Evaluation of Ground Properties and its Application to the Automatic Adjustment System for Vibrating Conditions in Vibratory Soil Compaction

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ABSTRACT

The compacting effect which a vibrating compactor has on the ground is greatly affected by its mechanical factors such as weight, frequency and dynamic force. In this paper, we study the relationship among the mechanical factors of a vibrating compactor, the ground conditions and the compacting effect of a compactor on the ground through a numerical simulation. The simulation made it clear that there exists an optimum frequency at which the compactor can generate its maximum compacting effect for the ground and that the optimum frequency is proportional to the ratio of the ground stiffness to the weight of the compactor. Based on the results of the simulation, we suggest a method to determine the optimum frequency for the ground. We also discuss the possibility of developing an automatic adjustment system by which the ground conditions can be evaluated, using the vibrating behavior of the compactor, and the vibrating conditions can then be adjusted according to the evaluated ground conditions.

1. INTRODUCTION

Operators of construction machinery which treat geotechnical materials (such as soil, gravel, rock and so on) as their working objects, generally evaluate the ground conditions and determine the most suitable operating method for the machinery, considering the ground conditions. When construction robots do the same job in construction fields, they should be able to evaluate the ground conditions and then determine the best method for controlling themselves according to those ground conditions. The evaluation of ground conditions and the application of the results, used for controlling the machines 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 and its application to the automatic adjustment system for the vibrating conditions of compactors.

In the construction of roads, dams, airports and other structures which are built with geotechnical materials such as soil, gravel and rock, the materials should be densified by compactors in order to build stable structures. A vibratory compactor is representative of soil compactors 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.

The compacting effect which a vibrating compactor has on the ground is thought to depend not only on the ground conditions, but also on the mechanical factors of the compactor such as its frequency, dynamic force and weight. In this paper, we study the relationship among the mechanical factors of a vibrating compactor, the ground conditions, and the compacting effect that the compactor has on the ground through a numerical simulation. Based on the results of the simulation, we suggest a method to determine the vibrating conditions suitable for the ground, and we discuss the possibility of developing an automatic adjustment system by which ground conditions can be evaluated by the vibrating behavior of the compactor and the vibrating conditions can be adjusted according to the evaluated ground conditions.

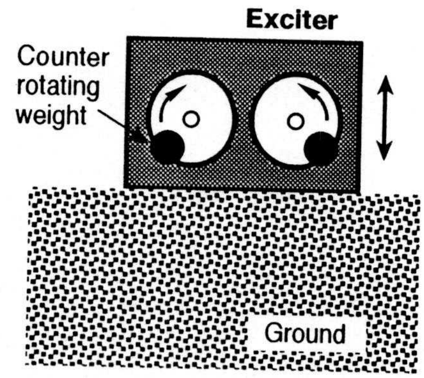

Figure 1 An exciter vibrating on the ground

2. NUMERICAL SIMULATION

In the simulation, the ground is replaced by a Voigt model composed of a spring and a dash pot. The exciter is supposed 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, as shown in Figure 2.

$$m\ddot{y} + c\dot{y} + ky = mg + F\ \sin(2\pi f_0\, t) \cdots\cdots (1)$$

in which

m : mass of the exciter (kg)
F : 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/sec^2)

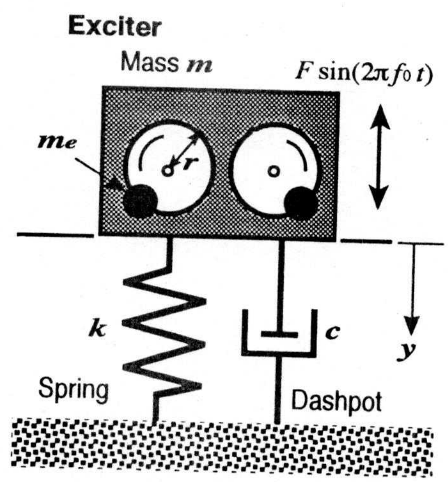

Figure 2 Simulation model for the exciter -ground system

A dot · added over the character y indicates a differentiation with respect to time. The spring constant corresponds to the ground stiffness and the damping coefficient contributes to the attenuation of the vibration. Dynamic force F depends on frequency f_0 and eccentric momentum $m_e r$, and can be determined by the following equation:

$$F = (2\pi f_0)^2\, m_e\, r \cdots\cdots (2)$$

where

m_e : the mass of the counter rotating weight (kg)

r : the radius of the rotation of the counter weight (m)

The exciter jumps up from the ground surface at a certain time during the vibrating process under certain conditions of vibration. In the simulation, the spring constant and the damping coefficient are both set at zero in the calculation process just when the exciter is judged to be lifting off the ground. A time series for displacement y and acceleration $\ddot{y}$ of the vibrating exciter is calculated by solving equation (1) with the finite difference method.

The compacting effect which an exciter has on the ground can be evaluated by the contact force generated between the exciter and the ground. This is because it induces the propagation of stress in the ground, which plays a major role in soil compaction. A large contact force is expected to be generated when the compactor bumps back on to the ground surface after it jumps up from it. The contact force can be obtained by the value of $c\dot{y} + ky$ in the simulation, which expresses the reaction force of the ground.

Table 1 shows the parameters of the exciter used in the calculation, which represent various sizes of exciters used in field construction. The values for ground stiffness k represent various degrees of ground stiffness, from a soft-compacted ground to a hard-compacted ground, referring to the results of plate-loading tests conducted 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 [1] :

$$c = 2D\sqrt{m\,k} \cdots\cdots\cdots (3)$$

where D is the damping ratio of the ground. Referring to research by Richart, F.E. etc. [1] on the vibrating behavior of certain structure foundations, $D = 0.4$ in this paper.

Table 1 Parameters of the numerical simulation

mass of exciter	m	(kg)	500, 800, 1100, 1400, 1700, 2000
eccentric momentum	$m_e r$	(kgm)	0.4, 0.6, 0.8
operating frequency	f_0	(Hz)	10 ~ 70
spring constant of the ground	k	($\times10^7$ N/m)	4, 8, 12, 16, 20

3. RESULTS OF THE NUMERICAL SIMULATION

Figure 3, 4 and 5 express some examples of the calculated results for the relationship between the frequency of the exciter and the contact force which is defined as the maximum amplitude of a time series for the contact force. The figures show the effect of the ground stiffness, the dynamic force and the mass of the exciter, respectively, on the relationship between the contact force and the frequency of the exciter.

The contact force is expected to increase with the dynamic force of the exciter, because a large dynamic force induces a large jumping height of the exciter from the ground surface and the following large contact force at the moment the exciter bumps back on to the ground. The dynamic force is determined by the product of the eccentric momentum and the square of the frequency as shown in equation (2). It is expected, therefore, that the contact force will increase with the frequency of the exciter. However, Figures 3, 4 and 5 show the existence of an optimum frequency where the contact force exhibits its peak against the frequency of the exciter. This phenomenon is thought to be caused by the fact that increases in frequency bring about not only an increase in the displacement induced by the increase in the dynamic force, as shown in equation (2), but also a reduction in the displacement of the exciter by restricting the movement of the exciter under the vibration of a large frequency. When the contact force reaches its maximum, therefore, an optimum frequency is induced as a result of the balance of both effects.

Figures 3, 4 and 5 also suggest that the optimum frequency increases with the ground stiffness, that it doesn't depend on the dynamic force, and that it increases with a decrease in the mass of the exciter, respectively.

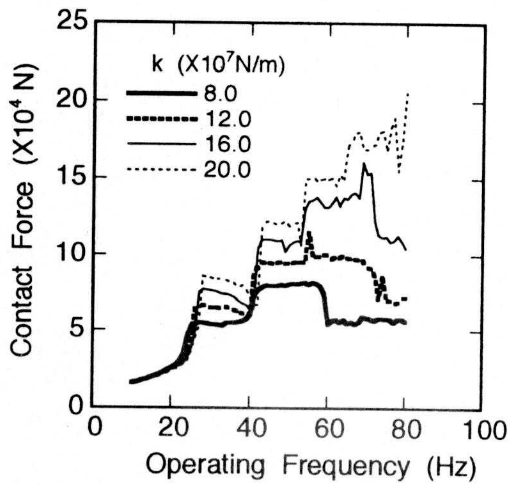

Figure 3 The results for the calculation of the relationship between contact force and frequency with the parameters of ground stiffness k (m = 1400 kg, $m_e r$ = 0.6 kgm)

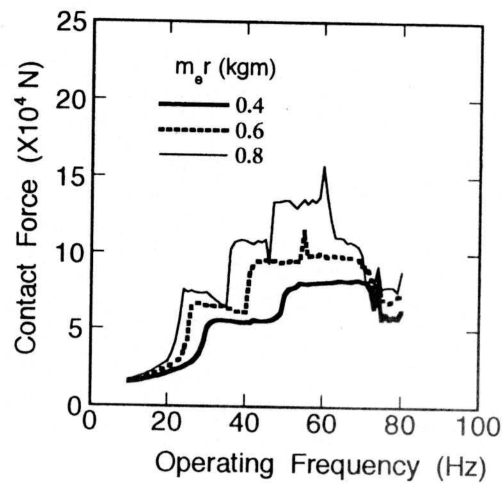

Figure 4 The results for the calculation of the relationship between contact force and frequency with the parameters of eccentric momentum $m_e r$ (m = 1400 kg, k = 12x10^{7}N/m)

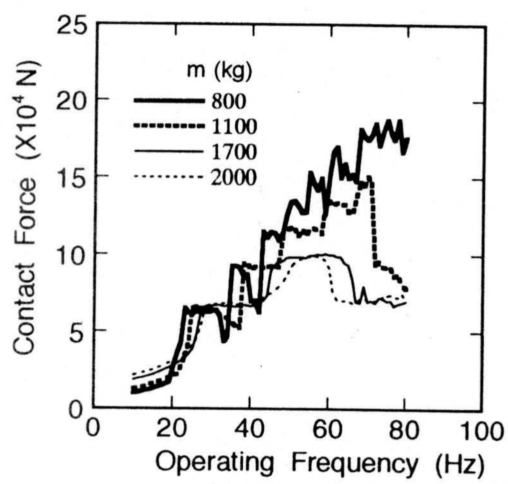

Figure 5 The results for the calculation of the relationship between contact force and frequency with the parameters of mass of the exciter m ($m_e r$ = 0.6 kgm, k = 12x10^{7}N/m)

Figures 6, 7 and 8 express the results of the numerical simulation which quantitatively show the effects of the ground stiffness, the dynamic force, and the mass of the exciter, respectively, on the optimum frequency of the exciter. It is clear from these figures that the optimum frequency is proportional to the ground stiffness, that it doesn't depend on the dynamic force, and that it is inversely proportional to the mass of the exciter.

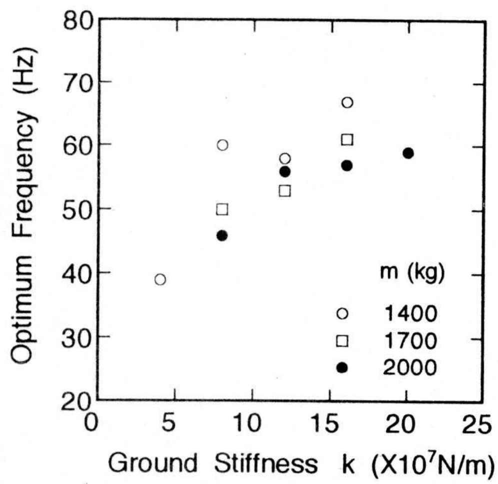

Figure 6 The effects of ground stiffness on the optimum frequency ($m_e r = 0.8$ kgm)

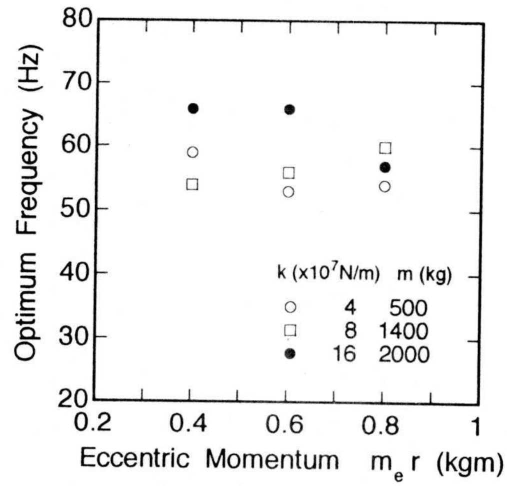

Figure 7 The effects of eccentric momentum on the optimum frequency

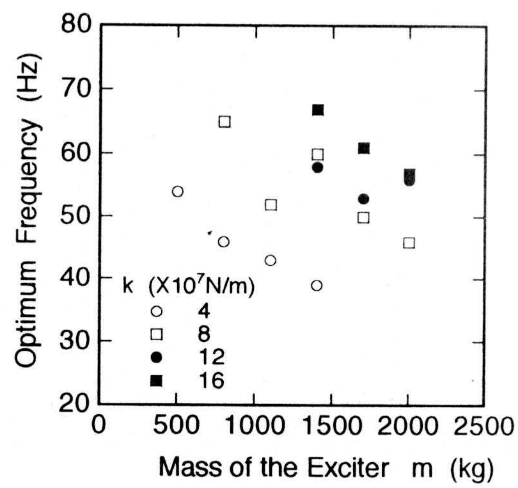

Figure 8 The effects of mass of the exciter on the optimum frequency ($m_e r = 0.8$ kgm)

Figure 9 expresses all the results of the exciter when the optimum frequency is plotted against the ratio of the ground stiffness to the mass of the exciter according to the knowledge obtained from Figures 6, 7 and 8. It is clear from Figure 9 that the optimum frequency is closely related to the ratio of the ground stiffness to the mass of the exciter and that their relation can be approximated by the straight line shown in Figure 9.

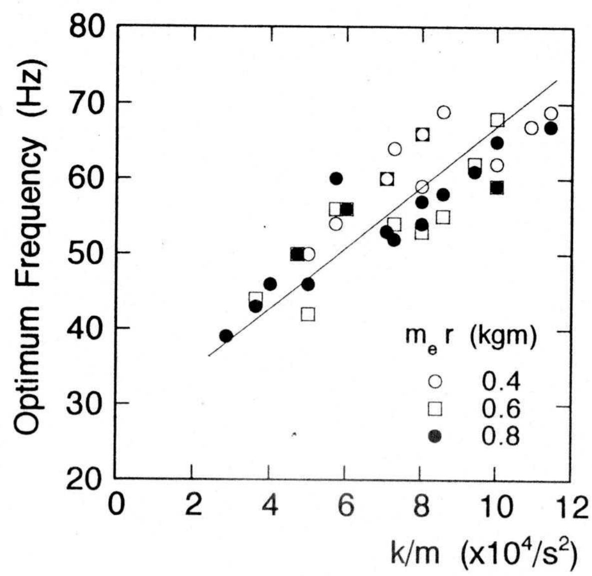

Figure 9 All the results for calculations on the optimum frequency

4. DISCUSSION OF THE LITERATURE

Selig discussed the effects of the operating frequency of a vibratory compactor on soil compaction using a number of experimental results [2]. Figure 10 shows the results of his research in which the dry densities of various types of soil, compacted by vibratory compactors, are plotted against the operating frequency of the compactors. He pointed out in this figure that there exists an optimum frequency at which the soil can be compacted most efficiently for each combination of soil type and compactor. After studying the optimum frequency in Figure 10, we arranged the data as shown in Figure 11.

The values of the optimum frequency are plotted against the ratio of the dry density to the weight of the compactors in Figure 11, referring to Figure 9. It can be seen from Figure 11 that the optimum frequency, at which the maximum dry density is obtained, is closely related to the ratio of the dry density of the soil to the weight of the compactors. Their relation can be approximated by a proportional relation.

Figures 9 and 11 can not be directly compared because the ground stiffness is employed as a ground property in Figure 9, although the dry density is employed in Figure 11. Since the ground stiffness closely depends on the dry density of the soil, however, the results in Figure 11 are thought to support the reliability of Figure 9. The applicability of Figure 9 should be studied through field compaction tests using real vibratory compactors.

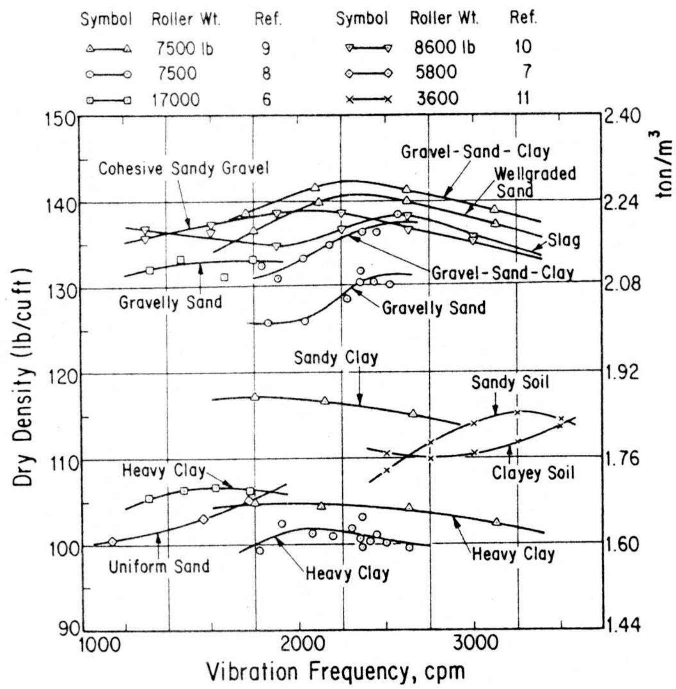

Figure 10 Experimental results of vibratory soil compaction (Selig, E.T., 1977[2])

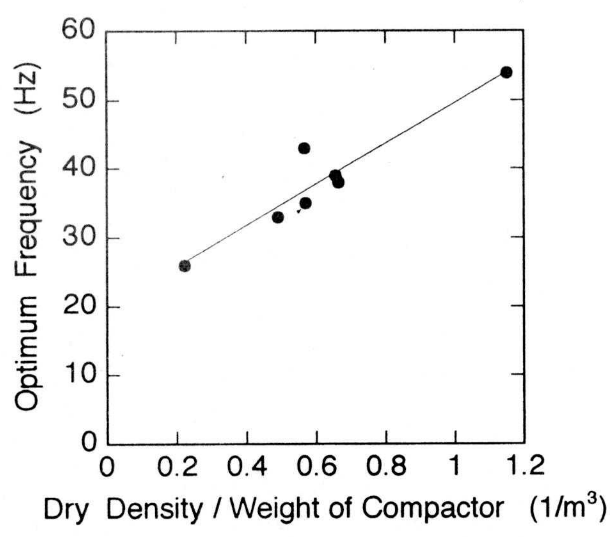

Figure 11 The arrangement of the experimental results of Selig

5. DEVELOPMENT OF THE VIBRATORY CONDITIONS ADJUSTMENT SYSTEM

It is possible to determine the optimum frequency for compacting the ground with Figure 9 when the values for the ground stiffness and the mass of the exciter are given. The mass of the exciter is known when an exciter is specified and thus a method for measuring the value of the ground stiffness is required to determine the optimum frequency for the ground. A method to determine the ground stiffness in real-time during construction has been suggested by the authors [3]. In this method, the vibrating behavior of the vibratory compactor, which evidently changes according to the ground stiffness, was applied for monitoring the ground stiffness during the process of construction. By combining this ground monitoring method and the suggested frequency adjustment system, a vibratory compactor can generate the maximum compacting effect for the ground conditions.

6. CONCLUSIONS

An automatic construction system was discussed in the field of vibratory soil compaction. In the system, the ground stiffness was monitored by the vibrating behavior of the compactors and the vibrating conditions of the compactors were then adjusted according to the monitored ground conditions in real time. A numerical simulation was carried out to develop the system and a figure at which the optimum frequency for the ground can be determined was suggested. The applicability of the system should be examined through field compaction tests.

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