AUTOMATIC CONTROL SYSTEM OF THE DEGREE OF COMPACTION OF A HIGH LIFTED DECOMPOSED GRANITE SOIL FOR A VERTICALLY VIBRATING AND JUMPING TRACKED VEHICLE

T.Muro and D.T.Tran

Faculty of Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama, Japan

Abstract: The purpose of this paper is to establish a new automatic control system of the degree of compaction of a high lifted decomposed granite soil i.e. the accurate controlling method of the number of dynamic compacting passes of a vertically vibrating and jumping tracked vehicle mounted with a vertical oscillator. In these tests, the spectrum disturbances of the wave of acceleration of the tracked vehicle were analyzed to evaluate the uniformly distributed dry density and the degree of compaction of soil. The relationships between the spectrum disturbance and the dry density of soil were discussed for the load ratio of a maximum vertical exciting force to a total weight of tracked vehicle of 1.0 and 2.0. As a result, it was clarified that the real time measurement of the spectrum disturbance was very useful to raise the quality of compacted embankment and the vibratory compaction effects of vertical exciting force of a tracked vehicle on the dynamic compaction of a high lifted decomposed granite.

Keywords: degree of compaction, soil, vibration, jumping, tracked vehicle.

1. INRODUCTION

In recent years, several automatic control systems of the degree of compaction have been considered to raise the construction speed for high lifted materials e.g. roller compacted dam concrete or soil in banking execution [1]. New compaction machinery achieving a distinguished highly efficient compaction at deep stratum should be developed. So far, the authors have demonstrated that the compaction method due to a dynamic plane load of vibratory tracked vehicle is better than that due to a dynamic line load of vibratory road roller [2] because of the highly efficient compaction work due to a confinement of lateral movement of soil particles [3]. The purpose of this paper is to evaluate the effects of a vertically vibrating and jumping tracked vehicle in the case of load ratio of maximum vertical exciting force to a total weight of tracked vehicle of 1.0 and 2.0 on the vibrating and jumping compaction of decomposed granite scattered to 45 cm thickness and to establish a new automatic control system of the degree of compaction of soil. Here, several vibratory compaction tests were executed in a large scale soil bin using a model rubber tracked vehicle of 4.9 kN weight including a vertical oscillator under condition of frequency of 16 Hz. The model tracked vehicle has the dimension of track length of 91 cm and track width of 20 cm, and the average contact pressure of 13.5 kPa. For every compacting passes, the amount of sinkage of terrain surface and distribution of dry density distribution of soil with depth were measured. In these tests, the spectrum disturbances of the wave of acceleration of the tracked vehicle were analyzed using a uniaxial accelerometer mounted on a model tracked vehicle to evaluate the dry density and the degree of compaction of soil. The relationships among the spectrum disturbance, the number of compacting passes, the dry density of soil and the degree of compaction of soil have been discussed to determine the number of dynamic compacting passes on real time to satisfy the 90 % degree of compaction of soil for the load ratio of 1.0 and 2.0.

2. EXPERIMENTAL METHOD

2.1 Test terrain

As a sandy soil sample, a decomposed granite sampled from Ehime Prefecture, Japan was prepared for the compaction test. The sandy soil had a maximum grain size of 4.75 mm, an average grain size of 1.00 mm, a coefficient of uniformity of 4.2, a coefficient of curvature of 0.9, and a specific gravity of 2.66. From the compaction test results having a dynamic compaction energy of 551.3 kNm/m^3 due to

Fig.1 Side view of running system of a tracked vehicle mounted with a vertically exciting oscillator

JISA 1210, 1.1a, it was observed that the maximum dry density of 1.98 g/cm^3 was obtained at the optimal moisture content of 10.6 % and the degree of saturation of 82.1 %.

A cone penetrometer test was conducted to measure the relationship between a cone index and a dry density of soil. As a result, the dry density of sandy soil ρ_d (g/cm^3) was expressed as the function of the cone index q_c (kPa) in the following non-dimensional equation;

$$\frac{\rho_d}{\gamma_W} = 1.384\left(\frac{q_C}{p_0}\right)^{0.107} \qquad (r = 0.998) \qquad (1)$$

where γ_W is the density of water of 1.00 g/cm^3, p_0 is the atmospheric pressure of 98.0 kPa and r is the coefficient of correlation.

The sandy soil sample adjusted to the optimal moisture content fell down from the height of 50 cm into a large soil bin of length of 540 cm, width 150 cm and height 60 cm. A flat test terrain with a depth of 45 cm having an initial uniform dry density of 1.20±0.04 g/cm^3 with depth was prepared for the compaction test.

2.2 Compaction test using a vertically vibrating tracked vehicle

The dimensions and specifications of a conventional flexible rubber tracked vehicle on the market which was selected as a model tracked vehicle are shown in Table 1. A vertically forced vibrating oscillator with the maximum vertical exciting force F_V of 4.90 and 9.80 kN at the vibrating frequency f of 16.0 Hz was prepared for this compaction test. The oscillator has two-axles and two eccentric masses so that the horizontal exciting force can be cancelled. The vibratory compaction test in the case of the load ratio α of the maximum vertical exciting force F_V (kN) to the total weight W (kN) of the tracked vehicle of 1.0 i.e. F_V =4.90 kN and the jumping compaction test in the case of α=2.0 i.e. F_V =9.80 kN were executed. As shown in Fig.1, the rear sprocket was driven by a 0.75 kW motor mounted on the tracked vehicle so that the vehicle could run at a speed of 3.75 cm/s during self-propelling action. The number of compacting passes N was counted at N times of the forward and backward movement of the tracked vehicle. Considering the actual compaction method in which the soil was compacted until obtaining a necessary dry density using vibratory compaction machinery after compacting the scattered loose soil using a bulldozer, the compaction test was conducted for N of 1 to 3 of non-vibration state and for N of 4 to 13 of vibration or jumping state. In this case , the compaction energy per unit volume of soil could be calculated as 277 kNm/m^3 for α=1.0, and 4,024 kNm/m^3 forα=2.0.

Table 1. Dimensions and specifications of tracked vehicle

Total vehicle weight	W	4.9 kN
Eccentricity of center of grav.	e	0.003
Height of center of gravity	h_g	32.0 cm
Track width	B	20.0 cm
Track length	L	91.0 cm
Track interval	C	45.5 cm
Radius of front idler	R_f	12.0 cm
Radius of rear sprocket	R_r	9.0 cm
Number of road rollers		4
Radius of road rollers	R_m	8.0 cm
Grouser height	G_H	2.5 cm
Grouser pitch	G_P	7.0 cm
Mean contact pressure	p	13.5 kPa
Vehicle speed	V	3.75 cm/s

For each given number of compacting passes, the amount of sinkage of the terrain surface *S* was measured as the average value of at least ten rut depths, and the cone index distribution with depth q_c was measured for at least five rut sites on the same lane using a cone penetrometer.

EXPERIMENTAL TEST RESULT

3.1 Amount of sinkage and number of compacting passes

Fig.2 shows the relationship between the amount of sinkage of terrain surface *S* (cm) and the number of compacting passes *N* for the frequency f =16 Hz of the vertically vibrating tracked vehicle in the vibrating compaction state atα=1.0 and in the jumping compaction state at α=2.0 respectively. For the number of compacting passes *N* from 1 to 3 at non-vibration state, the amount of sinkage of terrain surface *S* increased with the increment of *N* . For *N* from 4 to 13 at vibration or jumping compaction state, *S* increased rapidly with *N* at the first stage and also increased with α and it approached generally to each constant value. The final amount of sinkage at *N* =13 had a maximum value of 16.7 cm at the jumping compaction state of the load ratio α=2.0, of which the value became 1.29 times that of 12.9 cm at the vibrating compaction state of α=1.0.

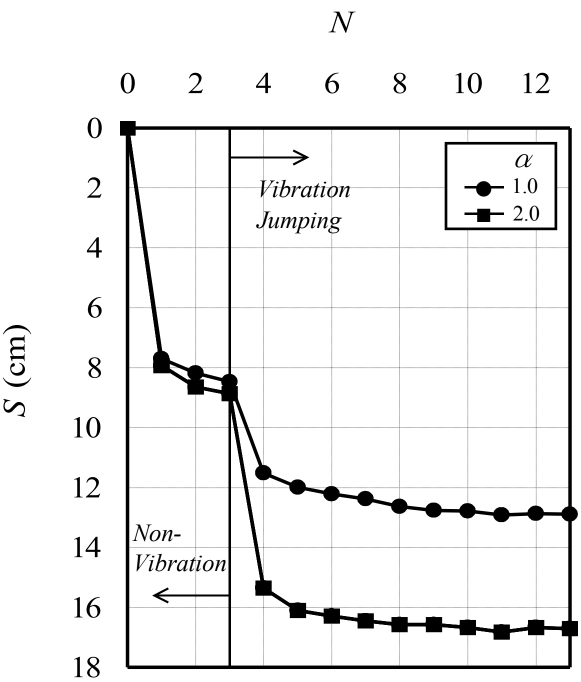
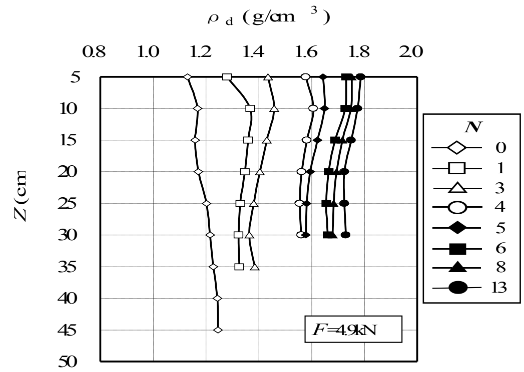


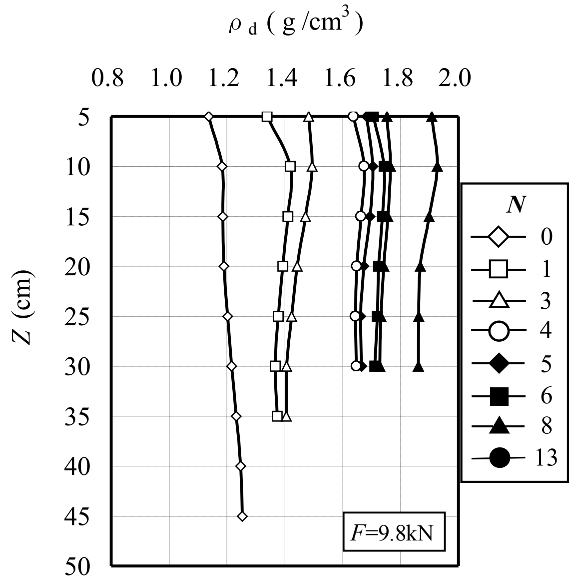
Fig.2 Relationship between amount of sinkage *S* and number of compacting passes *N* for each load ratio α

3.2 Dry density distribution and number of compacting passes

The cone index distributions with depth were measured at the rut sites made after the passes of the vertically vibrating tracked vehicle for each number of compacting passes using the cone penetrometer as mentioned previously. As the dry density of the compacted sandy soil was expressed as a function of the cone index in Eq.(1), the cone index distributions with depth could be converted into the distributions of dry density with depth. As an example, Figs.3(a)(b) show the relationships between the dry density of



(a) f =16 Hz and α=1.0



(b) f =16 Hz and α=2.0

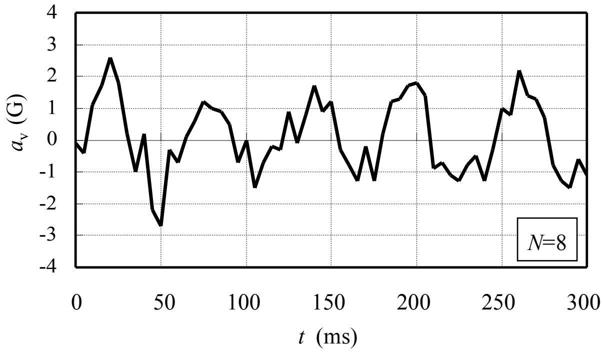
Fig.3 Relationships between dry density of soil ρ_d and depth *z* for each number of compacting passes *N* the compacted sandy soil ρ_d (g/cm^3) and the depth z (cm) for each number of compacting passes N for the frequency f =16 Hz in the vibrating compaction state at the load ratio of α=1.0 and in the jumping compaction state at α=2.0 respectively. It was observed that the distributions of dry density were generally almost uniform with depth for the whole range of the soil stratum and the dry densityρ_d increased generally with the number of compacting passes N. The average dry density at N =13 had a maximum value of 1.88 g/cm^3 at the jumping compaction of the load ratio α=2.0, of which the value became 1.11 times that of 1.69 g/cm^3 at the vibrating compaction ofα=1.0.

Moreover, the effect of the jumping compaction due to the tracked vehicle mounted with the vertically vibrating oscillator was found to be remarkable because the maximum average dry density 1.88 g/cm^3 overcame the degree of compaction of 90 % i.e. 1.78 g/cm^3 .

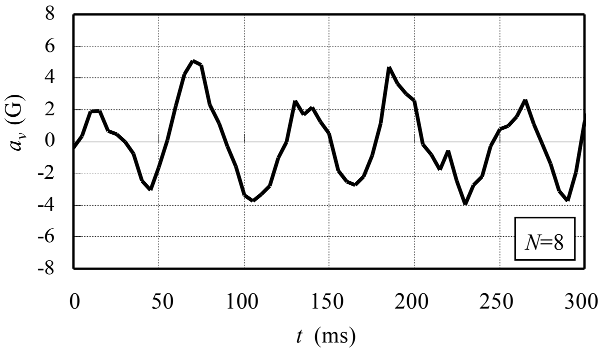
3.3 Distribution of vertical acceleration of tracked vehicle

The vibration behavior of the vertically vibrating tracked vehicle tends to vary with the increasing stiffness of terrain in the progress of soil compaction. Here, the vertical acceleration of the tracked vehicle was measured using an accelerometer attached to the vehicle to investigate the occurrence of high frequency spectrum due to the wavy disturbance of the vertical acceleration which was generated with the increment of the number of compacting passes.

As an example, Figs.4(a)(b) show the distributions of vertical acceleration a_V(G) of the vertically vibrating tracked vehicle for the frequency f =16 Hz and the number of compacting frequency N = 8 at the vibrating compaction of α=1.0 and at the jumping compaction ofα=2.0. The vibrating frequency measured for N = 8 was 16.9±2.1 Hz and 17.0±2.4 Hz forα=1.0 and 2.0, respectively. These frequencies were very close to the original frequency of the oscillator 16 Hz. In general, the wavy distributions of the vertical acceleration acting on the tracked vehicle became irregular with the increment of the number of compacting passes for both vibrating and jumping compaction.



(a) f =16 Hz and α= 1.0 F_v = 4.9 kN



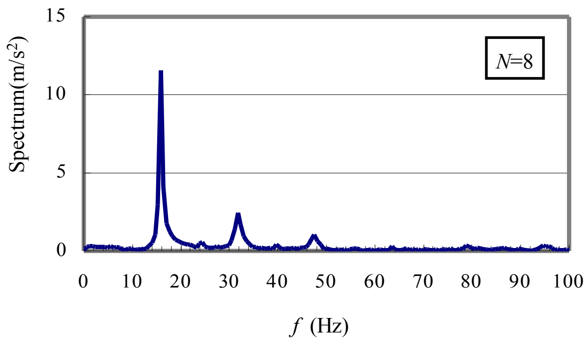
(b) f =16 Hz and α= 2.0 F_v = 9.8 kN

Fig.4 Distribution of vertical acceleration a_V acting on tracked vehicle

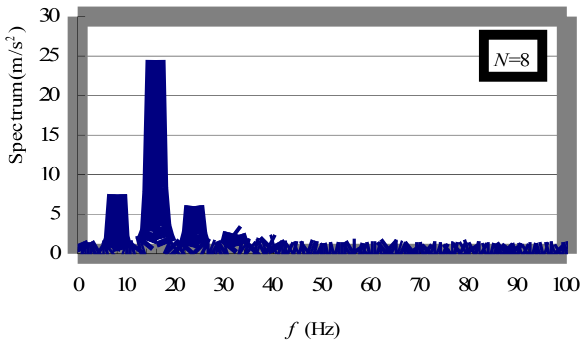
4. ANALYSIS OF VIBRATING BEHAVIORS OF TRACKED VEHICLE

For the vibrating behaviors of a vibratory roller, it was already predicted theoretically that the shape of acceleration wave of the vibratory roller showed almost the same shape as the regular sinusoidal wave developed in the exciter at an initial compaction stage but the shape of the acceleration wave tended to deform irregularly with the increment of the number of compacting passes N and then several numbers of frequency component having some integral number times as large as the frequency of the exciter f_0 would occur when the waves of acceleration were analyzed by use of a spectrum analytical method [4]. The vibrating behaviors of the tracked vehicle mounted with a vertical oscillator showed also, as shown in the previous diagrams, that the shapes of the acceleration wave were already deformed at the number of compacting passes N =8 and they deformed more irregularly with the increment of the number of compacting passes N and the load ratio α.

As an example, Figs.5(a)(b) show the results of spectrum analysis to evaluate quantitatively the wave disturbance of acceleration developed on the vibratory tracked vehicle mounted with a vertical oscillator for the load ratioα=1.0 and 2.0 at the number of compacting passes N =8. For both cases, several components of frequency other than the original frequency f_0 =16 Hz of the oscillator appeared. Especially for α=2.0, a large number of distinguished spectrum were observed and 1/2 component of the original frequency f_0 tended to occur with the increment of the hardness of the terrain surface. This phenomenon shows a non-linear vibration accompanying the jumping movement of the tracked vehicle due to the increment of non-linearity of vibration occurring at the time of impact



(a) f=16 Hz and α= 1.0 F_v = 4.9 kN



(b) f=16 Hz and α= 2.0 F_v = 9.8 kN

Fig.5 Relationship between spectrum and frequency f of tracked vehicle

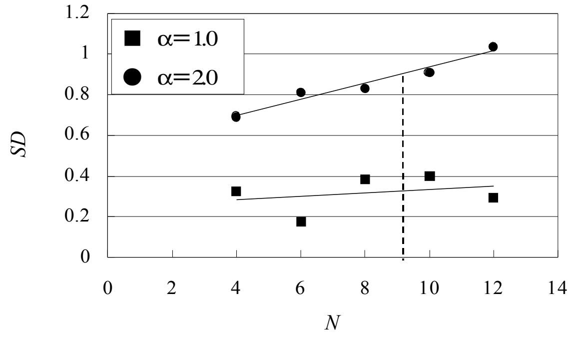


Fig.6 Relationship between spectrum disturbance *SD* and number of compacting passes *N*

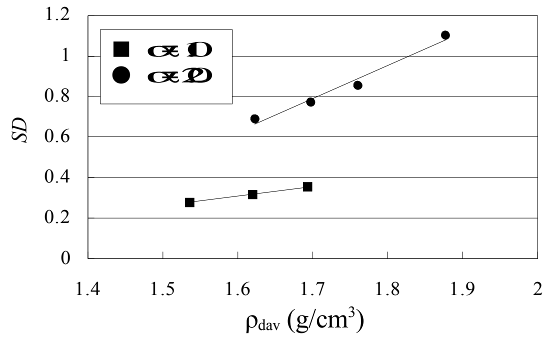


Fig.7 Relationship between spectrum disturbance *SD* and average dry density ρ_{dav}

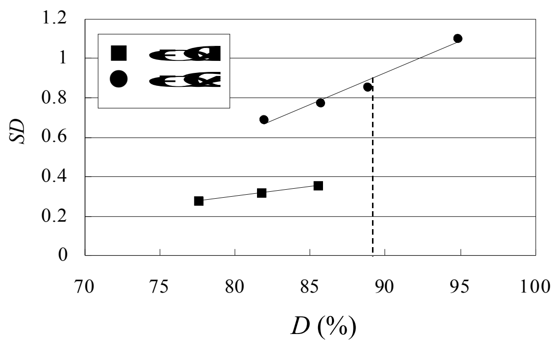


Fig.8 Relationship between spectrum disturbance *SD* and degree of compaction *D*

of the vehicle to the terrain surface with the increasing compacting dry density. In this case, it shows a mixed motion of tracked vehicle combining at least two kinds of periodical movement.

The spectrum disturbance *SD* of the wave of acceleration was defined as follows [5]:

Spectrum disturbance *SD*

$$= \frac{\text{Summation of spectrum of frequency except } f_0}{\text{Spectrum of frequency } f_0 \text{ of an exciter}}$$

$$= \frac{\sum_i S_i}{S_0} \quad (i = 1, 2, 3, \ldots\ldots) \qquad (2)$$

From the above equation, this means that the larger the wave disturbance the larger the spectrum disturbance *SD* that occurs and the spectrum component of other frequencies except the original frequency f_0 of the exciter becomes more distinguished.

Fig.6 shows the variation of the spectrum disturbance *SD* for the load ratio α=1.0 and 2.0 with the increment of the number of compacting passes *N*. As shown in this diagram, the value of *SD* increases with the increment of *N* i.e. the compacting dry density and also the values of *SD* for the jumping compaction of α=2.0 become larger than those values for the vibrating compaction of α=1.0.

Fig.7 shows the variation of the spectrum disturbance *SD* for the load ratio α=1.0 and 2.0 with the increment of the compacting average dry density ρ_{dav} (g/cm³). The gradient for the jumping compaction of α=2.0 became larger than that for the vibrating compaction of α=1.0.

Fig.8 shows the relationship between spectrum disturbance *SD* and degree of compaction of soil *D* calculated for the maximum dry density of 1.98 g/cm³.

Utilizing these phenomena, it becomes possible to evaluate automatically the degree of compaction of soil from the vibrating behaviors of the vibratory tracked vehicle mounted with a vertical oscillator. In this case, the spectrum disturbance *SD* could be read as 0.92 forα=2.0 when the compaction stage of soil reached the degree of compaction *D* of 90 %, i.e. the dry density of 1.78 g/cm^3. Then, the critical number of dynamic compacting passes N_{CD} and the critical number of total compacting passes N_C to reach the degree of compaction of 90% could be determined as 6 and 9 times respectively.

5. CONCLUSION

A small flexible rubber tracked vehicle of weight 4.9 kN which was mounted with a vertically vibrating oscillator having a frequency of 16 Hz was used to compare experimentally and theoretically the effects of a vibrating compaction of load ratio of 1.0 and a jumping compaction of load ratio of 2.0 on the compacting dry density distribution in a high lifted soil stratum of 45 cm depth using a decomposed granite adjusted to the optimal moisture content. It could be newly concluded that:

(1) For the number of compacting passes *N* from 1 to 3 at non-vibration state, the amount of sinkage of terrain surface *S* increased with the increment of *N* . For *N* from 4 to 13 at vibration or jumping state, *S* increased rapidly with *N* at the first stage and also increased with α and it generally approached to each constant value. The final amount of sinkage at *N* =13 had a maximum value of 16.7 cm at the jumping compaction state of α=2.0, of which the value became 1.29 times that of 12.9 cm at the vibrating compaction state of α=1.0.

(2) The final distribution of dry density with depth was comparatively uniform for the whole range of the high lifted soil stratum. The final average dry density at *N* =13 had a maximum value of 1.88 g/cm^3 at the jumping compaction state of α=2.0, of which the value became 1.11 times that of 1.69 g/cm^3 at the vibrating compaction state of α=1.0.

(3) The spectrum disturbance was 0.92 for the jumping compaction of the load ratio of 2.0 when the compaction stage of soil reached the degree of compaction of 90 %, i.e. the dry density of 1.78 g/cm^3. Then, the critical number of dynamic compacting passes and the critical number of total compacting passes to reach the degree of compaction of 90% could be determined as 6 and 9 times respectively.

(4) Utilizing the spectrum disturbance of the vibrating behaviors of the vibratory tracked vehicle mounted with a vertical oscillator, it becomes possible to evaluate automatically the degree of compaction of soil and to determine the necessary number of compacting passes on real time.

References

[1] Nohse, Y., Uchiyama, K., Kanamori, Y., Kase J., Kawai, Y., Masamura, K. and Tateyama, K.: An attempt applying a new control system for the vibratory compaction using GPS and CMV in the embankment construction (Part 1), Proc. of the 13th Int. Conf. of the ISTVS, pp.295-300, 1999.

[2] Muro,T., Yoshioka,N. and Miyoshi,M.: Effects of roller and tracked vehicle mounting a centrifugal oscillator on the vibro-compaction of a high lifted decomposed granite sandy soil, Journal of Construction Management and Engineering, JSCE, No.588/VI-38, pp.139-150, March, 1998 (In Japanese).

[3] Muro,T., Miyoshi,M. and Mitsubayashi,T.: Effect of a tracked vehicle mounting an oscillator on the vibro-compaction of a high lifted decomposed granite sandy soil, SOILS AND FOUNDATIONS, Vol.38, No.4, pp.129-144, Dec., 1998.

[4] Tateyama,K., Fujiyama,T. and Nishitani,M.: Some aspects of the vibrating behavior of a vibratory roller in soil compaction, Journal of Geotechnical Engineering, JSCE, No.554／III-37, pp.231-237, 1996.12 (In Japanese).

[5] Tateyama,K., Nakajima,S. and Fujiyama,T.: The evaluation of the degree of soil compaction by the behavior of vibrating exciters, Journal of Geotechnical Engineering, JSCE, No.487／III-26, pp.237-245, 1994.3 (In Japanese).