Automation and Robotics in Construction XII
E.Budny, A.McCrea, K.Szymanski (Editors)

Interaction between a model excavator and the surrounding ground during positioning control tests

R. Fukagawa[a], T. Muro[a], K. Hozumi[a] and T. Matsuike[b]

[a] Faculty of Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama, 790 Japan

[b] Konoike Construction Co. LTD, 4-3-55, Denpo, Konohana, Osaka, 554 Japan

Abstract

A series of laboratory tests by using a model excavator for the diaphragm wall method were carried out in order to investigate the interaction between the model excavator and the surrounding ground. The behaviour of the excavator was theoretically formulated and the theoretical values were compared with the experimental data. As a result, the calculated displacement of the excavator showed good accordance with the measured values for each ground condition investigated.

1.INTRODUCTION

The Diaphragm Wall Method is one of the construction methods used to make vertical and underground thin wall. This method is mainly used for constructing impervious wall and sometimes earth retaining wall. Positioning of the excavator for this method has to be carried out as precisely as possible since it has a great effect especially on the impervious characteristics of the diaphragm wall. Positioning is manually conducted at present, but the authors have attempted to automate the control of the positioning of the excavator. A series of tests using the same model excavator as in this paper were carried out and a part of the results has been already reported [1]. Although the interrelations among the control conditions, the ground conditions and the control results were quantitatively evaluated, the interaction between the model excavator and the ground was not so easily evaluated. It seemed that the ground conditions have to be correctly considered and reflected in the control conditions. Therefore, in this study the interaction between the model excavator and the surrounding ground was theoretically formulated first and the estimated values were compared with the experimental values. The good accordance shown in the comparison will result in a contribution to mechanically reasonable control conditions of the excavator.

2.EXPERIMENT

2.1 Experimental apparatus

The schematic diagram of the experimental apparatus is shown in Fig.1. Although the actual excavator used commonly in construction sites has 16 adjustable guides comprised of a hydraulic cylinder and a loading plate on each of its four sides for the positioning control, the model excavator designed had only one adjustable guide for each side and could rotate in a plane around one hinge. The experimental apparatus consists of hydraulic unit, solenoid valves, relay circuit, hydraulic cylinders, model excavator, soil bin, worm jack, motor and the frame for these equipments. The size of the loading plate connecting with hydraulic cylinder is 65mm in width and 100mm in height.

The hydraulic unit has the following specifications: pump pressure; 35.7kgf/cm^2 (3.5MPa), outlet oil volume from pump; 1.3l/min. Four solenoid valves are equipped with hydraulic units to change oil current direction. One hydraulic cylinder is operated with two solenoid valves. The hydraulic cylinder has a 32mm inner diameter and a 30 mm stroke length.

The excavator is penetrated into the model ground using a worm jack. The lifting speed of the worm jack was constant (1.0 mm/sec) in this study.

Please see Ref. [1] for further details of the experimental apparatus and the control system.

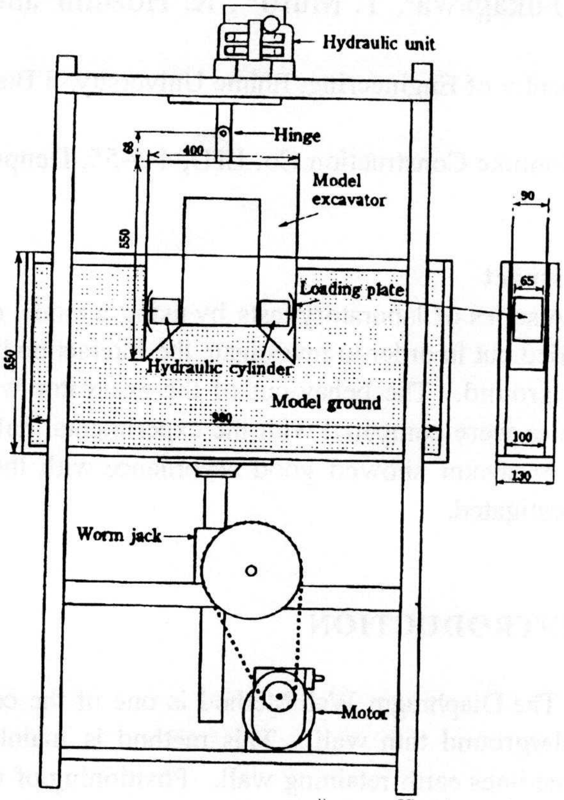

Figure 1. Schematic diagram of experimental apparatus

2.2 Proportional control action

Since proportional control action was used for the control, the program became simple and allowed high speed manipulation. The program consists of the input of the voltage signal, calculation (the proportional control action) and the output of the voltage signal. Since the displacement of the loading plate is expressed by voltage signals ranged from -5 to 5V and this is proportional to the control voltage of rotational number output to the motor, the following equation is obtained:

$$Vol.O = Gain \times Vol.I \quad (1)$$

where $Vol.O$ is the output voltage, $Gain$ is the proportional gain and $Vol.I$ is the input voltage.

In the positioning control in this study, the loading plate works as follows. Let's assume the case in which the proportional gain is equal to 5 in Fig.2. When the bottom of the excavator is displaced 1mm to the right from the reference position, 0.5V is input as the input voltage. Correspopnding to the input voltage, 2.5V is output as the output voltage and finally the loading plate expands 0.6sec. In this process, since the pump pressure supplied to the

Table 1 Physical properties of tested samples

	Specific gravity	ρ_{min} (g/cm^3)	ρ_{max} (g/cm^3)	Relative density of tested ground (%)	D_{50} (mm)
Styrofoam beads	0.0218	0.0108	0.0112	34	7.6
Polyethylene beads	0.90	0.58	0.64	23	2.8
Toyoura Sand	2.57	1.35	1.63	86	0.26
River Sand	2.64	1.42	1.73	36	0.97

hydraulic cylinder is constant, the expansion speed of the plate is also constant (26.1mm/sec). The maximum expansion distance of the cylinder is 30mm. Consequently 0.6sec for expansion means 15.7mm of the expansion distance. The cylinder begins to contract almost simultaneously after the prescribed time for expansion passes. The speed for expansion and contraction are almost the same. If the position of the excavator is much further from the reference position and control is difficult, the loading plate repeats full stroke expansion and contraction, which means 30mm displacement of the loading plate.

3.MODEL GROUND

3.1 Materials used

Four kinds of granular materials are used in this study, that is, Toyoura standard sand, styrofoam beads, river sand, and polyethylene beads. The physical properties of these materials and the relative densities in the experiments for positioning control are shown in Table 1.

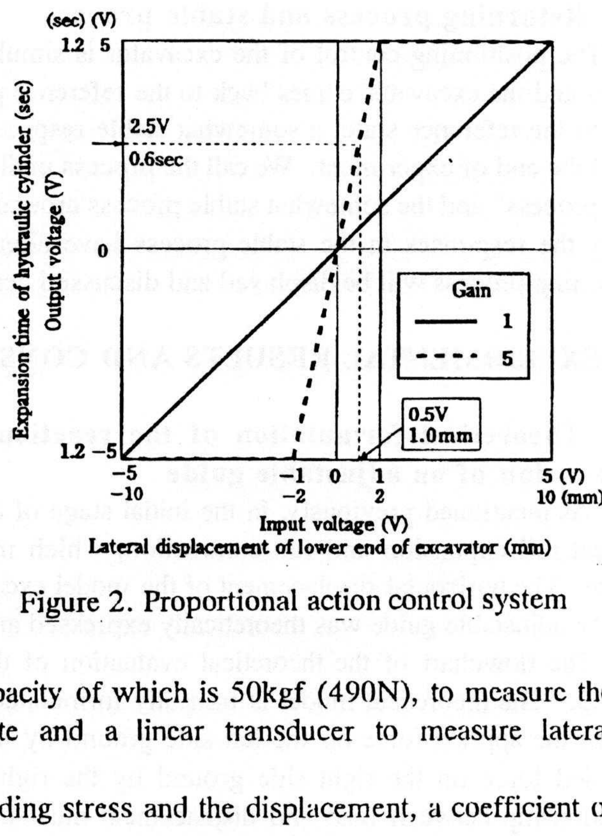

Figure 2. Proportional action control system

3.2 Evaluation of the deformability of model ground

Plate loading tests for lateral direction were carried out to evaluate the deformability of model ground. Test conditions are almost the same as in the experiments for position-ing control. A load cell, the capacity of which is 50kgf (490N), to measure the horizontal load acting on the loading plate and a linear transducer to measure lateral displacement are used in these experiments.

Based on the relationship between the loading stress and the displacement, a coefficient of subgrade reaction K is defined as follows:

$$K=p_{10}/d_{10} \qquad (2)$$

where p_{10} is the loading stress corresponding to 10mm displacement of the loading plate and d_{10} is the displacement of the loading plate (in this case 10mm is employed as its reference value). K defined in this way for Toyoura sand, styrofoam beads, river sand, and polyethylene beads are 0.130, 0.0086, 0.259, 0.0378 kgf/cm^3 (1.27, 0.084, 2.54, 0.37kN/cm^3) respectively.

4. EXPERIMENTAL PROCEDURE

4.1 Gain and excavating rate

An initial geometrical condition of the excavator is set in the same way for all materials used, that is the excavator is buried 230mm under the surface of the ground and the cutting edge of the excavator is displaced 10mm horizontally to the right from the reference position. The reference position is defined as the state in which the excavator is suspended naturally under the hinge situated over the center of the excavator. The positioning control tests for four kinds of materials were carried out under a variety of gains from 0 to 200 and finally an optimum gain was determined.

4.2 Returning process and stable process

The positioning control of the excavator is simultaneously begun at the start of the experiment and the excavator comes back to the reference position after some seconds. After returning to the reference state, a somewhat stable response around the reference position continues until the end of experiment. We call the process until returning to the reference state the "returning process" and the somewhat stable process around the reference state as the "stable process". Only the responses in the stable process have already reported [1] and the responses in the returning process will be displayed and discussed hereafter.

5. EXPERIMENTAL RESULTS AND CONSIDERATIONS

5.1 Theoretical formulation of the reaction of an excavator measured against expansion of an adjustable guide

As mentioned previously, in the initial stage of the returning process the adjustable guides repeat full expansion and full contraction, which means 30 mm displacement of the loading plate. The horizontal displacement of the model excavator measured against one full expansion of the adjustable guide was theoretically expressed and compared with the experimental data.

The flowchart of the theoretical evaluation of the model excavator response is shown in Fig.3. The theoretical model is basically formulated based on the equilibrium conditions between the applied force on the left side ground by the adjustable guide and the corresponding applied force on the right side ground by the right wall of the excavator (see Fig.3). The relationship between load and displacement must be predicted when a load is applied to the adjustable guide or the side wall of the excavator. These relationships are expressed with a kind of exponential function which was used to express the load-displacement relations in ordinary plate loading tests. The equation is expressed as Eq.(3) in Fig.3 (see Ref.[2][3] as to this equation). The first half of Fig.3 is concerned with the estimation of Eq.(3) and the latter half

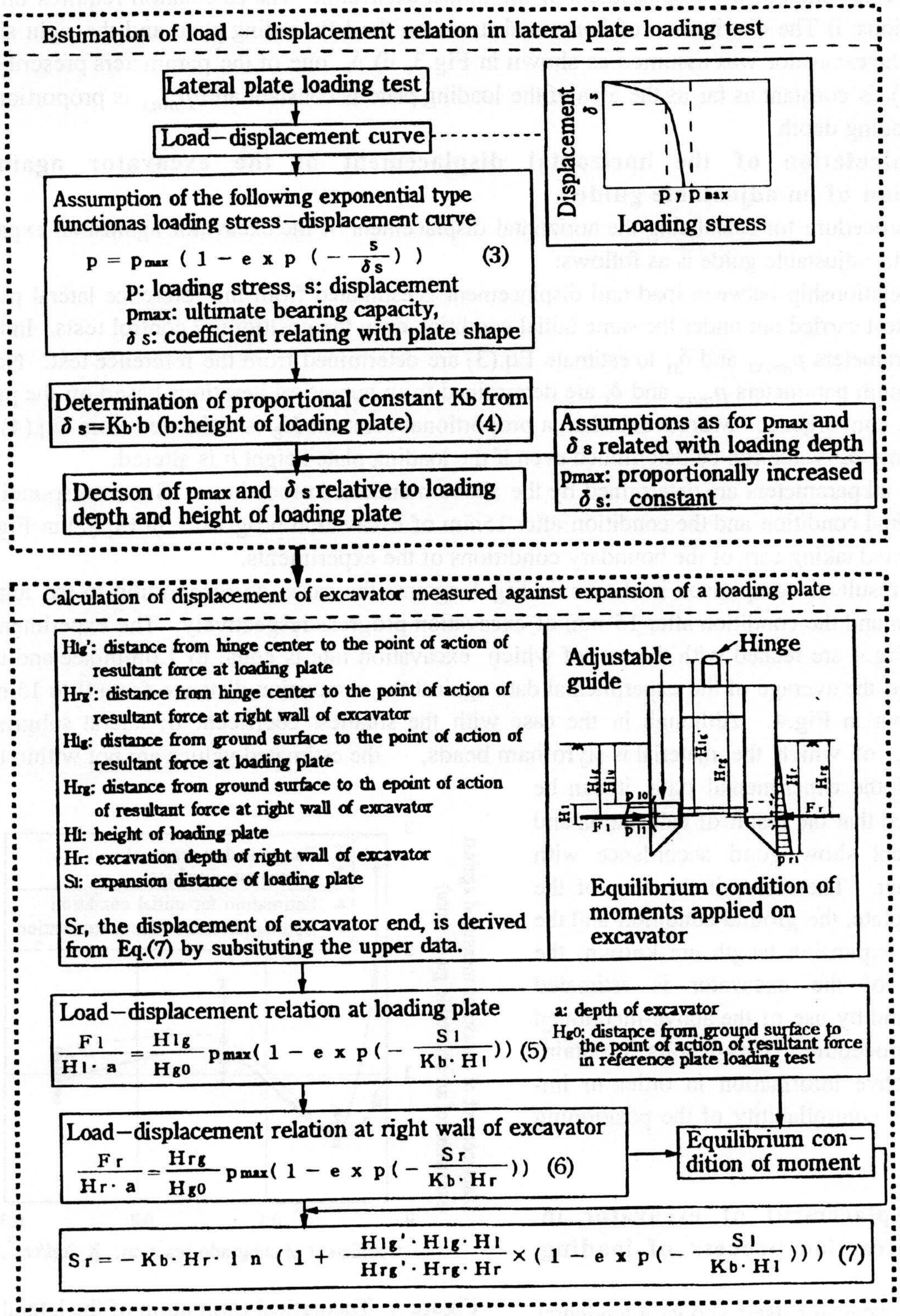

Figure 3. Calculation of the lateral displacement of excavator measured against expansion of an adjustable guide

with the calculation of the displacement of the model excavator. The calculation requires other assumptions: i) The distribution of horizontal stress on the left loading plate and the right side wall of the excavator was assumed as shown in Fig.3, ii) δ_s, one of the parameters prescribed in Eq.(3), is constant as far as the area of the loading plate is constant and p_{max} is proportional to the loading depth.

5.2 Calculation of the horizontal displacement of the excavator against expansion of an adjustable guide

The procedure for calculating the horizontal displacement of the excavator against an expansion of the adjustable guide is as follows:

1) The relationship between load and displacement is estimated from the reference lateral plate loading test carried out under the same initial condition as in the positioning control tests. Initial input parameters p_{maxi} and δ_{si} to estimate Eq.(3) are determined from the reference test. Next the optimum parameters p_{max} and δ_s are determined from numerical iterations based on the program for convergence. Moreover, when a proportional constant K_b is estimated from Eq.(4) in Fig.3, any δ_s -value can be determined even if the loading plate height b is altered.

2) Since all parameters are determined by the above-mentioned procedures, Sr, corresponding to the initial condition and the condition after 15mm of excavation progress, in Eq.(7) in Fig.3 is calculated taking care of the boundary conditions of the experiments.

The result of comparison is shown in Fig.4 against the cases corresponding to the initial condition and the condition after 15 mm of excavation progress respectively. The experimental data in Fig.4 are related with the test of which excavation rate is equal to 1.0mm/sec and the range and the average of the experimental data against the excavation distance from 0 to 15mm are shown in Fig.4. Although in the case with the smallest coefficent of lateral subgrade reaction, of which the material is styrofoam beads, the estimated values are not within the range of the experimental data, it can be concluded that the result of calculation and experiment show good accordance with each other. Therefore, if the area of the loading plate, the ground condition and the cylinder expansion length are known, the reaction of the excavator is estimated beforehand by use of the above-mentioned simple procedure. This results in obtaining effective information in order to improve the controllability of the positioning system.

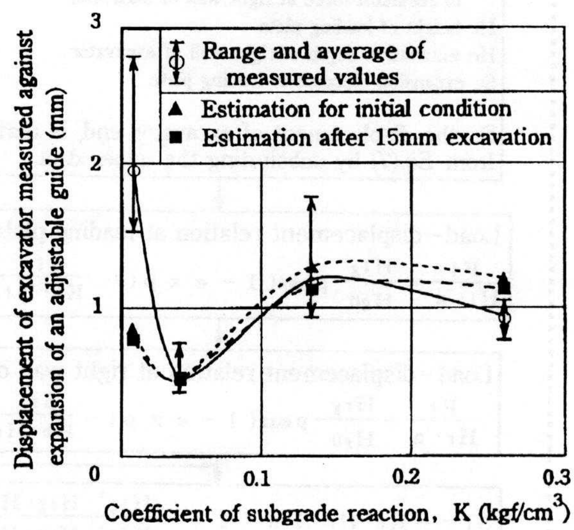

Figure 4. Theoretical estimation of the lateral displacement of excavator measured against expansion of an adjustable guide

5.3 Displacement of excavator in the contraction process of loading plate

The excavator itself shows a tendency to return to the opposite direction more or less in the contraction process. Fig.5

shows the returning displacement of the excavator when the loading plate contracts 30mm. This figure is also relative to the case in Fig.4 and the range and the average values corresponding to the excavation distance from 0 to 15mm. The softer the ground, the more the excavator tends to be displaced. The overall controllability canbe judged from the difference between the displacement in the expansion and contraction process of the loading plate.

The total displacement of the excavator corresponding to one cycle of the expansion and contraction of the loading plate can be calculated by subtracting the displacement relative to the expansion phase from that relative to the contraction phase. The result is shown in Fig.6. These plots are obtained by subtracting the average values in Fig.5 from those in Fig.4. Leaving the styrofoam beads out of consideration (as this case gives the smallest coefficient of subgrade reaction, since it is a slightly special material), it can be concluded that the returnability becomes worse in the case of softer ground or harder ground. Although the returnability is large when the coefficient of subgrade reaction ranges from 0.1 to 0.2 kgf/cm^3 (0.98 to 1.96 kN/cm^3), when the coefficient of subgrade reaction is more than or less than this value range, some countermeasure to accelerate the returnability should be planned if needed.

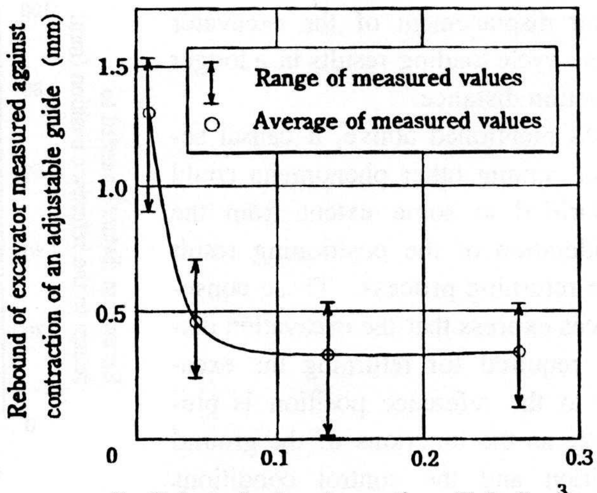

Figure 5. Rebound values of excavator measured against contraction of an adjustable guide

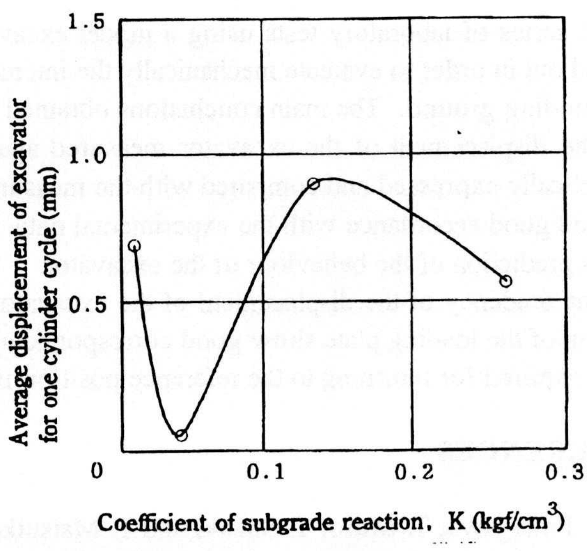

Figure 6. Average displacement of excavator for one cylinder cycle

5.4 Excavation distance for returning process

The excavation distance for the returning process, which is defined as the excavation distance required to return from the initial position, 10mm anticlockwise, to the reference position is shown in Fig.7 for the case for 1.0mm/sec of the excavation speed. Although similar trials for other excavation speeds were carried out, the tendency was consequently not altered very much. Comparing Fig.7 with Fig.6, which expresses the displacement of the excavator the one cycle of the expansion and contraction of the loading plate, both figures show good correspondence. The smaller displacement of the excavator for one cycle loading results in a longer excavation distance.

As mentioned above, a causal sequence among other phenomena could be clarified to some extent from the consideration of the positioning result in the returning process. These consequences express that the excavation distance required for returning the excavator to the reference position is predictable as the functions of the ground condition and the control conditions when some initial position for the reference position is given.

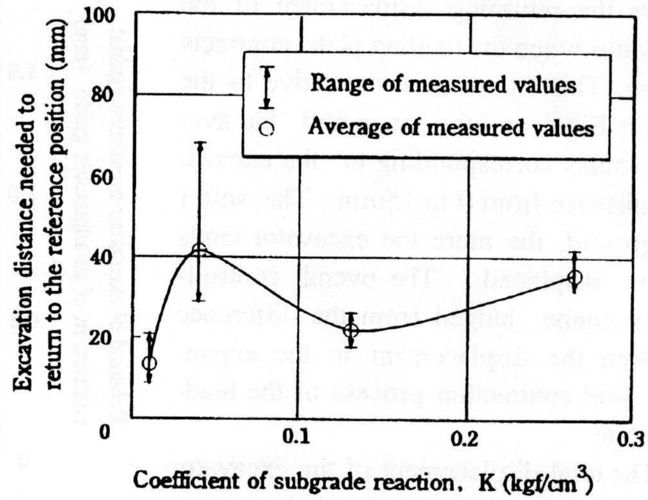

Figure 7. Excavating distance needed to return to the reference position

6. CONCLUSIONS

A series of laboratory tests using a model excavator for the diaphragm wall method were carried out in order to evaluate mechanically the interaction between the model excavator and the surrounding ground. The main conclusions obtained from this study are as follows.

(1) The displacement of the excavator measured against expansion of the adjustable guide is theoretically expressed and compared with the measured data. As a result, the theoretical values showed good accordance with the experimental data. This resulted in the possibility of a theoretical prediction of the behaviour of the excavator.

(2) The tendency of the displacement of the excavator for one cycle of the expansion and contraction of the loading plate show good correspondence with the tendency of the excavation distance required for returning to the reference position for each ground condition.

REFERENCES

1. R. Fukagawa, T. Muro, T. Suzuki and T. Matsuike: Basic study on automatic positioning control of the excavator for diaphragm wall method, Proc. of the 11th Int. Conf.of the Int. Soc. for Terrain-Vehicle Systems, Vol.2, pp.704-713, 1993.
2. R. Fukagawa and T. Muro: Alarm system to prevent the overturning of truck cranes considering possible ground failure, Proc. of the 11th ISARC, pp.27-34, 1994.
3. K. Uto, M. Fuyuki and M. Sakurai: An exponential mathematical model to geotechnical curves, Proc. of the Int. Symp. of Penetrability and Drivability of Piles, 1985.