Development of Automatic System for Diaphragm-Wall Excavator

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ABSTRACT

A diaphragm wall method needs high accuracy of excavation, and the necessity is larger with depth.

The authors have developed an excavation control system, as a supporting system for large-depth excavation, in which the excavator is positioned exactly and its displacement from a designed line is controlled under 30 ~ 50 mm.

At present, the excavation control system is a quasi-automatic system, because the manual operation is required partially. Therefore, it seems that ensuring the accuracy of excavation makes them hold in heavy tension. Hence, for the adjustment of excavator, the automatic system for a diaphragm-wall excavator, by using a fuzzy controller, is developed to save labors of construction work and advance the accuracy.

The automatic system have been verified the performance same as a skilled operator through the field work. This system presents constantly the homogeneous and accurate wall without hard work and the dependence of the skills of operators.

1. INTRODUCTION

Recently, the diaphragm wall method has become one of the important technology for development of underground, and a great advance of this technology has been made in the excavation depth and wall thickness along with the demand of large underground structures. Here, the most important factor of the construction of diaphragm walls is to ensure the vertical accuracy adapted for wall joints. Therefore, the authors have developed an excavation control system, which positions and controls an excavator in underground, as the construction supporting system of the large-scaled structural wall method (KSW-G). This method enables to construct the wall with 150 m depth and 2 m thickness.[1] Under the above system, excavator is capable of holding within 30 ~ 50 mm as the displacement from designed line and the construction work is supported efficiently by collaboration of a operator.

On recent construction scenes, the automatic operation system for an excavator has become of major interest on the background of the requirement for high quality and the luck and aging of skilled operators.[2)]

The authors have studied on the automatic system for adjusting the position of the diaphragm-wall excavator since 1992, and now have developed an full automatic control system with fuzzy control and applied to the field work.[3), 4)]

2. EXCAVATION CONTROL SYSTEM

On the excavation work of the diaphragm wall, it is necessary to catch the horizontal displacement of the excavator in underground and this importance becomes larger with the excavation depth. Moreover, this measuring technology should be made the basis of the realization of the automatic excavation. Here, on large-depth construction, the accuracy must be within 50 ~ 100 mm about horizontal displacement or less than 1/1000 ~ 1/2000 about verticality. Therefore, in order to adapt for automatic control, we have taken aim at the accuracy of less than 30 ~ 50 mm as for the displacement from a designed line.

The excavation control system is composed of the excavator positioning system and the excavation load control system. Fig. 1 shows the system component.

The excavation load control system, installed in the base machine (crane), controls the downward speed of the excavator (excavation speed) and the interpenetrating force to the earth (excavation load). The excavation speed is set on the setting panel in the operation cabin, and then, the set speed is maintained through the excavation work, by adjusting the braking force of the multiple disc clutch connected to the drive shaft of a torque converter. Simultaneously, the excavation force is held less than the set value.

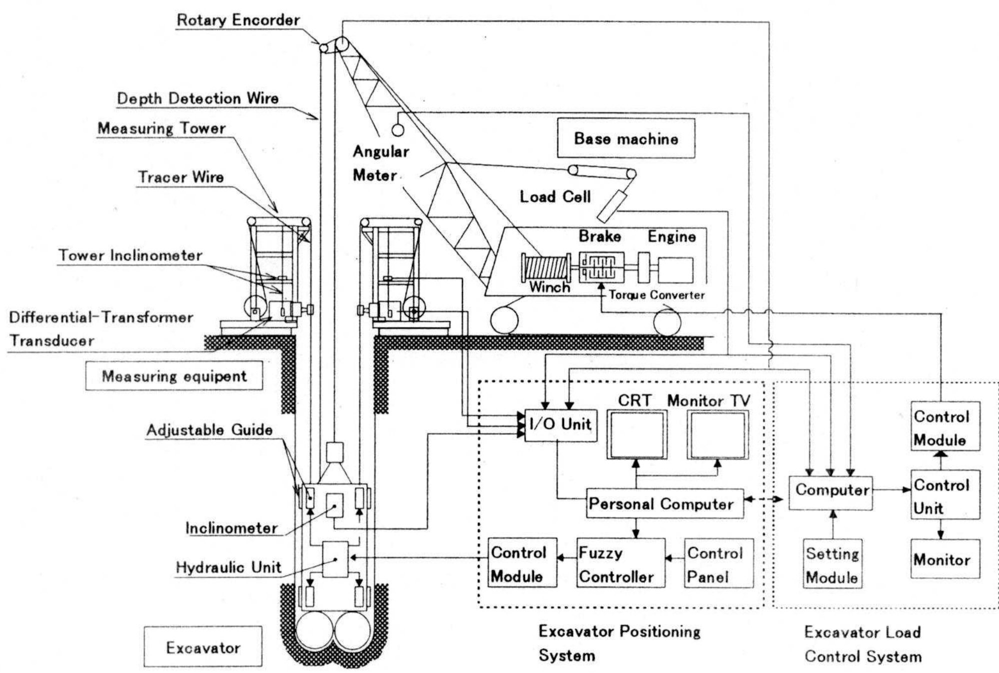

Fig. 1 System component of excavation control system

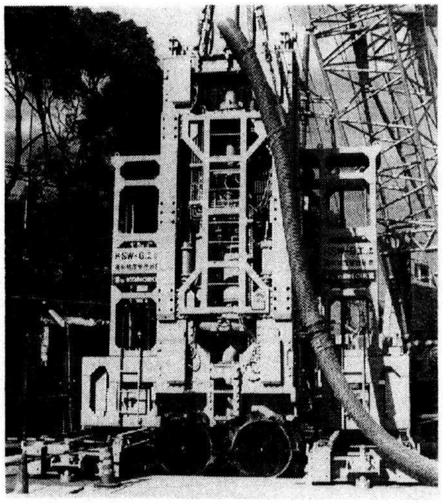

Photo. 1 Main view of excavator and control system

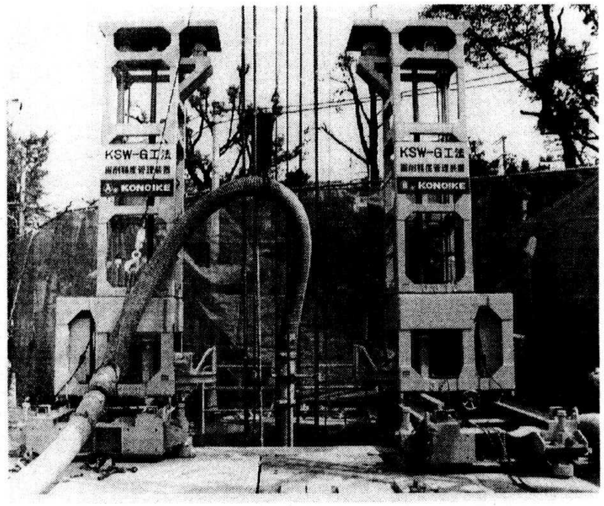

Photo. 2 View of excavation work

The excavator positioning system composing a main frame has the measuring equipment for the position of the excavator and the guidance equipment of the excavator. Through the functions of these equipment, the excavator can be detected with high accuracy and adjusted by the operation of adjustable guides attached on the side of the excavator.

The measuring equipment is characterized by one pair of the measuring tower and the tracer wire. Each tracer wire is doubly extended between the top of the measuring tower and the excavator via a sheave attached to the top of the excavator. One end of the tracer wire is connected to the measuring tower as the fixed point at the tower top and the other end is fixed to the wire reel producing constant torque on the base of the tower, so the wire can be pulled with the constant tension and brought synchronously with a up-and-down motion of the excavator. The position of the excavator is calculated by a proportional magnification of the horizontal displacements of two tracer wires, where the two dimensional displacement of each wire is accurately detected by the differential-transformer transducer on the base of the tower. In the dimensions of the tower, when the tracer wire shows the displacement 2 mm, the displacement of excavator takes 50 mm at 100 m depth in the underground. The measuring towers are placed separately at right and left side of the excavator, hence the accuracy of measurement for a rotation is highly precise because of the wide space between the wires. Photo. 1 shows the excavator and the excavation control system and Photo. 2 shows a view of excavation work.

The differential-transformer transducer automatically tracks to the movement of the tracer wire in the two dimensional range of 100 mm square and measures with the accuracy of ±0.05 mm. This detector is based on the untouchable magnetic system, so stable measurements are made in all weather without the influence of stains with mud water or other disturbances.

The accuracy of positioning is affected by the movement of the fixed point of the tracer wires on the tower top. Especially in summer, a thermal strain arises within the tower frame and the inclination of 40 ~ 100 seconds occurs on the whole tower. For example, if the tower has an inclination of 40 seconds from the initial position, there will be the error of 20 mm in measurement for the excavator position at 100 m depth. This error is proportional with the depth. In order to overcome this problem, the tower inclinometer is installed in the main frame of the measuring tower, and the inclination of the tower is adjusted within 20 seconds by means of screw jacks. As the results, the error of positioning can be controlled within 10 mm at 100 m depth.

The guidance equipment is useful to give the information of excavator work to a operator. As shown in Photo. 3, the monitor display projects the processed information, i.e., graphs, instructions, warnings and controlled data. Here, these collected data from sensors are made smooth to obtain the noise reduction and the stability of monitoring.

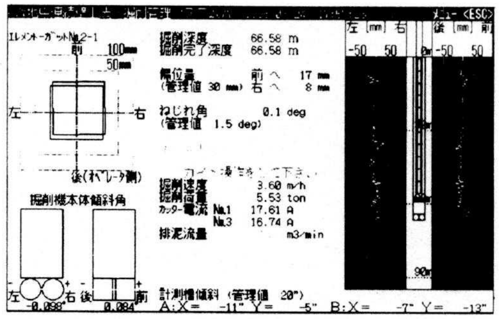

Photo. 3 Monitor display of guidance system

The displacement of the excavator, as the most important data for excavation control, is computed in the form of two dimensional displacement at the depth of the cutter center point in consideration of the displacements of the tracer wires, and the inclination and depth of the excavator. Moreover, the rotation of excavator is obtained from the horizontal displacements of two tracer wires. The position of the excavator is controlled by the operator according to the indication of the monitor. On this system, a skilled operator is capable of controlling the excavator position under 30 mm of indicated displacement. Then, for the excavator of 100 m depth, the operational accuracy of the excavator position is within 30 ~ 50 mm including the measuring error.

3. AUTOMATIC SYSTEM FOR EXCAVATOR

The excavation control system described above is quasi-automatic system, because a manual operation is required partially for the adjustable guides. Therefore, it seems that ensuring the accuracy of excavation makes them hold in heavy tension. The full automatic control system is developed for labor saving and more advanced accuracy, and is fit for these purposes. This system is equipped with a fuzzy controller for automatic control of excavator adjustment, so that the accuracy by skilled operators or more can be obtained. The direction control with fuzzy control technology for excavators has been developed for a shield tunneling work.[5] Comparing with a diaphragm-wall excavation, it may easily develop the automatic control system for a shield tunneling machine, because of horizontal excavation in a similar layer, direct measurement of a machine position and a certain reaction against an attitude adjusting. On the other, the

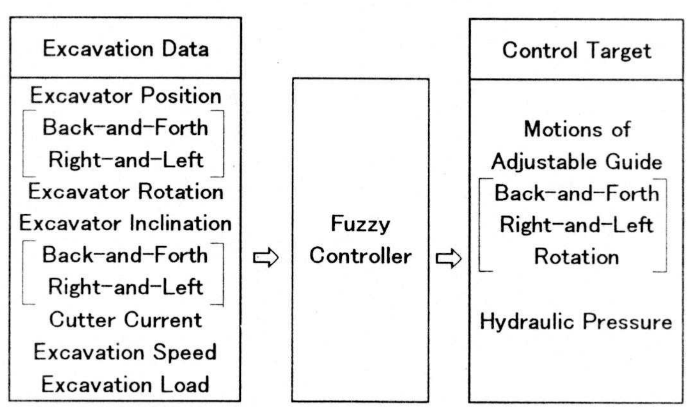

Fig. 2 Control functions of excavator

diaphragm-wall excavator excavates vertically through the unstable layers changing complicatedly. The design of the automatic system for the excavator requires an advanced technology with respects to a complicated ground, an unstable trench and an uncertain reaction. The automation is in difficulty without an investigation of characteristics of excavator motions. Therefore, the authors have been studied a basic interaction between control conditions and ground properties, based on the excavator position control system, and have established the control model, for the fuzzy controller.[3), 4)]

The position of the excavator is adjusted by pushing a trench wall with two or four adjustable guides diagonally arranged on the excavator. The motions of the adjustable guides are given by the fuzzy controller, where the variables of fuzzy control are the excavator position and the work conditions. Fig. 2 shows the control functions of the excavator.

The basic functions of excavator adjustment are below.

1. control for the adjustable guides to adjust the excavator within the planned limit of displacement and rotation.
2. estimation of the properties of layers from the excavation load.
3. control the motions of adjustable guides in response to the properties of a layer.

The component of the fuzzy controller is shown in Fig. 3. The fuzzy controller receives input data at each 5 seconds from the computer of the positioning system via RS-232C interface and outputs the motion times and the operating pressure of the adjustable guides at each 10 seconds. Here, the output results of fuzzy reasoning are the real numbers with positive weight. The reasoning part is divided three groups, the layer condition is judged as earth hardness on the fuzzy reasoning 1 and the motions of adjustable guides are given for the right-and-left position on the reasoning 2 and the back-and-forth position and rotation on the reasoning 3. The rule groups in the fuzzy reasoning 2 and 3 can be selected from four combinations, i.e. the standard excavating, the excavating in the

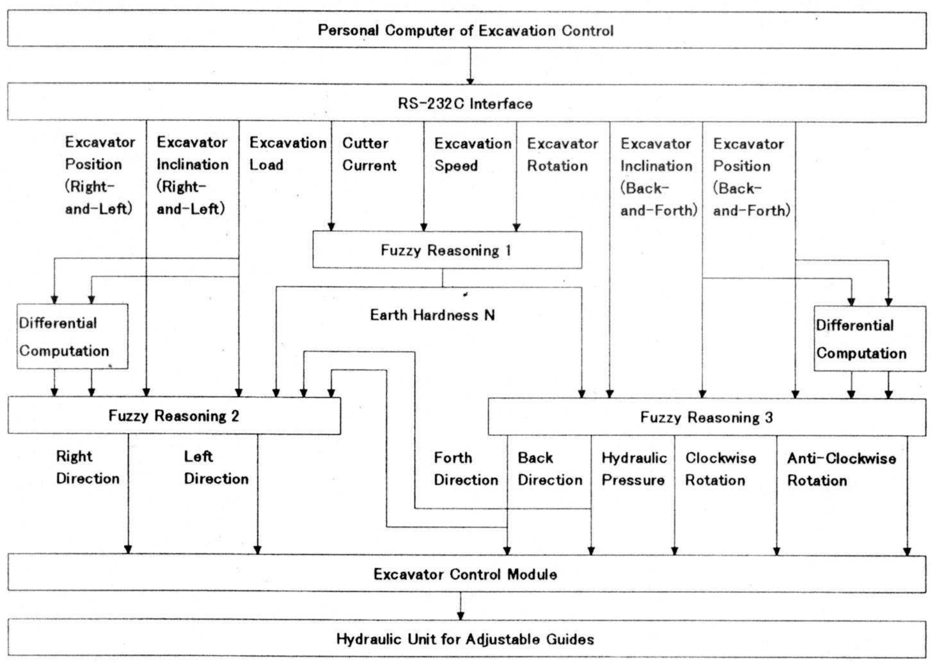

Fig. 3 Component of fuzzy controller

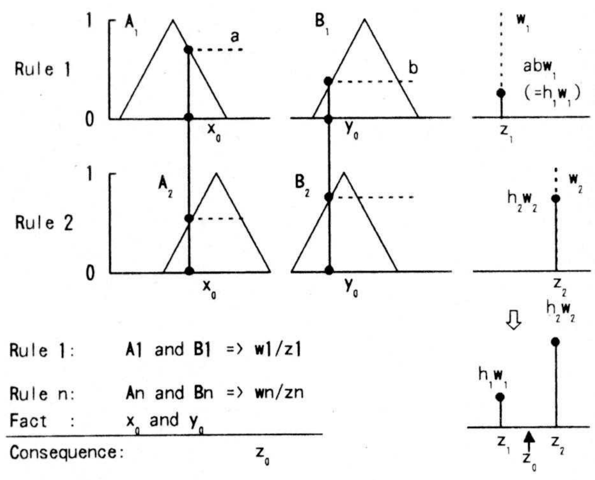

Fig. 4 Fuzzy singleton-type reasoning method[6)]

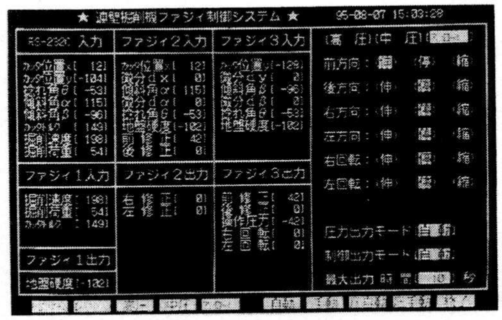

Photo. 4 Display of fuzzy control

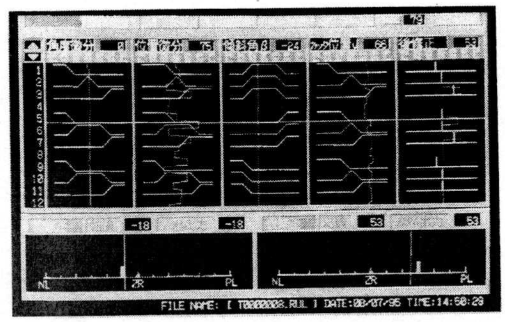

Photo. 5 Display of fuzzy rule building

case of the existence of a trench on right or left side and the excavating in the case of existence of concrete walls on both sides.

The fuzzy reasoning method employs the fuzzy singleton-type described in seven labels of the membership functions formed with four units of shape such as /\, /‾\, ‾|_ and ‾_ on the antecedent part, and with thirteen labels of singleton pole with weight on the consequence part. The fuzzy singleton-type reasoning method can adjust smartly the output signals by tuning the weights of fuzzy control rules, and realize the compact control and the fast execution of fuzzy inference, comparing with a min-max-gravity method, known as Mamdani's fuzzy reasoning method. The basics of the fuzzy singleton-type reasoning method is shown in Fig. 4.[6)] Moreover, the software for building the rules has the functions of emulation and simulation for fuzzy inference on the basis of the input dada, so the fuzzy rules can be adjusted and changed during the practice of excavation control by the emulation, and optimized in short time. Photo. 4 shows the display of fuzzy control and Photo. 5 shows the display for fuzzy rule building.

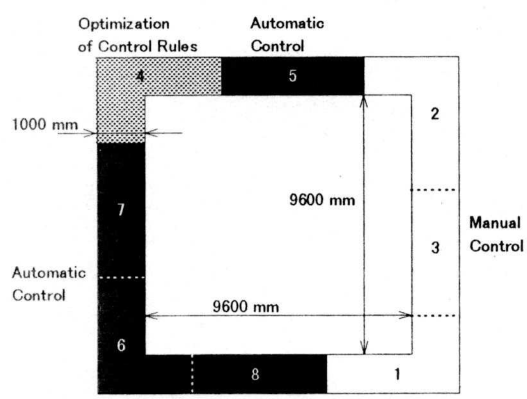

Fig. 5 Plane view of pit and panel arrangement

4. OUTLINES OF FIELD APPLICATION

We applied this system to a field work (steel diaphragm wall type) which constructed for the an arrival pit of shield tunneling at Torishima area in Osaka, Japan. In this site, there are various kind of layer, i.e. which deposited diluvial clay and sand or gravel, and the ground in a shallow depth than 22.5 m is solidified by mixing cement. The specification

Table 1 Specification of wall

Wall Construction	Steel Diaphragm Wall Method
Structure	Structural Wall (Rigit-Jointed)
Wall Thickness	1 m
Total Wall Length	10.6 × 4 sides = 42.4 m
Wall Depth	G.L.-68 m
Excavation Depth	G.L.-69.5 m (Maximum)
Wall Dimensions	2883.2 m^2
Sectional Shape	Square
Pit Depth	G.L.-34 m

Table 2 Range of control data

Control Data	Negative Large	Zero	Positive Large
Excavator Position (Back-and-Forth)	-42mm (back)	0mm	+42mm(forth)
Excavator Position (Right-and-Left)	-42mm (left)	0mm	+42mm(right)
Excavator Inclination (Back-and-Forth)	-0.35°(back)	0°	+0.35°(forth)
Excavator Inclination (Right-and-Left)	-0.35°(left)	0°	+0.35°(right)
Excavator Rotation	-1.8° (clockwise)	0°	+1.8° (anti-clockwise)
Cutter Amplifier	0 A	15 A	30 A
Excavation Speed	0 m/h	4.5 m/h	9 m/h
Excavation Load	0 ton	6 ton	12 ton
Driving Time of Adjustable Guide	contraction 3.75 sec	stop	expansion 3.75sec

of the diaphragm wall is shown in Table 1. The section of the pit is composed of eight panels in a square shape and each panel are excavated in three units. For all panels, the excavation control system is adapted. On the excavation for first three panels, the manual excavation data are collected and analyzed for building the control rules, and last five panels are controlled automatically. Fig. 5 shows the plane view of this pit and the excavating way. The control rules are formed in the combination of feed-back and feed-forward control for avoiding hunching and overshoot. On No.4 panel, the rules are optimized with the emulation of each control results, basically within 20 mm of the displacement, 0.8° of the rotation and 0.2° of the inclination of the excavator as the upper limit. As a result, the number of rules becomes in eighteen for the reasoning 1, twenty-seven for the reasoning 2 and thirty for the reasoning 3. Table 2 shows the range for the input data.

5. ACCURACY OF EXCAVATION AND RESULTS OF CONTROL

5.1 ACCURACY OF POSITIONING AND RESULTS OF MANUAL OPERATION

A supersonic wave measurement is the only method to detect the shape of the wall of a trench. As an example of a back-and-forth direction regarding the accuracy of the measuring equipment and the performance of excavation control, Fig. 6 shows a comparison of the center point data on the 1 m depths of the supersonic wave measurement with the data of the measuring equipment. On the supersonic wave measurement, there are the overcutting or small fall of wall surfaces at gravel or clay layer. It is difficult to compare the data at these points, but there is good agreement between both data at the whole range. Here, the average of difference in both data is -0.92 mm and its standard deviation is 7.4 mm. As the results, it become clear that the measuring equipment and the excavation control have high accuracy and fine performance.

Fig. 7 shows an excavation data on the 1 m depths of a back-and-forth direction by manual operation. The results of the operation are kept within 30 mm of the displacement limit. On this result, it is recognized that the performance of positioning and control of this man-machine system is excellent. For the rotation of the excavator, the excavator is controlled within 1.5°. On the detection for the rotation, the excavator has a mechanical tendency that rotates anti-clockwise, so it was necessary to operate in clockwise rotation during the excavation work.

5.2 RESULTS OF AUTOMATIC EXCAVATION

The control rules had been built at the first unit of No.4 panel and optimized through the second and third unit. In the optimization, the span of input and output data are adjusted and the rules are conformed so as to avoid a hunching phenomenon. The last four panels are excavated automatically with this optimized rule.

The control data of automatic excavation at each 1 m depths in a back-and-forth direction are shown in Fig. 8. The displacements are within 30 mm of the limit, same as manual operation. In the comparison with the manual operation shown in Fig. 7, the accuracy of the automatic control is higher in the whole range of depth, because of the scattering of these data is small.

The percentages of frequency of the excavation data are shown in Fig. 9 as the comparison of manual and automatic control. In this figure, each line indicates the data of a standard operator with dotted lines, a skilled operator with broken lines and the automatic control with solid lines. The displacements and inclination of excavator by the automatic control are close to the data of the skilled operator. For the rotation, which has tendency

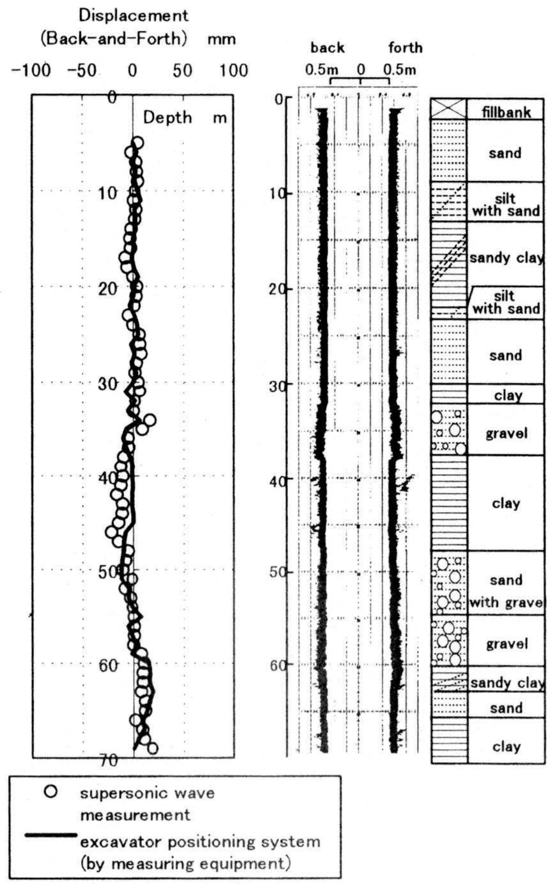

Fig. 6 Comparison of excavation data

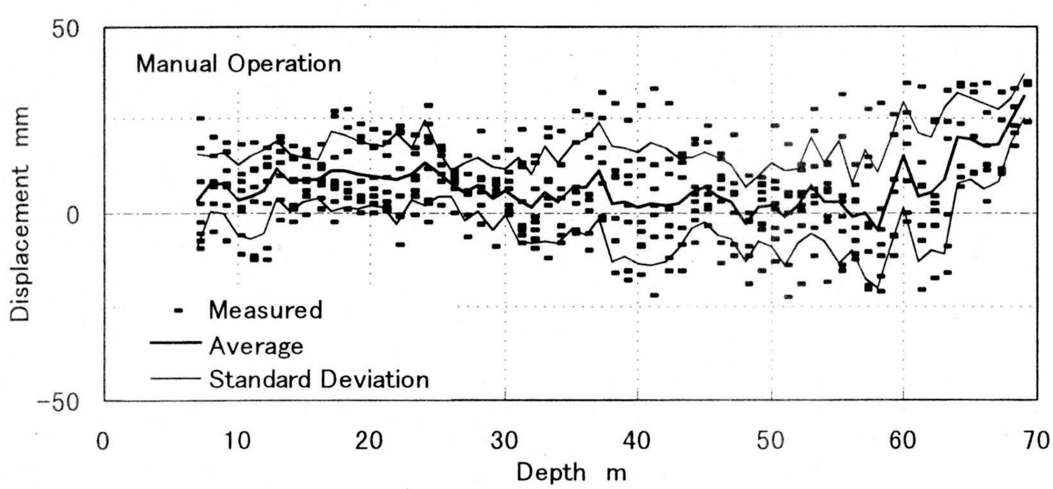

Fig. 7 Excavation data of manual control

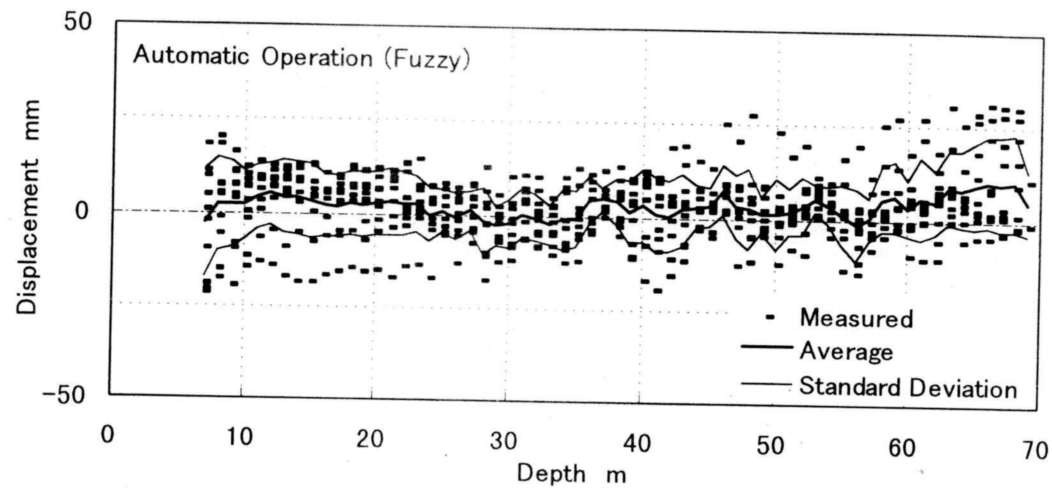

Fig. 8 Excavation data of automatic control

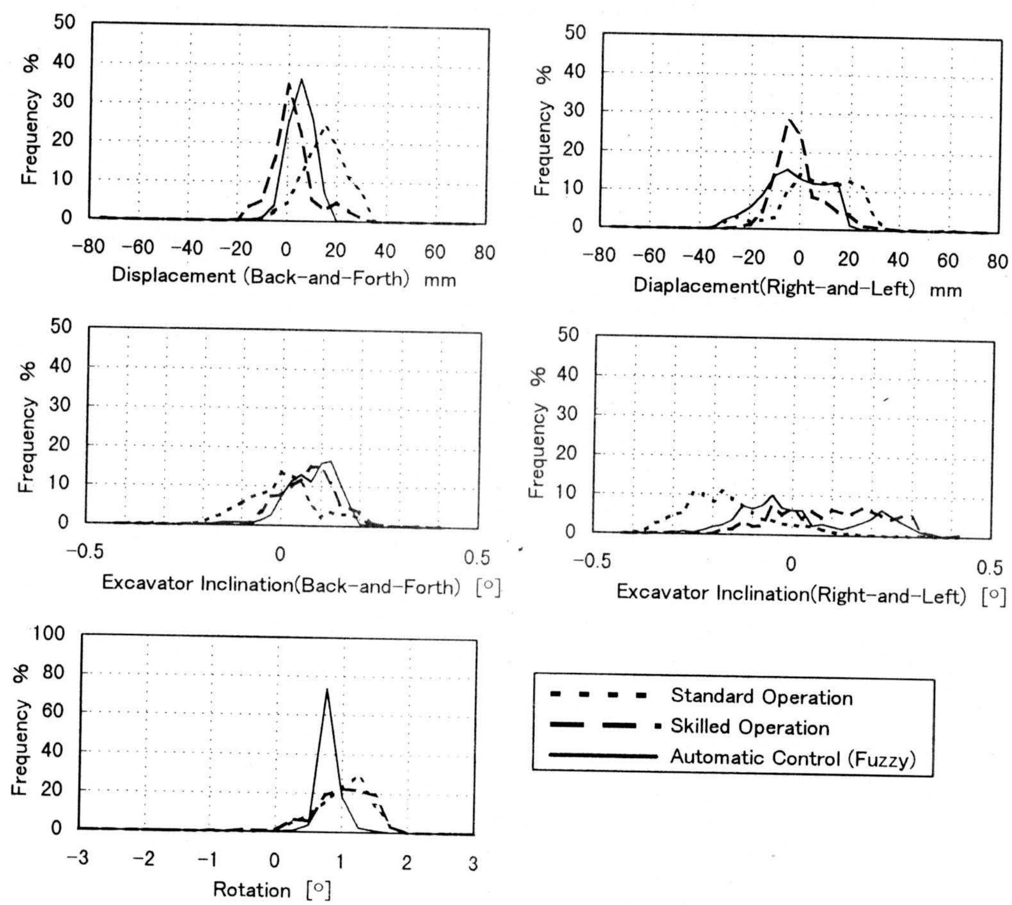

Fig. 9 Frequency distribution of excavation data

mentioned above, the skilled operator is disposed to control near the upper limit. On the other, the automatic system maintains in a range of small deviation. However, the excavator can not be controlled on both back-and-forth direction and rotation in same time because of the functions of a hydraulic system. Then, the back-and-forth operation was given priority treatment and consequently the average of rotation could not be within 0.6°.

It is verified through this field work that the automatic system for the excavator can complete well respect to a skilled operator, and the system has sufficient accuracy for the positioning and high reliability. After this, operators will be released from a suffering work of positioning control. Moreover, an excavation of inferior quality by over-control will be removed and differences among individuals will be avoidable in operation.

6. CONCLUSION

It is expected that the diaphragm wall will be applied to more variable field, especially to a large-scaled underground structure. Hence, the excavation control system becomes the essential technology to present the large-scaled diaphragm wall with high quality. In addition, the automatic system for a excavator constructs the homogeneous and accurate wall without a hard work and the dependence on ability of an operator. This system is also applicable to the concrete cutting. We would like to express our appreciation for all those who helped in research and development of this system.

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