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

THE EVALUATION OF GROUND PROPERTIES AND ITS APPLICATION TO THE AUTOMATIC CONTROL OF VIBRATORY SOIL COMPACTORS

Kazuyoshi TATEYAMA[a], Satoshi NAKAJIMA[b], Tetsuo FUJIYAMA[c]

[a] Department of Civil Engineering, Faculty of Engineering, Kyoto University, Sakyo, Kyoto 606-01, JAPAN
[b] The Technical Institute of Hazama Corporation, Karima, Tsukuba 305, JAPAN
[c] Department of Civil Engineering, Faculty of Engineering, Kyoto University, Sakyo, Kyoto 606-01, JAPAN

Abstract

A ground-evaluating method was suggested which makes use of the behaviour of an exciter that vibrates on the ground. Numerical simulations were carried out to investigate the relationship among the vibrating behaviour of the exciter, the ground stiffness and the vibrating conditions of the exciter. A method that evaluates the ground stiffness with the vibrating behaviour of any exciter was derived from the results of the numerical simulations. The applicability of this method was examined by field experiments and its application to the automatic control of a vibratory soil compactor was discussed.

1. INTRODUCTION

Operators of construction machines which treat geotechnical materials, such as soil, gravel, rock and so on, as their working media usually evaluate the ground conditions and determine the most suitable operating method for the machine, considering the ground conditions. When construction robots are employed on construction sites, they should evaluate the ground conditions and then determine the best method for self-control according to those ground conditions. The evaluation of ground conditions and the application of the results of the evaluation used for controlling the machine are expected to become two of the most important functions that construction robots possess in the future. We have carried out research On the ground-evaluating system and the automatic control of construction machinery, according to the evaluated ground conditions, for various types of construction. In this paper, we present a ground-evaluating system in the field of vibratory soil compaction.

In the construction of roads dams, airports and other structures which are built using the geotechnical materials such as soil, gravel and rock, the materials should be consolidated, in order to built stable structures. A vibratory compactor is the most typical soil compactor and can compact soil with a cyclic force generated by an exciter. An exciter is a mechanical device which generates a cyclic force by synchronized counter-rotating weights, as shown in Figure 1.

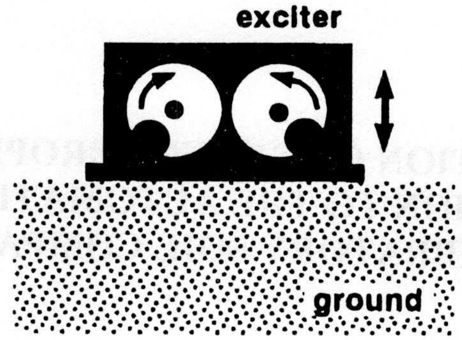


Figure 1. An Exciter Vibrating on the Ground

When the exciter vibrates on the ground, its vibrating behaviour varies with certain properties of the ground. Making use of this phenomenon, on the ground properties can be evaluated by measuring the vibrating behaviour of the exciter.

The concept of this ground-evaluating method has already been employed in field compaction with a vibratory compactor [1]. However, its vibrating behaviour varies not only with the ground properties, but also with the mechanical parameters of the exciter, such as frequency, weight, etc,. Thus, the influence of these mechanical parameters must be eliminated in order to make this ground-evaluating system useful.

In this paper, a numerical simulation was carried out to study a) the relationship between ground properties and the behaviour of an exciter, and b) the influence of the mechanical parameters of the exciter. We tried to develop a method which could evaluate the ground conditions by making use of the behaviour of an exciter, and discussed its application to the automatic control of vibratory soil compactors.

2. NUMERICAL SIMULATION

In the simulation, the ground is replaced by a Voigt model composed of a spring and a dashpot, and the exciter is expected to vibrate on the modeled ground by a cyclic dynamic force, as shown in Figure 2.

Equation (1) expresses the equation of motion for an exciter-ground system.

$$my + cy + ky = mg + F_0 sin(2\pi f_0\, t) \qquad (1)$$

where

m : mass of the exciter (kg)

F_0 : maximum dynamic force (N)

f_0 : operating frequency (Hz)

k : spring constant of the ground (N/m)

c : damping coefficient of the ground (Nsec/m)

y : displacement of the exciter measured from the original ground surface before the exciter is set on (m)

t : time (sec)

g : acceleration of gravity (m/sec2)

A dot · added over the character y indicates a differentiation with respect to time.

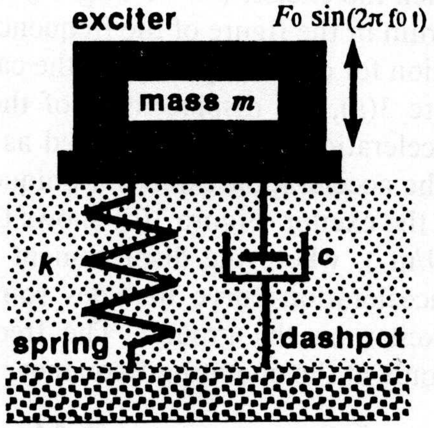


Figure 2. Simulation Model for the Exciter-ground System.

The exciter jumps up from the ground surface at certain time in the vibrating process under certain conditions of vibration. In the simulation, the spring constant and the damping coefficient are both set to zero in the calculation process just when the exciter is assumed to be lifted off the ground surface. A time series for displacement y and acceleration y of the vibrating exciter is calculated by solving equation (1) with the finite difference method. The obtained acceleration curve of the exciter is translated into the frequency characteristics with the frequency analysis method in order to make a quantitative evaluation of the vibrating behaviour.

Table 1 shows the parameters of the exciter used in the calculation, which represent various sizes of exciters, from a small model exciter for laboratory experiments to a large sized exciter used in field construction. The values for ground stiffness k represent various degrees of ground stiffness, from a soft-compacted to a stiff-compacted ground, referring to the results of the plate-loading tests carried out in construction fields. The values for damping coefficient c are determined from each value of ground stiffness k and mass of the exciter m by the following equation [2]:

$$c = 2\,D\,\sqrt{m\,k} \quad \cdots\cdots(2)$$

where D is the damping ratio of the ground. Referring to research by Richart, F.E. etc.[2] on the vibrating behaviour of certain structure foundations, $D = 0.4$ in this paper.

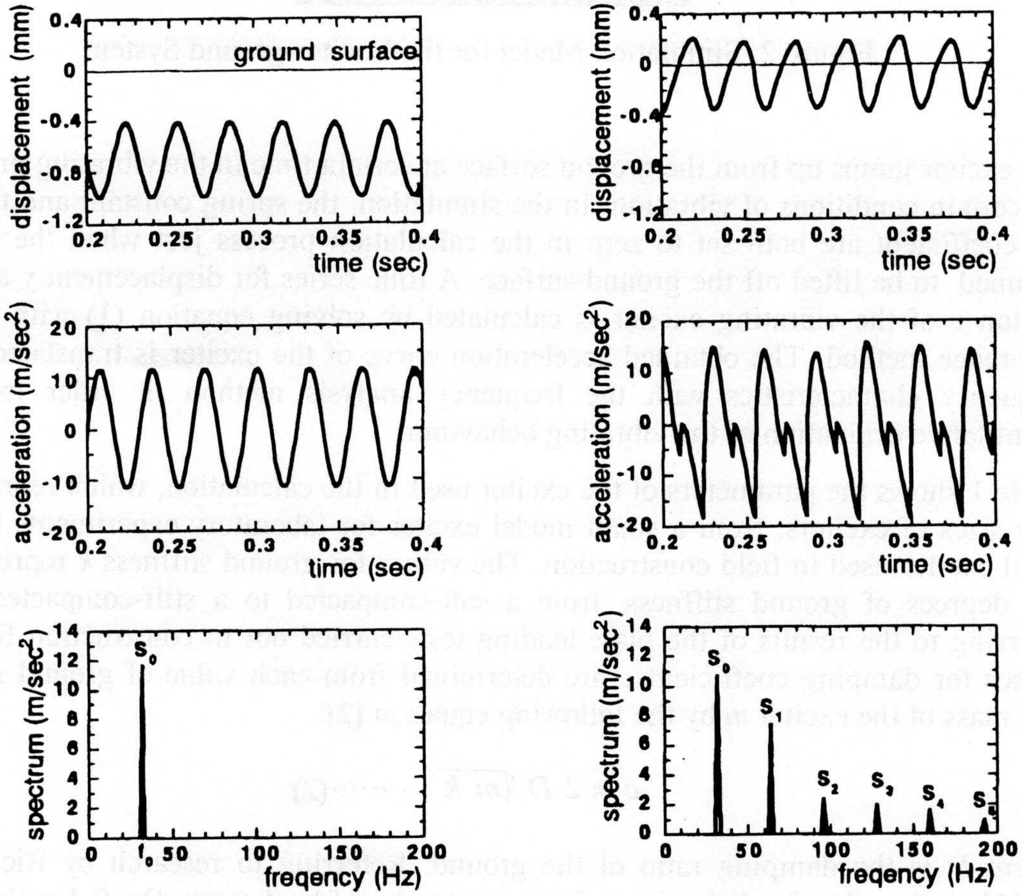
Table 1. Parameters of the numerical simulation

Table 1 Parameters of the numerical simulation

mass of exciter	m	(kg)	20	200	2000	20000	
maximum dynamic force	F_0	(N)	mg	$2mg$	$3mg$		
operating frequency	f_0	(Hz)	12	20	32	40	48

3. RESULTS OF THE NUMERICAL SIMULATION

Figure 3 shows the calculated results for displacement, acceleration and frequency characteristics for a case in which the exciter (m =20 kg, F_0=196 N, f_0= 32 Hz) vibrates on two types of ground. Spectrum in the figure of the frequency characteristics expresses the component of the acceleration for each frequency. In the case of a soft ground (k = 2.8 X 105 N/m), shown in Figure 3(a), the displacement of the exciter does not lift off the ground surface and the acceleration curve is displayed as a simple sine curve. The frequency characteristics of the acceleration express a unique spectrum component only at the operating frequency of the exciter. Figure 3(b) shows the calculated results for a stiff ground (k = 1.7 X 106 N/m), where the displacement of the exciter goes above the ground surface and the acceleration curve includes some disturbance induced by an impact of the jumping exciter on the ground. The frequency characteristics express spectrum components not only at the operating frequency, but also at other frequencies.



(a) k =2.8 X 10^5 N/m

(b) k =1.7 X 10^6 N/m

Figure 3. Calculated behaviour of the vibrating exciter

A specific value for spectrum disturbance, SD, is introduced, shown by equation (3), to quantitatively express the disturbance of the acceleration curve, namely,

$$SD = \frac{\textit{sum of the spectrum for frequencies other than the operating one}}{\textit{spectrum for operating frequency of the exciter}} = \frac{\sum_{i=1}^{n} S_i}{S_0} \text{.........} \quad (3)$$

The large value for *SD* expresses the greatly-disturbed acceleration curve.

Figure 4 shows the results of the numerical simulation in which the relationship between the spectrum disturbance and the spring constant are expressed for various combinations of mechanical parameters m, f_0 and F_0.

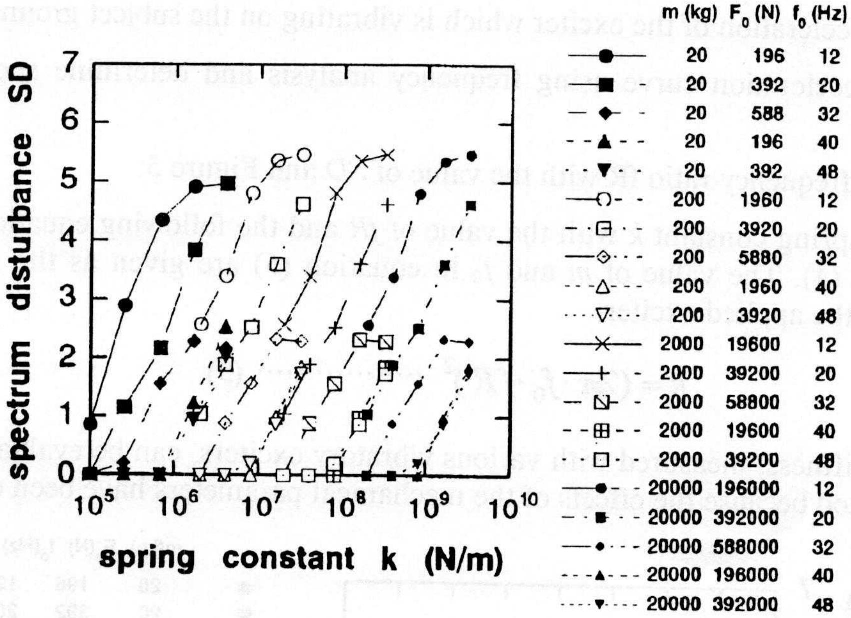


Figure 4. Spectrum Disturbance vs. Spring Constant for Various Combinations of Mechanical Parameters.

This figure shows that the spectrum disturbance increases with the spring constant of the ground for each combination of mechanical parameters, but its relation is much affected by the combination of mechanical parameters. It is understood from this fact that the spring constant, that is, the ground properties cannot be uniquely specified from the value of the spectrum ratio and that in cases where this method is applied to field measurements, a specified curve which is suitable for each combination of mechanical parameters must be prepared before the measurement. Considering that various types and sizes of vibratory compactor exist for use on construction sites, however, the application of this method to field measurements is considered to be insufficient because the specified curves should be prepared for each vibratory compactor when this method is applied to field compaction.

We introduce the following index, frequency ratio *fR*, to eliminating the influence of the mechanical parameters of the exciter. The frequency ratio *fR* is a dimensionless number and can be expressed by the relative position of the resonant frequency of the exciter ground system f_r to the operating frequency of the exciter f_0 :

$$fR = \frac{f_r}{f_0} = \frac{1}{2\pi f_0}\sqrt{\frac{k}{m}} \quad \text{..............(4)}$$

The value of ground stiffness is included by a form of a square root in the frequency ratio *fR* .

Figure 5 shows the results of a rearrangement of Figure 4, which is obtained by replacing spring constant *k* of the horizontal axis to frequency ratio *fR*. It becomes clear from this figure that spectrum disturbance *SD* is uniquely specified by the value of frequency ratio *fR* for various conditions of the exciter.

Using this figure, the stiffness of the ground can be evaluated by the following process:

(1) Measure acceleration of the exciter which is vibrating on the subject ground;

(2) Plot the acceleration curve using frequency analysis and determine spectrum disturbance *SD*:

(3) Determine frequency ratio fR with the value of *SD* and Figure 5;

(4) Calculate spring constant *k* with the value of *fR* and the following equation obtained from equation (4). The value of *m* and f_O in equation (5) are given as the mechanical parameters of the applied exciter:

$$k = (2\pi \cdot f_0 \cdot fR)^2 \quad \cdots\cdots\cdots\cdots\cdots \quad (5)$$

The ground stiffness, measured with various vibratory exciters, can be evaluated directly with this method because the effects of the mechanical parameters have been eliminated.

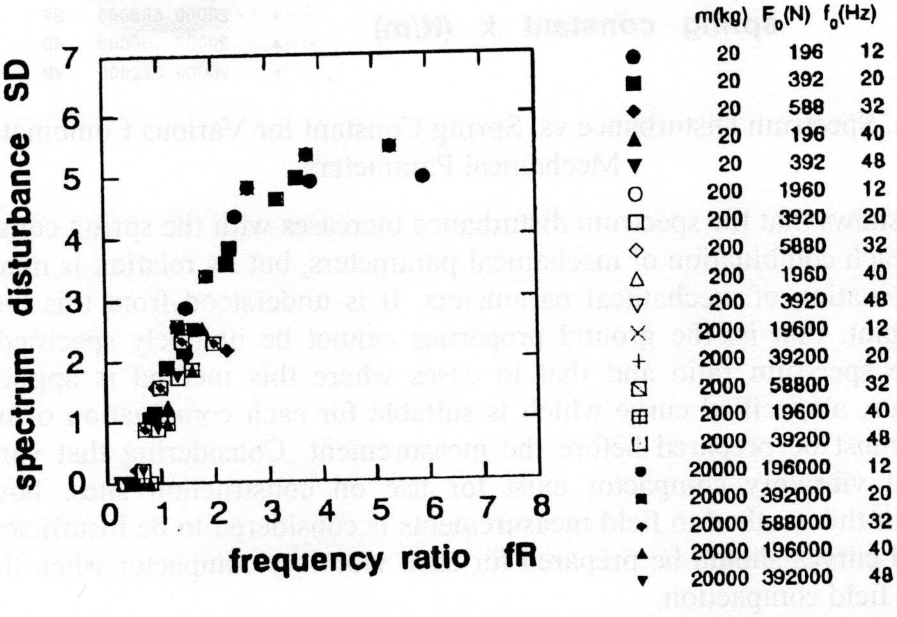


Figure 5. Results of the arrangements in Figure 4 with the frequency ratio *fR*

4. VERIFICATION BY FIELD EXPERIMENTS

Field experiments were carried out to examine the application of the above method. The exciter used in the experiments is of a large size and is one that is generally employed for soil compaction in the construction of dams, roads, or other embankments. The mass and other mechanical parameters of this exciter are m = 20,000 kg, F_O =460,000 N, f_O = 10 Hz. The exciter was tested on site and its acceleration was measured with an accelerometer. The measured acceleration curve was processed with an FFT analyzer and the spectrum disturbance was obtained from the output of an FFT analyzer. The ground stiffness *K*- values are specified using the obtained values of spectrum disturbance *SD* by the above mentioned method. The *K*-value is equivalent to the spring constant in calculation.

The plate loading tests were carried out to measure the real stiffness of the same ground in the test field. This test is a typical representative of in-situ tests, to measure the ground stiffness *K*-value. In the test, a steel plate put on the ground is loaded and the settlement of the plate is measured. The ground stiffness *K*-value is determined from the inclination of the load-settlement line in the elastic domain of the relation. The ground stiffness *K*- value generally depends on the loading area. The loading area of the exciter used in the field test is a rectangle of 2 m x 3 m and that of the plate-loading test is a round shape of 0.3 m diameter. The *K*-values measured by the plate-loading test were converted to the values of the exciter-loading by considering the difference of the area in both methods.

Figure 6 shows the results of the experiment, where the values for the ground stiffness measured by the plate-loading test are plotted against those evaluated from the exciter vibration. Although the values of ground stiffness measured by the plate-loading test correlate with those predicted from the behaviour of the exciter, the former is larger than the latter. It seems that the discrepancy was caused by the difference in the domain under the ground for which the ground stiffness was evaluated in each method. Namely, the exciter used in the field test had larger loading area than that in the plate-loading test, as mentioned above, and thus the stiffness of the deeper layer under the ground level is thought to be evaluated in the exciter method than in the plate-loading test. The stiffness in deep part of the compacted ground is generally smaller than that in shallow part in the construction field . The plate-loading test in which the same size of plate were employed as that of the exciter method would give closer values of the ground stiffness.

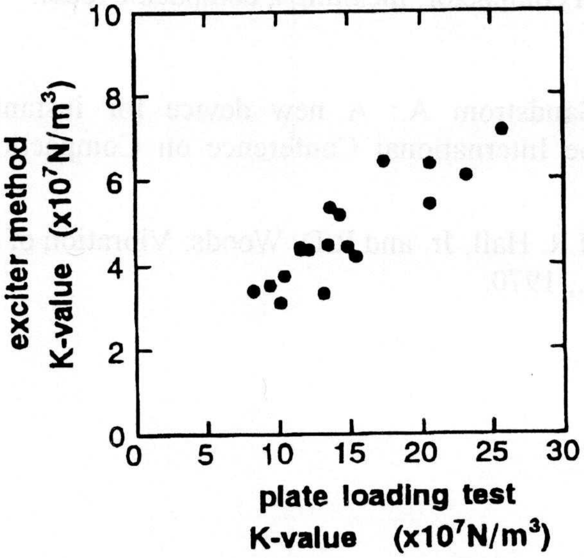


Figure 6. Comparison of the *K*-values measured by the plate-loading tests with those predicted from the exciter method

5. APPLICATION TO AUTOMATIC CONTROL OF VIBRATORY SOIL COMPACTION

Two topics can be discussed as applications of the ground-evaluating system to the automatization in soil compaction. The first one is an application to a real-time and automatic ground-evaluating system. Vibratory compactors equipped with this ground evaluating system can measure the degree of soil compaction in construction fields. Thus, the compactors will be able to find the areas in a field where the soil has been insufficiently compacted and give additional compaction to those areas.

The second application is an automatic adjustment of the vibratory condition of a compactor according to the evaluated ground conditions. The vibrating behaviour of a compactor is greatly affected by the ground conditions and the compacting effect, which the compactor supplies to the ground, also depends on it. The vibrating condition of the compactor needs to be adjusted according to the ground conditions in order to generate a maximum compacting effect. We have studied the relationship among the compacting effect of a vibratory roller, its vibratory and ground conditions, and have obtained some information on the optimum vibrating conditions suitable for the ground conditions. The application of the ground-evaluating system to the automatic adjustment of the vibrating conditions of compactor will be reported separately.

6. CONCLUSIONS

A ground-evaluating method in the field of vibratory soil compaction was discussed, making use of the behaviour of an exciter through some numerical simulations. A method for evaluating the ground stiffness from the vibrating behaviour of the exciter is suggested, using the results of the simulations. Field experiments were carried out with a large-sized vibratory compactor and the application of this method was verified, although there is a separate problem of measuring the base layer under the ground. The method suggested in this paper can be used effectively in the future when it is applied to an automatic controlled compactor, meaning a compactor robot.

REFERENCES

[1] Thurner H. et Sandstrom A.: A new device for instant compaction control, Proceedings of the International Conference on Compaction, Vol.2, pp.611-612, 1980.

[2] F.E. Richart, Jr., J.R. Hall, Jr. and R.D. Woods: Vibration of Soils and Foundations, Prentice-Hall, Inc., 1970.