Evaluation of Ground Properties in Deep Soil Improvement Method and Its Application to Construction Automatization

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Abstract

As one of the studies on automatization in the deep soil improvement method, theoretical and experimental studies were carried out to develop a method to estimate soil properties in real-time during construction. In the theoretical study, the resistance acting on the improving machines from the ground was studied with soil cutting theory, and the relationship among the resistance and the ground properties was discussed. The results of the theoretical study were examined through field experiments, and a method was suggested for evaluating the values of the SPT of the ground, the N values, from information on the resistance acting on the machines from the ground. Applications of this soil-estimating method to automatization in the deep soil improvement method were discussed through the determination of the best operating method for the DJM machine according to the soil properties estimated by the suggested method.

1. Introduction

The deep mixing method is a representative method used to improve the deep soft soil in a construction field. Mixing blades attached to a square steel pipe are rotated on the axis of the pipe and are driven into the ground. After the blades reach a firm soil layer, they are pulled out of the ground A chemical agent is then sent down through the pipe with highly compressed air and is injected into the soft soil during either the rotating penetration into or the rotating pull out of the ground. The injected agent is mixed with the soft soil and a chemical reaction between the agent and the water in the ground creates firm columns in the ground.

This method is often used not only in soil stabilization, but also in the construction of various structural foundations. Figures 1 and 2 show the structure of the mixing blades and the dry jet mixing process of this method, respectively .

An evaluation of the ground conditions is an important part of this method. This is not only because the arrival of the blades at the bottom firm soil layer should be judged precisely in order to determine the completion of the penetration, but also because the amount of chemical agent injected through the pipe should be controlled according to the soil properties at each depth in the ground in order to make uniform and improved soil columns.

We have conducted research to develop a method for evaluating the ground properties during construction. At the construction site, the ground properties are often evaluated through the Standard Penetrating Test (SPT). The values of the SPT (the N-values) are the most popular index for evaluating the ground properties in the fields. In this research, therefore, the N values have been applied as the ground properties to be evaluated and a method has been developed to estimate the N values using the data from the mixing torque, which acts on the blades, and the penetrating and mixing conditions of the blade during construction.

In the first approach of our research, fuzzy reasoning was applied to the evaluation process in order to treat the various obscurities both in the ground and in the interaction between the machine and the ground [1]. In the second approach, a theoretical discussion is carried out with the soil cutting theory to study the relationship between the soil properties and the mixing torque, and a method to evaluate the N values is suggested based on the discussion.

2.Theoretical study on the mixing torque

The mixing torque acting on the blades, which is driven into the ground while rotating is thought to be caused by the soil cutting resistance. The soil cutting theory was employed to study the phenomenon in which the torque is induced during the mixing process, as follows:

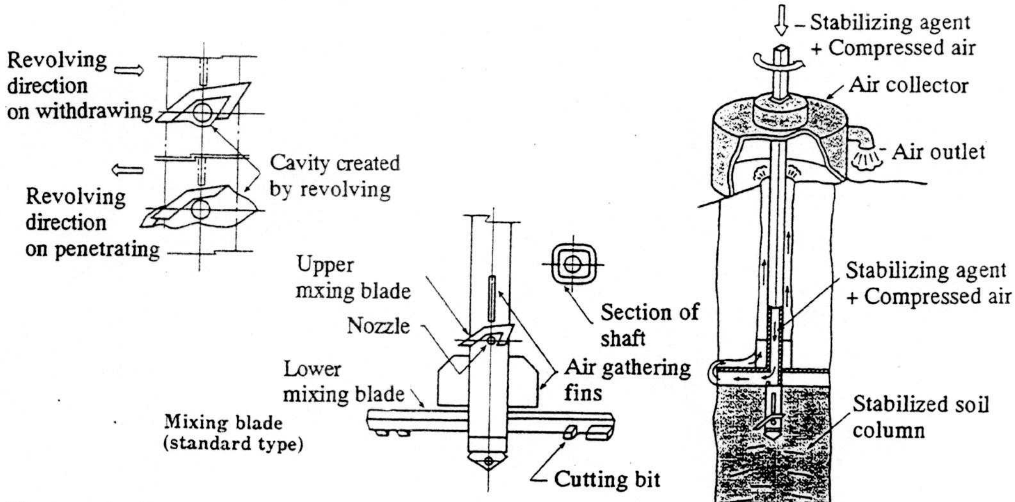


Figure 1 Structure of the mixing blades

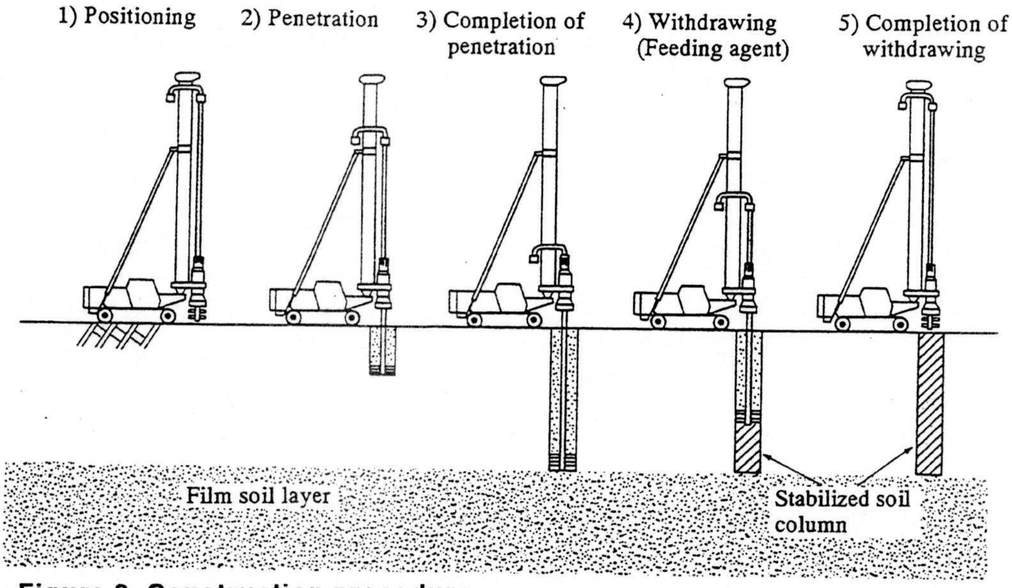


Figure 2 Construction procedure for the deep mixing method

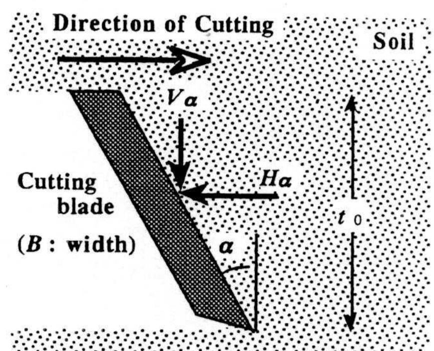


Figure 3 A sketch of the stationary-depth cutting

a) Stationary-depth soil cutting

Figure 3 gives a sketch of the cutting blade which cuts the soil horizontally in the ground (stationary-depth cutting). Hata [2] suggested an empirical relation for the horizontal component of cutting resistance H_α (N) by the following equation (1), where t_0, B and α denote the height (m), the width (m) and the rake angle of the cutting blade (deg), respectively, as

$$H_\alpha = 1.82\, B t_0^2 R_S 10^{-m\alpha} \quad (1)$$

where R_S is the specific cutting resistance which expresses the strength of the soil against the cutting. The way to measure it will be explained later. m denotes the experimental constant and has been obtained as 7.85×10^{-3} for sandy soil and 3.84×10^{-3} for clay.

b) Changeable-depth soil cutting

When the cutting blades penetrate into the ground during the cutting process, as shown in Figure 4 (changeable-depth cutting), the penetrating resistance acts on the tip of the blades from the soil. The cutting resistance, in the case of the changeable-depth soil cutting, can be shown by the sum of the stationary-depth cutting resistance H_α, expressed by equation (1), and the following resistance H_p, due to penetration of the blades into the ground [2], namely,

$$H_p = Bbt\frac{dt}{dx}\tan\delta \qquad (2)$$

where b is the penetrating coefficient (N/m^2) which depends on the specific cutting resistance, R_S, and the rake angles of the blades, α. [3]. t is the depth of the blade tip from the ground surface, dt/dx is the inclination of the track which the tips of the blades pass in the ground (x : the horizontal distance) and δ is the friction angle between the blades and the soil.

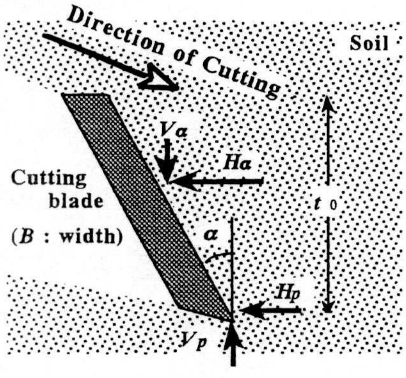


Figure 4 A sketch of the changeable-depth cutting

c) Calculation of the mixing torque

In the deep mixing method, the blades are rotated on the axis of the pipe and are driven into the ground during the mixing process. Thus, the above-mentioned cutting resistance acts on the blades and the pipe attached by the blades is required to generate the rotating torque for mixing. Figure 5 shows the mixing blades attached to the square pipe. The mixing torque which acts on the blades can be calculated by integrating the momentum of the cutting resistance around the axis of the pipe, provided that the cutting resistance is treated as the sum of the stationary-depth resistance and the changeable-depth cutting resistance expressed by equations (1) and (2), respectively.

When the mixing blades are driven into the ground with vertical penetrating speed v (m/sec) and rotational frequency f (number/sec), mixing torque T (Nm) induced by stationary-depth cutting resistance T_c (Nm) and changeable-depth cutting one T_p (Nm) are expressed respectively by the following equations (3):

$$T = T_c + T_p \qquad (3)$$

$$T_c = 4\int_{r_1}^{r_2} 1.82 R_s\left\{(l_1\cos\alpha_1)^2 10^{-m\alpha_1} + (l_2\cos\alpha_2)^2 10^{-m\alpha_2}\right\} r\,dr$$

$$= 3.64\, R_s(r_2^2 - r_1^2)\left\{(l_1\cos\alpha_1)^2 10^{-m\alpha_1} + (l_2\cos\alpha_2)^2 10^{-m\alpha_2}\right\}$$

$$T_p = 4\int_{r_1}^{r_2} b\,t\frac{v}{2\pi f}\tan\delta\, dr = \frac{2b}{\pi}\,t\,\frac{v}{f}\tan\delta\,(r_2 - r_1)$$

where r is the coordinate of a point on each blade measured from the rotating axis, and r_1, r_2, l_1, l_2, α_1 and α_2 are the length and the rake angles concerning the shape of the blades (in Figure 5).

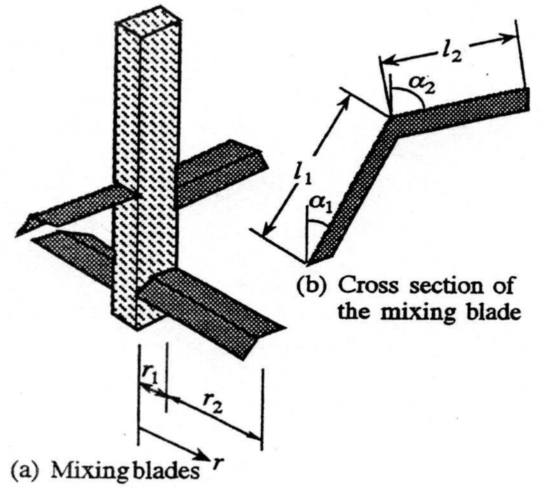


Figure 5 A sketch of the mixing blades attached to the pipe

d) Soil properties

In this paper, the soil properties are represented by specific cutting resistance R_S which expresses the strength of the soil against the cutting. Figure 6 shows a sketch of the in-situ test to measure specific cutting resistance R_S. To carry out the test, a b_{RS} (m) wide plate is driven into the ground to a depth of x_{RS} (m) and a lateral support is installed to provide a fixed point of rotation on the ground surface. The top of the plate is then pulled until failure occurs at force p (N). Index R_S (N/m^3), known as the specific cutting resistance, is then given by the following relationship [2]:

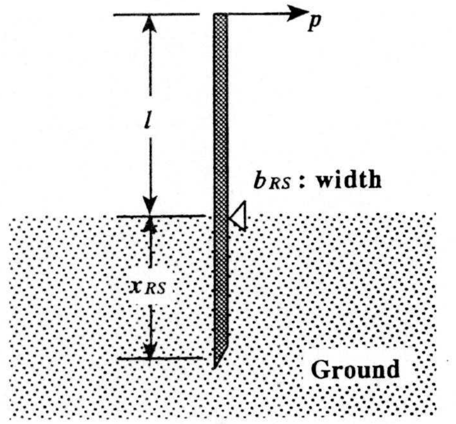


Figure 6 A method for determinating the specific cutting resistance R_s

$$R_s = \frac{p\,l}{b_{RS}\,x_{RS}^3} \,. \tag{4}$$

The relationship between specific cutting resistance R_s and the soil parameters for strengths c and ϕ (c : cohesion (N/m²), ϕ : internal friction (deg)) was discussed, and the following relation has been obtained through a theoretical study [4]:

$$R_s = \pi\left(\frac{1}{3b_{RS}} + \frac{1}{2x_{RS}}\right)(c + p(z,\phi)\tan\phi) \tag{5}$$

where $p(z,\phi)$ is the earth pressure which acts on the blades in the ground. It can be expressed as a function of the depth in the ground and the strength parameters of soil ϕ [5]. The N values are related to the strength of the soil; and thus, the relationship between the N values and soil parameters c and ϕ has been discussed to propose their various relations. The following relations are applied to express the relation for sand and clay in this paper [6]:

sand : $\phi = \sqrt{20N} + 15$ (6)

clay : $c = N/4$ (kg/cm²) $= 2.45\,N \times 10^4$ (N/m²) . (7)

The relationship between cutting resistance R_s and the N values can be discussed through intermediate of soil parameters c and ϕ with equations (5), (6) and (7).

e) Relationship between the N values and the mixing torque

The relationship between the N-values of the ground and the mixing torque can be obtained by combining the series of equations from (3) to (7).

3. Calculation of the relationship between the N values and the mixing torque

The relationship between the N values and the mixing torque in the DJM method was discussed using the calculation of the above mentioned process. The parameters employed in the calculation were determined by referring to a real construction machine and the following popular values for ground properties:

$r_2 = 0.05$ m $r_1 = 0.5$ m $\alpha_1 = 50$ deg $\alpha_2 = 80$ deg
$l_1 = 0.15$ m $l_2 = 0.15$ m $B = 1.0$ m
$\delta = 25$ deg (sand) $\delta = 6$ deg (clay)
$v = 0.2, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0$ m/min
$f = 40$ number/min.

Figures 7 and 8 show the results of the calculation for sand and for clay, respectively. It is clear from these figures that the mixing torque increases both with the N value and the penetrating speed. The results of the calculation bring about the derivation of the following equation for the general relation of the mixing torque and the N values of the ground and for the effect of the penetrating speed to the relation:

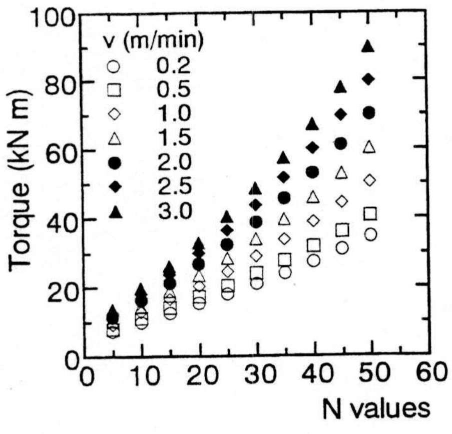


Figure 7 Results of the calculation of the relationship between the torque and the N values for sand

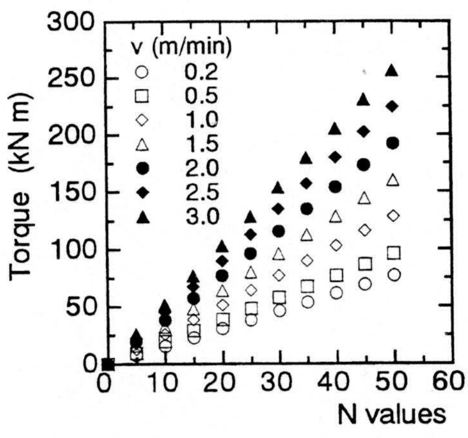


Figure 8 Results of the calculation of the relationship between the torque and the N values for clay

$$T = a(v + b)(N + c) + d \qquad (8)$$

where a, b, c and d are constants determined by the soil type and the size of the machines.

Figure 9 shows an example of the records for the N-values of the ground, the penetrating speed and the mixing torque that have been measured at the construction site. The same measurements were carried out at 18 points in the six fields and their records are arranged in Figure 10 as the relation of the N values and the mixing torque with the parameter of the penetrating speed. Although the mixing torque increases with the N values, their relationship depends on the type of soil and the penetrating speed in this figure.

The data plotted in Figure 10 were studied individually for each type of soil and the penetrating speed by referring to equation (8). The following relations were obtain for sand and clay:

$$\text{sand} \;:\; T = 401\,(v + 2.0)\,(N + 0.56) + 1417 \qquad (9)$$

$$\text{clay} \;:\; T = 1200\,(v + 2.0)\,N + 2000 \qquad (10)$$

The N values of the ground can be estimated in real time by measuring the mixing torque and the penetrating speed at the construction site with equations (9) and (10). Figure 11 shows the results of the estimation where the N values estimated by this method are plotted against the measured ones at the construction site.

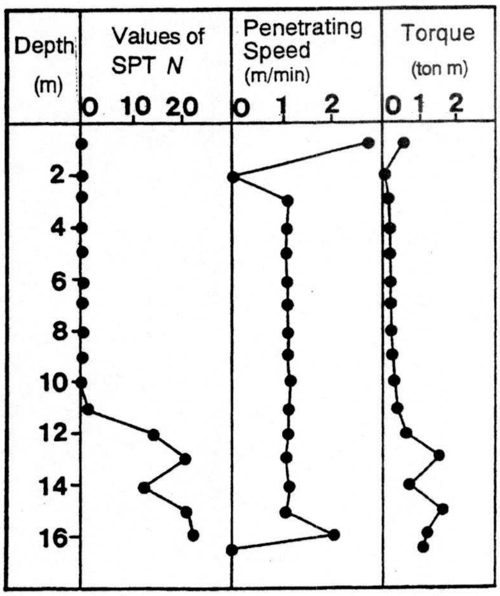


Figure 9 An example of the data measured in the field experiments

Although some dispersion appears in the figure, the estimated N values are close to the measured ones. It may be concluded from this figure that the N values of the ground can be evaluated during the DJM construction by the method suggested in this paper, that is, the ground properties can be monitored in real time at the construction site.

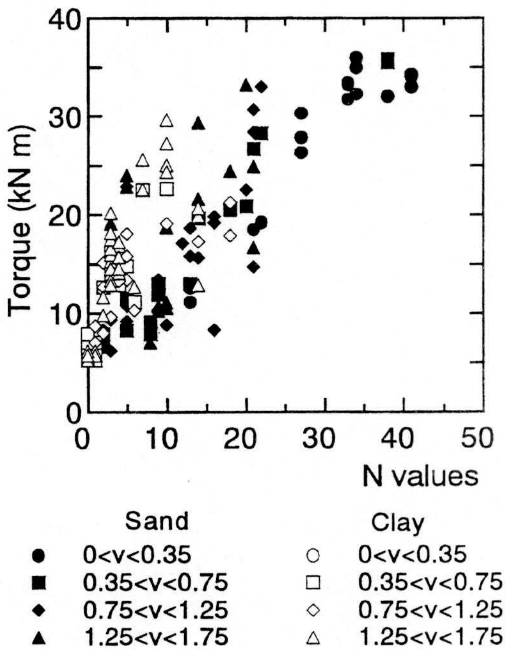


Figure 10 The results of the field experiments

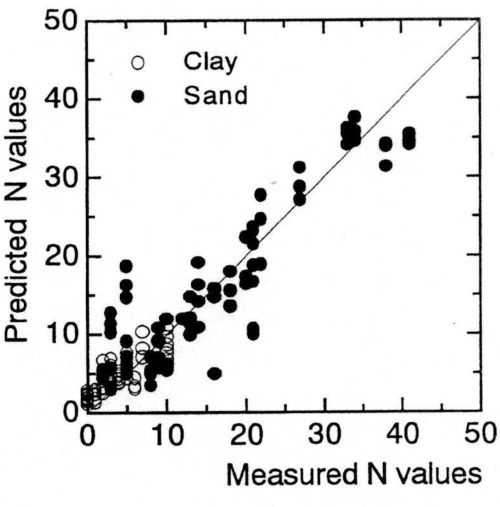


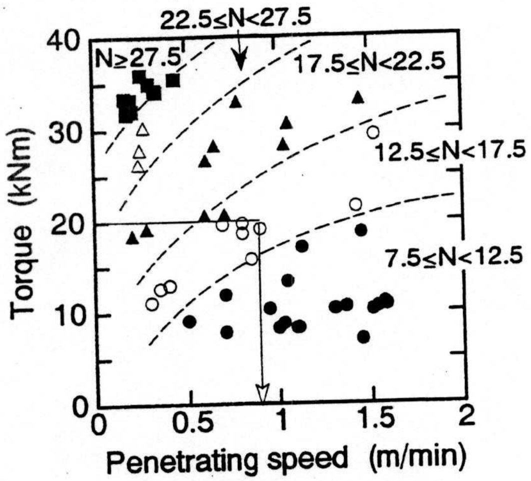
Figure 11 Comparison of the measured N values and the predicted ones

4. Application of the ground monitoring system to construction

It is possible to effectively apply the ground evaluation method suggested in this paper to the construction. The first application is the confirmation of the arrival of the blades at the bottom firm soil layer. Judging the time of the blades' arrival at the bearing stratum is an important function of the mixing machine because this judgment of the completion of the penetration affects the efficiency of the construction. The ground evaluation method suggested here is expected to be used effectively for such judgments and to contribute to the rationalization of construction.

The second application is the adjustment of the amount of chemical agent injected into the ground. The amount of chemical agent should be adjusted according to the properties of the soil at each depth in the ground in order to make improved and uniform soil columns. The N values at each depth in the ground will be evaluated with the suggested method, and the amount of chemical agent will be adjusted according to the evaluated ground properties.

The third application is the adjustment of the operating method for the mixing machine. The machine's operating method should be changed according to the ground properties in order to attain maximum efficiency in the construction.



●	7.5≤N<12.5	△	22.5≤N<27.5
○	12.5≤N<17.5	■	27.5≤N
▲	17.5≤N<22.5		

Figure 12 The results of the field experiments on the relationship between the torque and the penetrating speed

Data on the machine loads and the N values, measured at the above mentioned construction site, are arranged in Figure 12, where the torque is plotted against the penetrating speed with the parameters of the N values. The lines in the figure express the boundaries of the plotted data for each range of N values.

The optimum penetrating speed of the blades can be determined by limiting the torque, specified for each mixing machine, and by data on the N values evaluated by the suggested method. The method is shown in the figure with an arrow for determining the optimum penetrating speed for a case where the maximum torque of the machine is 20 kNm and the N value $N = 15$ is obtained by the suggested method. The feedback from the evaluated N values to the determination of the operation of the mixing machine is expected to contribute to the automatization of the construction.

5. Conclusions

The soil cutting theory is applied to create a method with which ground properties can be evaluated in DJM construction. We concluded that the N values can be evaluated during DJM construction by the method which is discussed in this paper. We expect this method to contribute to the construction of high-quality stabilized columns under the ground as a real-time construction control system because the construction conditions will be adjusted according to the soil properties monitored through this method during the construction process.

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6. References

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