The Prediction of the Interaction Between an Excavator for the Diaphragm Wall Method and the Surrounding Ground

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ABSTRACT

The aim of this paper is to propose a reliable mechanical model which can explain the interaction between an excavator for the diaphragm wall method and the surrounding ground. The non-linear interaction between the control plate of the excavator and the ground was formulated by an exponential type function. The subgrade reaction corresponding to the action of the control plate was expressed by an equation proportional to the lateral displacement at the depth and the coefficient of the subgrade reaction. The estimated behaviors of the excavator showed good accordance with the experimental ones. An intelligent control method considering ground properties was finally proposed based on the mechanical model.

1. INTRODUCTION

This paper focuses on the excavator of the diaphragm wall method (D.W.M.). This is a construction method developed to build high-quality, thin, slurry underground walls mainly used to prevent ground water infiltration. For several years, the authors have been trying to automate the positioning control of the excavator. It was made clear through our studies[1)2)] that the mechanical response of the excavator corresponding to the ground conditions has to be investigated in order to attain effective control results.

The proposed mechanical model in this study, the prototype of which has already been published in the 12th ISARC[2)], is now modified to better express the real behavior of the excavator. As the result of this study, the estimated behaviors of the excavator showed good accordance with the measured ones. This resulted in the possibility of obtaining mechanically clear information on the ground properties and having intelligent control methods consider the ground conditions.

2. MECHANICAL EVALUATION OF EXCAVATOR RESPONSE

It is desirable that the control model include an algorism which can alter the control conditions according to the ground conditions. As the first step of such a trial, the displacement of the excavator against the full expansion of a control plate is theoretically formulated based on the equilibrium conditions of the force moment around the rotation center of the excavator .

2.1 Equilibrium condition of moment around the rotation center

Figure 1 shows the distribution of some forces contributing to the equilibrium of the moments around the rotation center O. Each distributed load is finally represented by a concentrated load and the concentrated load is assumed to be acting on the center of gravity. The distance from the rotational center O to each acting point of the concentrated load is also demonstrated in Figure 1. In this paper, the displacement of the excavator against the expansion of left upper and right lower control plates are calculated as a trial. Of course the selection of the left lower and right upper control plates would give the equivalent conclusions. The equilibrium equation of the moment around O is expressed by the following equation:

$$z_{rl2}\cdot P_{rl} + z_{lu2}\cdot P_{lu} + z_{ll2}\cdot P_{ll} + z_{ru2}\cdot P_{ru} + 2\,M_f = 0 \qquad (1)$$

where M_f is a moment caused by the friction between the excavator and the ground at the front and back of the excavator. Resistances at the upper and bottom face of the excavator are normally negligible.

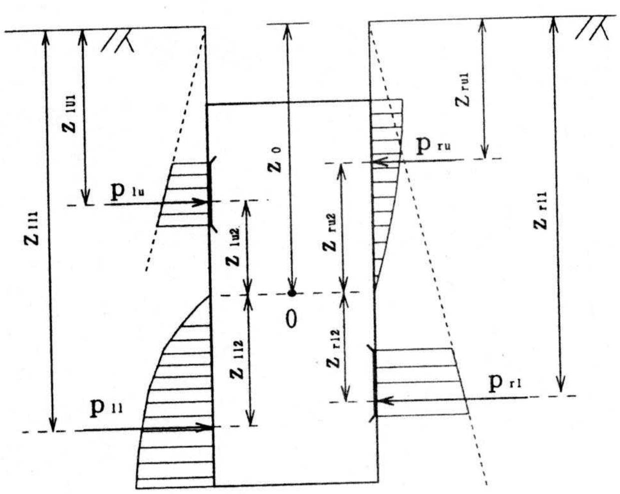

Figure 1 Applied forces to the side face of an excavator

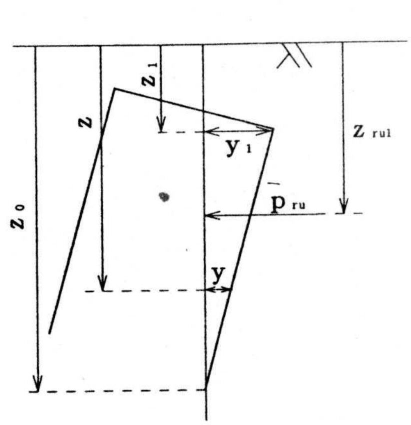

Figure 2 Displacement of an excavator at right upper side face

2.2 The load acting on the side faces of the excavator

Since the displacement of the excavator at the side faces against the loading of the control plates is ordinarily small, the displacement can be regarded as "within (quasi-) elastic deformation". Hence the following equations could be assumed.

$$p(z) = K_h(z) \cdot y(z)$$
$$\Delta p(z) = K_h(z) \cdot y(z) \cdot B \cdot \Delta z \tag{2}$$

where $K_h(z)$: is the coefficient of subgrade reaction at the depth z obtained from the lateral plate loading test, $p(z)$: the subgrade reaction stress at the depth z, $\Delta p(z)$: the subgrade reaction stress acting on the infinitesimal strip Δz at the side face of the excavator, B : the width of the side face of the excavator. Since $y(z)$ can be approximated as a linear function, $y(z)$ becomes the following equation when considering the boundary conditions at the right upper side surface (see Figure 2).

$$y = \frac{y_1}{z_1 - z_0}\left(z - z_0\right) \tag{3}$$

where z_0 : is the distance from the ground surface to the rotation center, z_1 : the distance from the ground surface to the upper end of the excavator, y_1 : the lateral displacement of the upper end of the excavator.

There is a variety of research available on the lateral coefficient of the subgrade reaction K_h especially concerning the lateral resistance of a pile. If we refer to the results of such typical research, the following equation could be obtained for K_h[3].

$$K_h = \alpha E_0 B^{-3/4} \tag{4}$$

where E_0 : is the elastic modulus of the ground, α : correction coefficient for E_0, B : width of pile. It is possible to estimate the coefficient of the subgrade reaction from Eq.(4) by using some conventional laboratory tests and in situ tests. Substituting Eqs.(3) and (4) into Eq.(2), and ignoring the change of E_0 against the depth range in the calculation, P_{ru} could be formulated as the following equation:

$$P_{ru} = \alpha E_0 B^{1/4} \frac{y_1}{2}\left(z_0 - z_1\right) \tag{5}$$

P_{ll} is also obtained similarly to P_{ru}.

$$P_{ll} = \alpha E_0 B^{1/4} \frac{y_2}{2}\left(z_2 - z_0\right) \tag{6}$$

where the suffices ru, ll denote the values at the right upper and left lower positions.

2.3 The load acting on the control plates

The relationship between the loading stress p and the displacement S is well approximated by the following exponential type function[4].

$$p = p_{\max}\left\{1 - \exp\left(-\frac{S}{\delta_s}\right)\right\} \tag{7}$$

where p_{max} : is the ultimate bearing capacity of the ground, δ_s : reference displacement. It is supposed that the Broms method[5)-7)] concerning the lateral resistance of a pile foundation is effectively used to estimate p_{max} for the lateral loading. If the Broms method in the case of a short pile and fixed pile end were applied to this case, p_{max} corresponding to clayey and sandy grounds are as follows respectively :

$$p_{max} = 9c_u \tag{8}$$

$$p_{max} = \frac{3}{2}K_p\gamma\left(H + 2l_0\right) \tag{9}$$

where c_u : is the undrained shear strength of clay, K_p=tan^2(45+ϕ/2), ϕ : internal friction angle, γ : effective bulk density, H : loading plate height, l_0 : the distance between the ground surface and top end of the loading plate.

Although there is no formula concerning the determination of δ_s, it is possible to determine δ_s by the following procedure. First δ_s is theoretically defined as the displacement corresponding to the yield stress p_y. Therefore Eq.(9) gives the following equation.

$$p_y = p_{max}\left(1 - e^{-1}\right) = 0.632 \cdot p_{max}$$

Next, since the coefficient of subgrade reaction K_h is determined by Eq.(4), the displacement when the yield first starts, that is similar to δ_s, is given by the following equation.

$$\delta_s = \frac{0.632 \cdot p_{max}}{K_h} \tag{10}$$

The subgrade reaction forces at the right lower and left upper control plates against arbitrary displacement of the control plate, s_{rl}, s_{lu}, are determined by Eq.(7) as follows:

$$P_{rl} = H_{rl} \cdot B_{rl} \cdot p_{maxrl}\left\{1 - \exp\left(-\frac{S_{rl}}{\delta_{srl}}\right)\right\} \tag{11}$$

$$P_{lu} = H_{lu} \cdot B_{lu} \cdot p_{maxlu}\left\{1 - \exp\left(-\frac{S_{lu}}{\delta_{slu}}\right)\right\} \tag{12}$$

The distances from the rotation center to the applying point on the control plate, z_{rl2}, z_{lu2}, are easily obtained by assuming such a trapezoidal shape distribution as shown in Figure 1.

2.4 Friction at front and back of the excavator

If the distribution of the coefficient of friction and the horizontal subgrade reaction force along the front and back of the excavator can be roughly evaluated, it is possible to estimate the friction at the front and back of the excavator.

2.5 Calculation of the displacement of the top and bottom center of the excavator

If the load etc. obtained from the consideration mentioned above are substituted into Eq.(1), the displacement of the top and bottom center of the excavator y_1, y_2 would be finally determined from Eqs.(13), (14).

$$y_1 = \frac{2HB\left[z_{rl2}p_{max\,rl}\left\{1 - \exp\left(-\frac{S_{rl}}{\delta_{srl}}\right)\right\} + z_{lu2}p_{max\,lu}\left\{1 - \exp\left(-\frac{S_{lu}}{\delta_{slu}}\right)\right\}\right]}{\alpha E_0 B^{1/4} z_A + 4M_f} \tag{13}$$

$$y_2 = z_B y_1\,,\quad z_A = z_{ll2}\frac{\left(z_2 - z_0\right)^2}{z_0 - z_1} + z_{ru2}\left(z_0 - z_1\right),\quad z_B = \frac{z_2 - z_0}{z_0 - z_1} \tag{14}$$

Since the size of the loading plates of the excavator is the same as in ordinary cases, not depending on the positions, the size is simply expressed by the dimensions H and B. Since any parameters except S, y_1, y_2 and the position of the rotation center are known, y_1 and y_2 can be determined by substituting the position of the rotation center of the excavator and arbitrary expansion distance S of the loading plate.

3.CONTROL TESTS WITH A MINIATURE EXCAVATOR

3.1 Test apparatus

The test apparatus consists of the hydraulic unit, the miniature excavator itself, the soil bin and the frame etc. The outline of the measurement system of the miniature excavator is shown in Figure 3. The miniature excavator has two control plates for each side. The total number of the loading plates is therefore 4. The control plate is equipped with a load cell and a linear transducer, hence the load applied to the control plate and the distance of the control plate moved can be measured. The dimensions of the miniature excavator were $150 \times 400 \times 930$mm and the weight was 91.50kgf (897N).

3.2 Model ground

Test material was the Toyoura Standard Sand. The specific gravity, ρ_{min} and ρ_{max} of air dried Toyoura Sand were 2.57, 1.35g/cm^3, 1.63g/cm^3 respectively. The average water contents and average wet densities were 11.6%, 1.33g/cm^3 respectively. Test ground was formed as follows: first wet Toyoura Sand was quietly poured into the soil bin through a sieve of 19.1mm and next the ground was compacted by pounding several times a plate of 1.6kgf weight for each 5cm ground depth. Altering the falling height of the weight, a variety of test grounds, which have different wet densities, were prepared.

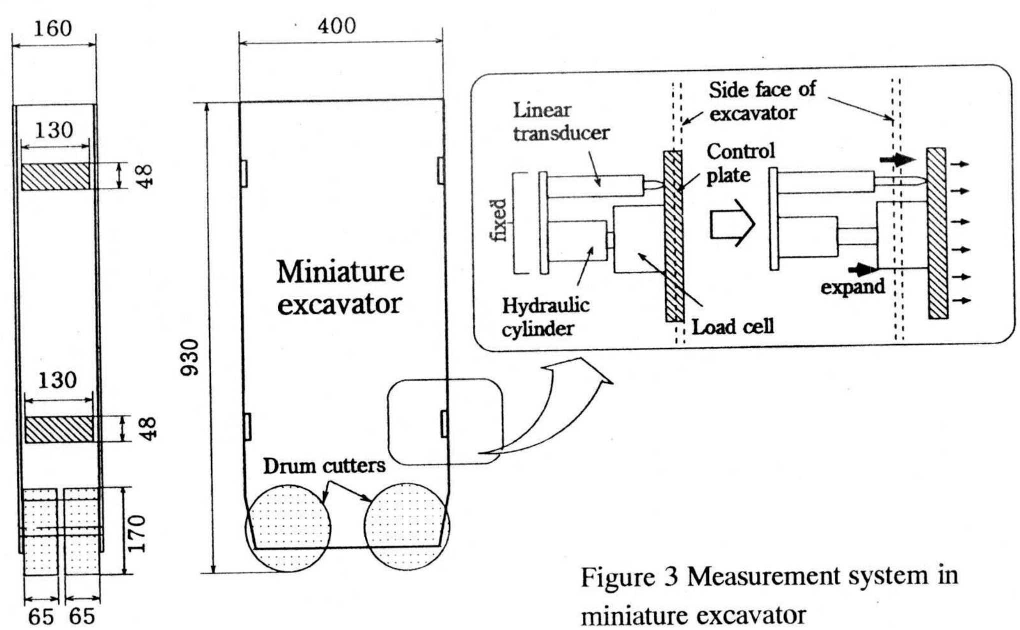

Figure 3 Measurement system in miniature excavator

3.3 Test procedure

A series of tests, in which the left upper and the right lower control plates of the model excavator were expanded, were conducted against the various grounds mentioned above. The measurement items of the tests were i) the horizontal displacement at the center of the top end and the bottom end of the excavator, ii) the loading stress of the control plate, iii) the displacement of the control plate. The initial position of the top end of the excavator was at a height of 10cm below the ground surface.

4. SIMULATION FOR THE MINIATURE EXCAVATOR

The mechanical model in the section 2 was formulated against an actual excavator for the diaphragm wall method. However, necessary information was often lacking in the case of the actual excavator. Hence, the effectivness of the proposed mechanical model will be evaluated by applying it to laboratory miniature excavator tests.

4.1 Application of mechanical model to miniature excavator tests

a) Rotation center O

The rotation center O was determined from the measured data based on the next equation.

$$X = \frac{|y_1| \cdot L}{|y_1| + |y_2|} \tag{15}$$

where X : is the distance from the top center of the excavator to the rotation center, y_1, y_2 : see section 2.5, L : the height of the excavator.

b) Coefficient of subgrade reaction for horizontal direction K_h

In the miniature excavator tests, the load and the displacement of the control plates in the diagonal position were measured during the expansion process of the control plate. This behavior is the same as conventional horizontal plate loading tests. Therefore, the coefficient of subgrade reaction for horizontal direction K_h was determined by this measured stress-displacement curve. K_h was defined by the following equation:

$$K_h = \frac{p_{10}}{S_{10}} \tag{16}$$

where p_{10} is the loading stress against the displacement of the control plate of 10mm, and S_{10} is the displacement of the control plate of 10mm.

In a series of tests in this study, since the wet densities were precisely measured in each test, the relationship between the calculated K_h and the wet densities were evaluated next. The result is shown in Figure 4. It is clearly shown that K_h is well estimated from the wet densities. These relations are represented by the following equation based on the regression analysis.

$$K_h = 0.0134 \times \gamma_t^{9.308} \qquad (r = 0.836) \tag{17}$$

K_h in the simulation analysis was determined by substituting γ_t into this equation.

c) Ultimate bearing capacity p_{max} and reference displacement δ_s

The ultimate bearing capacity p_{max} used in the simulation was defined by the maximum pressure during one full expansion process of the control plate. Moreover, the reference displace-

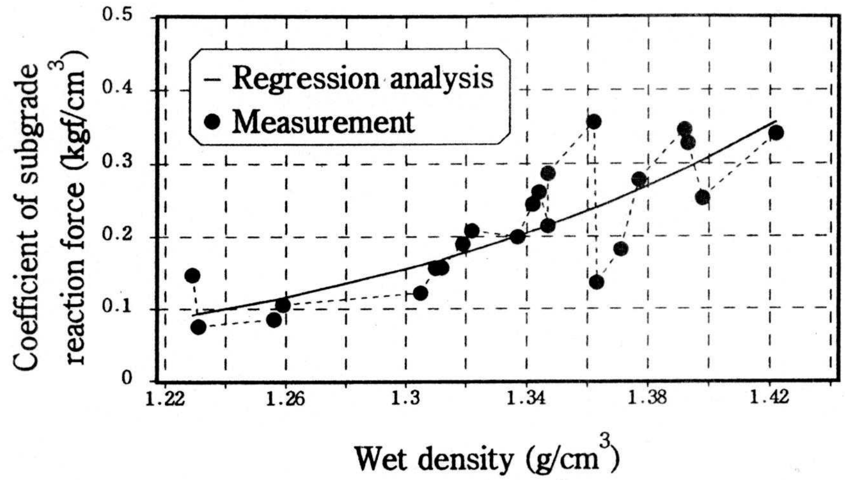

Figure 4 Relationship between coefficient of subgrade reaction force and wet density ($1kgf/cm^3=98N/cm^3$)

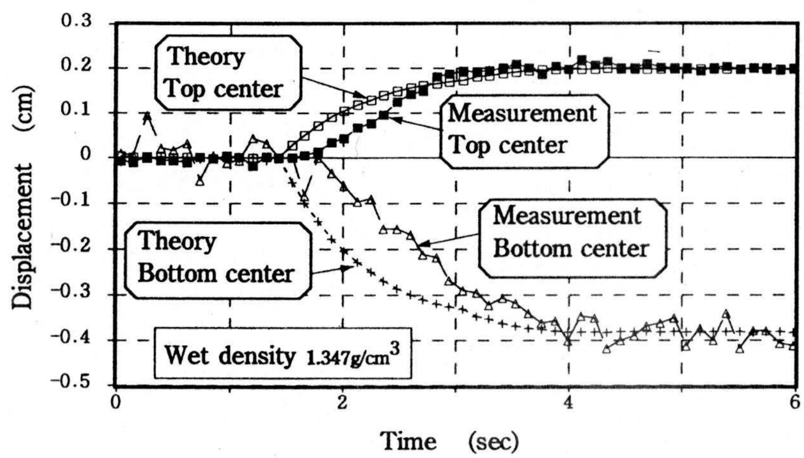

Figure 5 Excavator response -theory and practice-

ment δ_s was determined by the process proposed in section 2.2.

d) Moment M_f caused by frictional force at the front and the back of excavator

Since the experiments were carried out taking care not to yield to the friction between the soil bin and the front and back of the excavator, the moment M_f was judged to be negligible.

4.2 Results and considerations

The displacement of the excavator against one expansion of the control plate could be estimated based on the theoretical equations Eqs.(13), (14). A typical example, which compares the theoretical values with the experimental ones, is shown in Figure 5. This figure shows good correlation between the values. Other cases corresponding to various ground conditions also show good results. The relationship between the theoretical values and the experimental values of the maximum displacement of the top center and bottom center of the

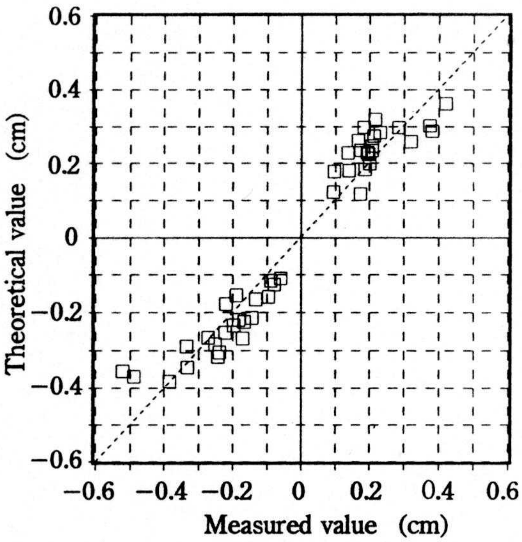

Figure 6 Comparison of displacement at top and bottom center of an excavator -theory and practice-

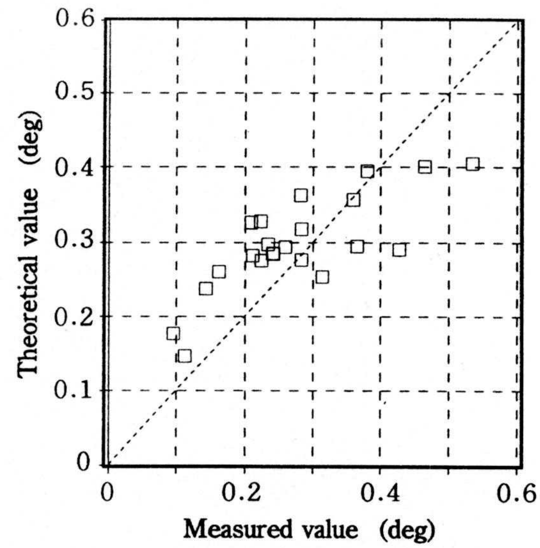

Figure 7 Comparison of inclination angle of an excavator -theory and practice-

excavator is shown in Figure 6. The theoretical values were in good agreement with the experimental ones. Figure 7 also shows the results of comparison between theory and experiment in the maximum inclination angle of the excavator. The inclination angle θ can be calculated from the following equation:

$$\theta = \tan^{-1}\left(\left(y_1 + y_2\right)/L\right)$$

The result shown in Figure 7 also showed good accordance. It was clear that the displacement and the inclination of the excavator could be estimated well by the theoretical equations proposed in the section 2. This will result in the effective application of these theories to the actual positioning control of the excavator.

5. POSITIONING CONTROL METHOD CONSIDERING GROUND PROPERTIES

A new intelligent control method considering ground properties can be proposed based on the results obtained from this study. The procedure of the proposed control method is compiled in Figure 8. The rough procedure is as follows:

i) The initial values of some parameters required in the simulation model are first determined by use of in situ tests or laboratory tests.

ii) After one full expansion of a control plate, the initial values of some parameters would be modified as they express more clearly the ground properties than do the initial values.

iii) The subsequent controlled displacement of the control plate is determined by Eq.(13) based on the modified parameters.

Since the direct evaluation of M_f is very difficult, it should be indirectly considered in the process of the modification of ground deformability. That is, the ground should be evaluated to

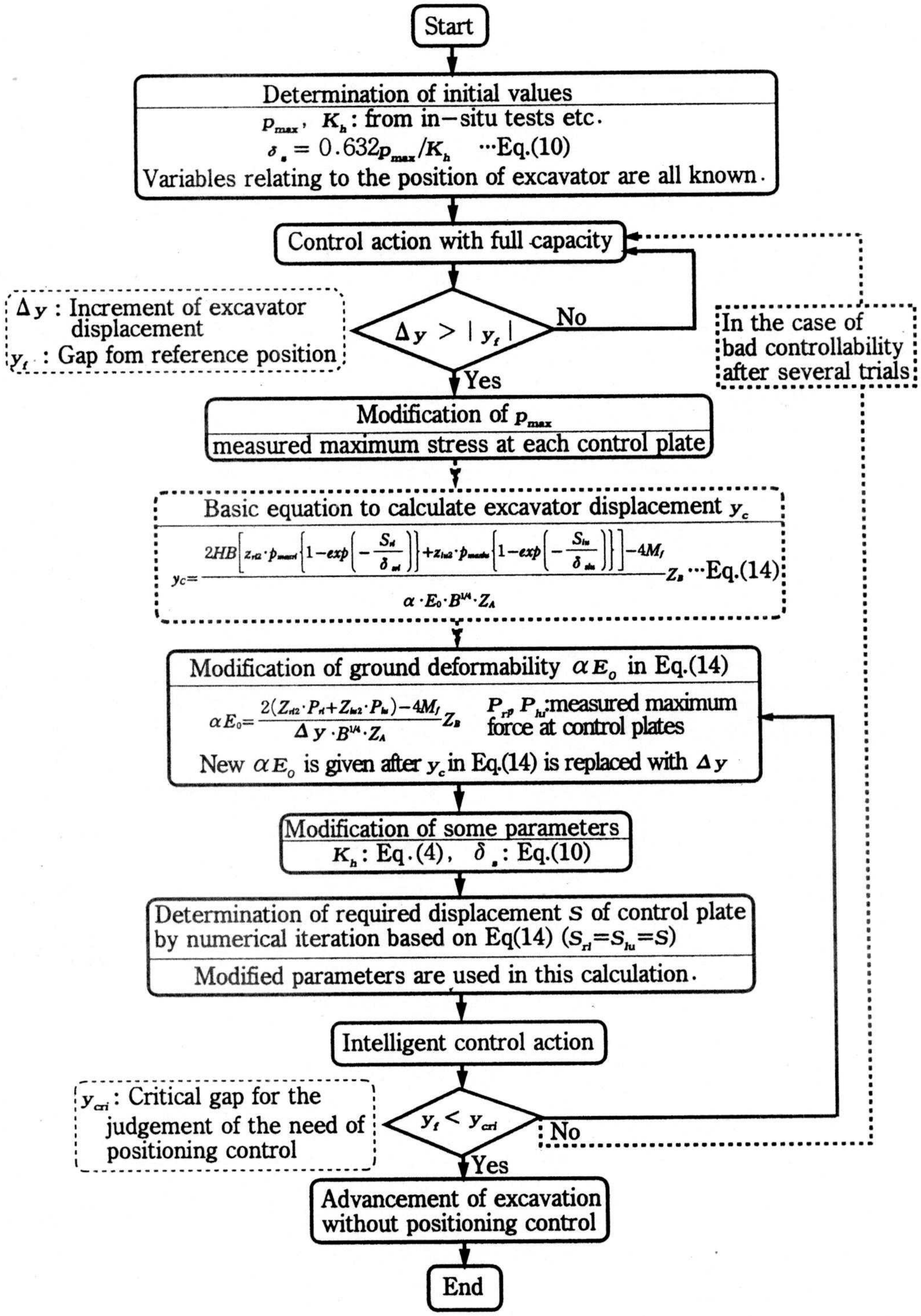

Figure 8 An intelligent control method considering ground properties

be stiffer than as it is, if M_f is not negligible in the ground.

This system would result in the improvement of the convergence and the stability of the excavator around the reference position.

6. CONCLUSIONS

Main conclusions obtained from this study are as follows:

(1) Theoretical equations to estimate the interaction between the control plate action and the corresponding behavior of an excavator were formulated based on the equilibrium condition of moment.

(2) A series of laboratory tests using a miniature excavator were carried out to investigate the effectivness of the proposed mechanical model. The results of simulation showed a good accordance with the experimental results.

(3) A new method of positioning control considering ground properties was proposed.

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