external points (reflectors) from a point on the machine.

E. Optical Guiding Method
Guide beams oriented along the path guide the machine.

Methods A and E were discarded because the former, if not used in conjunction with other methods, was not accurate enough and, the latter involved a difficult setup of

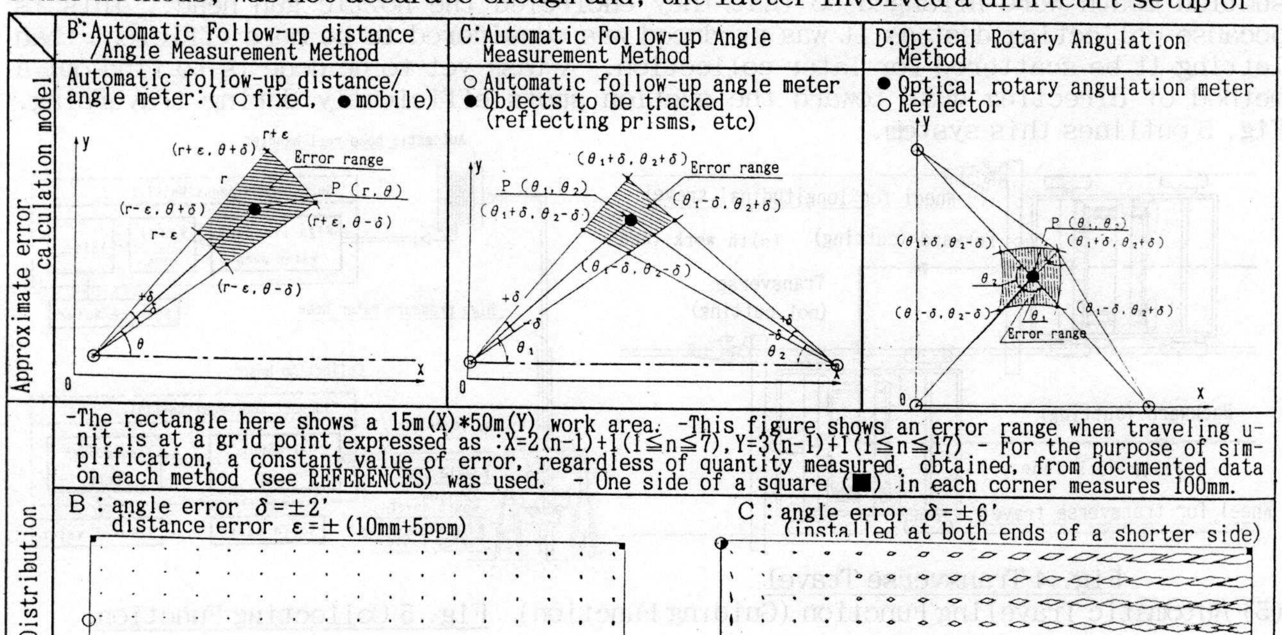


Fig. 6 Estimation of Error Distribution by Methods B, C, D

guide beam equipment. For the remaining three methods, error distribution(Fig. 6) and the effect of obstacles were simulated by use of a simple model.

As a result, Method B was adopted for the following reasons:

- Since errors in angle measurement have greater effects than errors in range measurement, Method B is more reliable than Methods C and D which solely rely on angle measurement.
- The greatest labor-saving in preparatory work can be expected from Method B.

As shown in the equipment configuration of Method B in Fig. 2(a), the mobile and fixed units perform automatic tracking in such a manner that they always face each other. At the same time, distances are measured by an electro-optical distance meter installed on the fixed unit, and angles are measured by counting pulses of optical axis revolution drive motors (horizontal and vertical). Functions these fixed and mobile units are to perform are as follows:

Fixed unit:
The position of the mobile unit is calculated on a small computer from measured (r,θ) on polar coordinate systems. Results of the calculation are then sent through an optical communication system to a computer on the mobile unit.

Mobile unit:
The orientation of the mobile unit is determined from measured angles between the centerline of the mobile unit and the direction of the fixed unit. The orientation thus obtained and the position of the mobile unit sent from the fixed unit are compared with the target path for the correction of snaking motion and the control of longitudinal and transverse motions.

Preparatory work needed was the installation of equipment and the definition of the target path. It was considered to be impractical, however, since it required previous coordinate calculation and survey. It was decided, therefore, that the fixed unit was to be installed at an arbitrary point, and the target path was to be generated automatically by measuring the end points of the working area and the initial position of the mobile unit(Fig. 7).

It is difficult, however, to achieve high enough reliability in guiding with the current method alone since there are some elements, such as unexpected obstacles and misguiding direct sunshine or other strong light, that make successful optical communication difficult to perform. It is thought that there is a need to combine the current method with a dead-reckoning method so that shortcomings of each method are covered by the other.

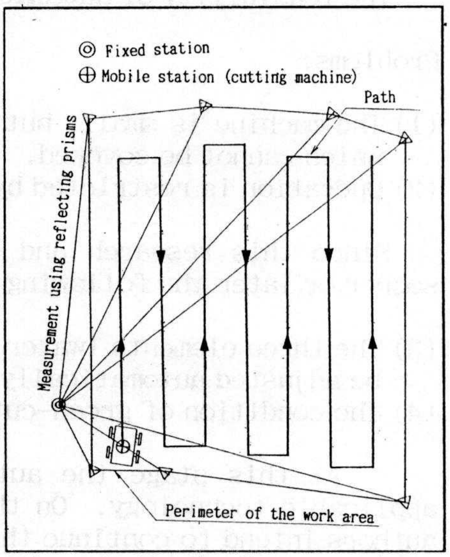


Fig. 7 Path Generation

4. Verification Test

In order to verify the applicability of the system under actual working environment, a test was conducted at the site of a dam which was being constructed by the block construction method. Table 2 summarizes operating conditions and times required for individual operations involving of the dam's construction joints. The test indicated that the actual standoff distance that had the least influence on feedrates was about two centimeters. This meant that a mechanism allowing the nozzle head to follow greater unevennesses was needed. The estimated working capacity within ordinary placement cycles was 100m² /h-150m² /h.

Table 2 Results of Verification Test at a Dam Site

(a) Operating Conditions

Hours after Placement	σ_c (kg/cm²)	Standoff Distance (cm)	Water Jet Pressure (kg/cm²)	Traverse Feedrate (m/min)	Travel Speed (m/min)	Maximum Capacity (m²/h)
24	28	8~10	400~800	14	1.61	155
48	64	6~8	600~800	13	1.50	144
72	75	5~6	700~900	12	1.38	132
96	94	4~6	800~1,000	11	1.27	121
120	105	4~6	800~1,000	11	1.27	121
144	113	4~6	800~1,000	11	1.27	121

(b) Time Required for Each Step

Preparatory Work	Handling, installation and connection of the mobile unit, etc	60(min)
	Definition of target path(instllation of the fixed unit, path generation)	10(min)
Operation	Longitudinal Travel(cutting run)	L/Vm(min)
	Transvesal Travel(lane change) No. of transeversal travels: No. of lanes-1	45(sec/ lane change)
Removal	Disconnection, retrieval, etc.	45(min)

(L ; total traveling distance (m), Vm; traveling speed (m/min))

5. Conclusion

The verification test using the prototype resulted in promising findings on the whole, but some problems remain.

Promising Findings:

(1) The system is highly practical.
Any part of equipment used can be carried with a 4.5t crane. High flexibility in the layout of equipment makes application to varying operating conditions easy. As long as placement cycles are within their ordinary ranges, green cutting can be performed at any time by adjusting operating conditions. Therefore, green cutting can be scheduled in the most favorable manner, taking account of the progress of other work.

(2) Operation can be automated.
The feasibility of automation including preparatory work has been confirmed.

Problems:

(1) The machine is small, but is does not turn round; therefore, there is a dead area which cannot be covered.
(2) Operation is restricted by obstacles.

Since this research and development effort is aimed at achieving automation, sooner or later the following problems will have to be addressed, too:

(3) The three elements (water pressure, standoff distance and nozzle feedrate) should be adjusted automatically.
(4) The condition of green-cut surfaces should be checked.

At this stage the authors suppose the emerging fuzzy control might be an applicable technology. On the basis of the findings obtained through the test, the authors intend to continue their research and development efforts to achieve a higher level of automation.

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