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Hideo Tsuboi
Fudo Construction Co., Ltd., Tokyo, Japan

Tamotsu Matsui
Osaka University, Osaka, Japan

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CASE HISTORIES AND VIBRATORY CHARACTERISTICS OF VIBRO-DRIVEN PILES

Hideo TSUBOI
Fudo Construction Co., Ltd.
1-2-1 Taito, Taito-ku, Tokyo 110, Japan

Tamotsu MATSUI
Professor, Osaka University
2-1 Yamadaoka, Suita-shi, Osaka 565, Japan

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ABSTRACT

The vibratory characteristics of vibro-driven piles into the ground have not so far been discussed systematically in detail. This paper concerns the results of monitoring vibro-driven piles in various types of ground. In order to assess the monitoring of vibration performance, time-series monitoring data on the reaction force at the pile tip and the vibratory acceleration of the pile top are analyzed in relation with the soil profiles of four monitoring sites. As the results, it has been elucidated that the pile tip reaction force and vibratory acceleration are systematically presented by the dynamic force and the mass weight of the vibrohammer and pile. Furthermore, engineering applications of the vibratory characteristics of vibro-driven piles are presented.

KEYWORDS

vibro-driven pile, monitoring, reaction force, vibratory acceleration, soil profile, ground improvement

INTRODUCTION

Tsuboi et al (1997) developed a monitoring system of the pile tip reaction force and the vibratory acceleration of vibro-driven piles, regarding a casing for a sand compaction pile (SCP) as a penetrated pile. The pile tip reaction force is measured by fitting a thin hollow reaction force meter with an outer diameter equal to that of the casing pipe to the pile tip, while the vibratory acceleration by fitting a vibratory acceleration meter at around the pile top.

In this paper, using the developed monitoring system, case histories of vibro-driven piles into actual ground are collected at four sites. From the recorded data obtained at these sites, the relation between the pile tip reaction force and the vibratory acceleration is analyzed in free penetration state without any control through the suspension of pile. This study also investigates the engineering vibratory characteristics of vibro-driven piles and gives some comments on their further application.

MONITORING PROCESS

Fig. 1 shows the vibro-driven steel pipe casing and the thin hollow reaction force meter whose outer diameter is the same as that of the pile. The vibratory behavior of the pile is monitored by taking repeated measurements of such items as the reaction force, vibratory acceleration and driving time. Fig. 2 gives an outline of the monitoring and data processing system.

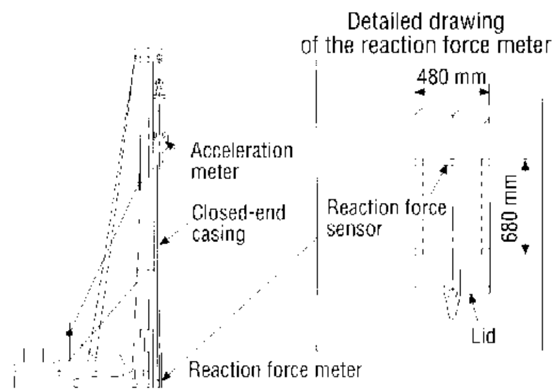


Fig. 1 Outline of pile-driving and hollow reaction force meter at the tip of the vibro-driven pile

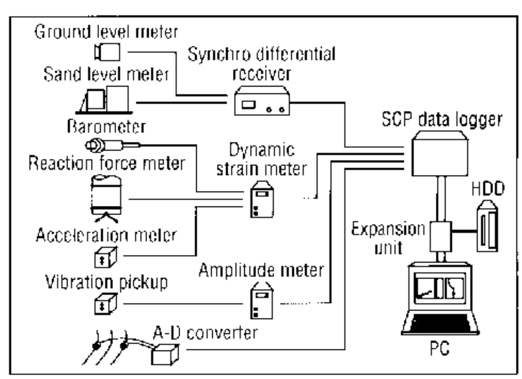
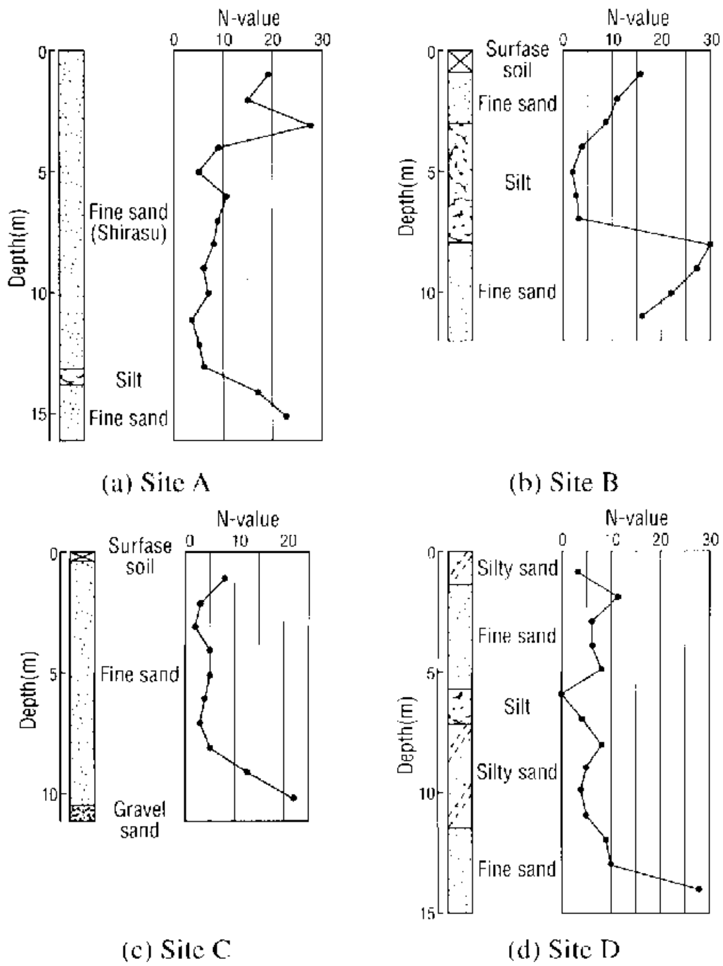


Fig. 2 Monitoring and data processing system

MONITORED SITES

Field measurements were made at four sites of recently reclaimed sandy land fills, with soil profiles as shown in Fig. 3 and with pile specifications in Table 1. The ground at each site consists of a thickness of 12 to 15m with sandy soil layers partly containing silt.



(a) Site A (b) Site B

(c) Site C (d) Site D

Fig. 3 Soil profiles

Table 1 Outline of monitored sites and pile specifications

Site	No. of borings	No. of measurement	Ground profiles	Penetration depth (m)	Vibrohammer used	Pile weight (kN)
A	1	2	Sandy soil Volcanic ash (Shirasu)	13	V-150 V-75	126 99
B	3	12	Sandy soil Mostly fine sand	10	V-180	180
C	1	1	Sandy soil	10	V-75	99
D	1	4	Silty sand	12	V-75	86

RELATION BETWEEN PILE TIP REACTION FORCE AND VIBRATORY ACCELERATION

For the vibro-driven pile through fine sandy layers at the four sites, free penetration state without any control through suspension of pile was focussed. A linear relationship can be seen between the peak values of the pile tip reaction force and vibratory acceleration, as shown in Fig. 4. Even clearer linearity is evident from separately examining the relation for each site in the figure. The differences between the four sites might be due to variations in the capacities of the vibrohammer and the differences in the pile weight and ground characteristics.

In controlled penetration state, in which the casing is suspended from above, the force of inertia is canceled out by the vibromotive force of vibrohammer. Therefore, the vibratory acceleration remains almost constant in the idling state, in which the pile tip is in mid air and does not touch the ground surface. Fig. 5 shows the relation between the pile tip reaction force and the vibratory acceleration from the idling state to free penetration state at site A.

In consideration of these results, the linear relation with the pile tip reaction force in free penetration state indicates that the pile tip reaction force (Fd) can be represented as the force of inertia plus the pile weight, minus the vibromotive force, as follows:

$$Fd = M \cdot \alpha + Q_0 - F_0 \qquad (1)$$

where, M : the pile mass
Q_0 : the pile weight
F_0 : the vibromotive force of the vibrohammer
α : the vibratory acceleration

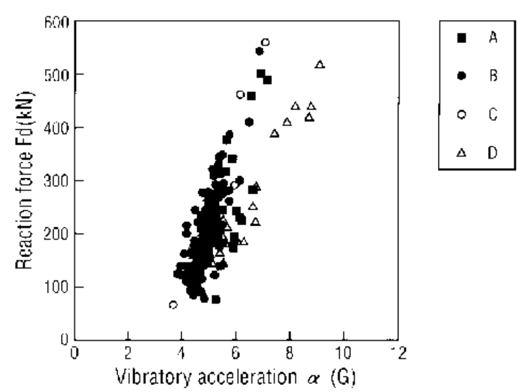


Fig. 4 Relation between pile tip reaction force and vibratory acceleration

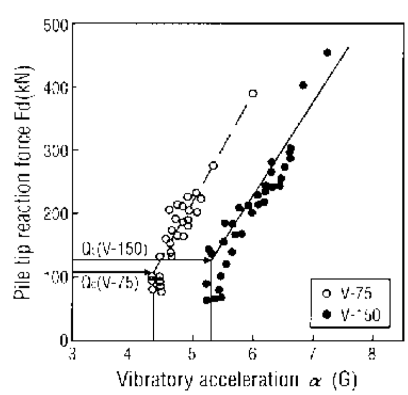


Fig. 5 Relation between pile tip reaction force and vibratory acceleration (Site A)

Using Eq. (1), we can calculate the pile tip reaction force with acceleration values recorded at each site, and compare the results with actual measurements, as shown in Fig. 6. The figure shows a close agreement between the measured and calculated values.

The relation between pile tip reaction force and vibratory acceleration is affected by such various factors as the type of vibrohammer, and the strength and confining pressure of the ground. The results of laboratory experiments conducted by O'Neill et al. (1989), in which piles were vibro-driven through the model ground of sandy soil with different relative densities and confining pressures, showed the same sort of relation, supporting the trends indicated by case history results from actual site measurements.

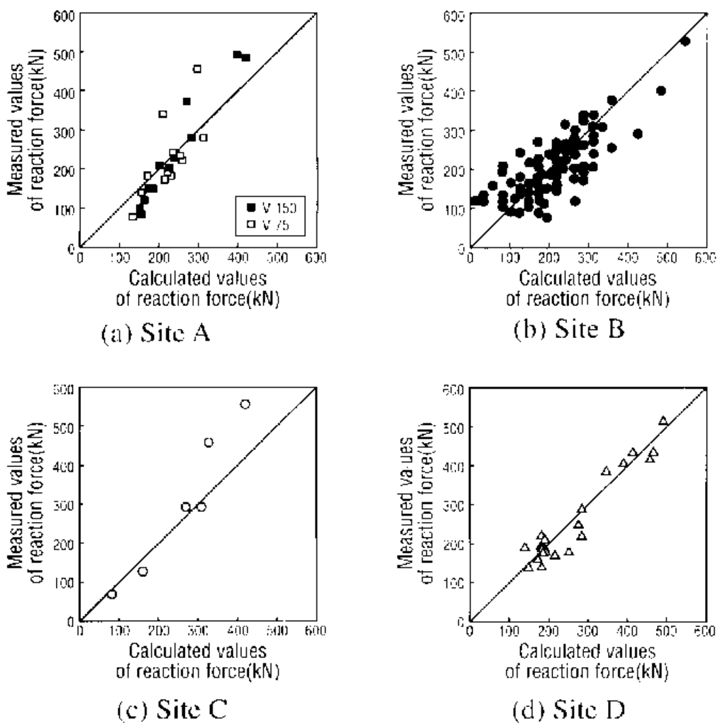


Fig 6 Comparison between measured and calculated values of pile tip reaction force

FORMULATION OF RELATION BETWEEN PILE TIP REACTION FORCE AND VIBRATORY ACCELERATION

Based on above-mentioned considerations, Fig. 7 shows schematically the relation between pile tip reaction force and vibratory acceleration. For the pile weight Q_0, the vibratory acceleration is α_0, which is the idling acceleration. The relation corresponding to the force of inertia is also shown in the figure as a broken line.

When the pile tip reaction force (Fd) meets resistance exceeding the pile weight (Q_0), the vibratory acceleration increases in accordance with the additional resistance. It exceeds the value of reaction force (F_0 - Q_0) (called the impact threshold value), and in actual measurements it increases linearly until it reaches a peak pile tip reaction force of 2π times the pile weight (Q_0). This linearity shows a high degree of correlation especially in case of free penetration state, as shown in Fig. 5. This linear relation occurs after the vibro-driven pile tip touches the ground and begins to insert it beyond the idling state in which the total pile weight is suspended. This means that the linear relation between pile tip reaction force and vibratory acceleration can be established based on the force of inertia in downward direction minus the vibromotive force plus the pile weight.

The linear relation between Fd and α, taking the vibratory acceleration during idling as α_0, can be shown as follows:

$$Fd = Q_0 + \mu(\alpha - \alpha_0) \tag{2}$$

where μ is the characterization factor of the vibro-driven pile, as shown in Eq. (3).

$$\mu = \frac{F_0 - 2Q_0}{\alpha_i - \alpha_0} \tag{3}$$

where α_0 :the vibratory acceleration during idling, and
α_i :the impact threshold value of the vibratory acceleration (see Fig. 7)

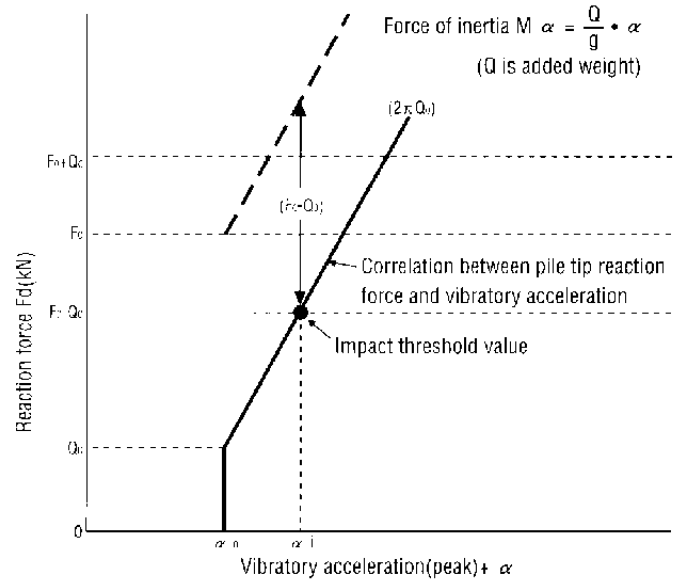


Fig. 7 Schematic diagram of relationship between pile tip reaction force and vibratory acceleration

Generally, the vibromotive force (F_0) can be taken from the number of rotations (n) and the eccentric moment (k), and can be obtained from Eq. (4).

$$F_0 = \pm \frac{2m \cdot r \cdot \omega^2}{g} \ (N) \tag{4}$$

where $\omega = 2\pi f, \quad f = \frac{n}{60} \ (Hz) \tag{5}$

$$k = 2m \cdot r \ (N \cdot cm) \tag{6}$$

m : the eccentric weight (N)
n : the rotation speed (cpm)

r : the eccentric distance (cm)
k : the eccentric moment (N • cm)
f : the vibration frequency (Hz)
ω : the angular velocity (sec^{-1})
g : gravitational acceleration (cm/sec^2)

Thus if the values of k, ω, Q_0, α_0, α_i are identified from the vibrohammer and pile specifications and the ground conditions, by using Eq. (3) and Eq. (4), the relation between Fd and α can be determined from Eq. (2).

Generally, the values of k, ω, Q_0 and α_0 are established once the vibrohammer and pile specifications are decided. Then, if actual measured values from different sites are used for the value of α_i, the relation between Fd and α is obtained. In Fig. 5, by using measured values of α_i at actual ground, the relation between Fd and α_i is shown as a solid line (V-150) and a broken line (V-75). The fact that both lines and their data points correspond well confirms the validity of Eq. (2).

ENGINEERING APPLICATIONS OF THE VIBRATORY CHARACTERISTICS OF VIBRO-DRIVEN PILES

Fig. 8 shows the relation between pile tip reaction force and N values. The reaction force shows a strong correlation with the N values of the soils, and can be an index reflecting ground characteristics.

Fig. 9 shows the relation between specifications of vibrohammers and acceleration (α), pile tip reaction force (Fd), and reaction force per unit area (q_c). The relation between Fd and q_c in this figure can be determined by taking q_c as corresponding to Fd per unit area. For the relation Fd ~ α, if characteristic values based on the specifications of the various vibrohammers (Fd and α_0) and the pile weight (Q_0) are used, the relation with α can be determined from Eq. (2). In the figure, this can be obtained from the conditions of the various piles and vibrohammers, and is shown as straight lines.

Through the application of this figure, it becomes possible to select the suitable specifications of vibrohammer for a particular type of ground. It also becomes possible to determine the appropriate marginal speed for insertion operations that incorporates operational efficiency of pile insertion.

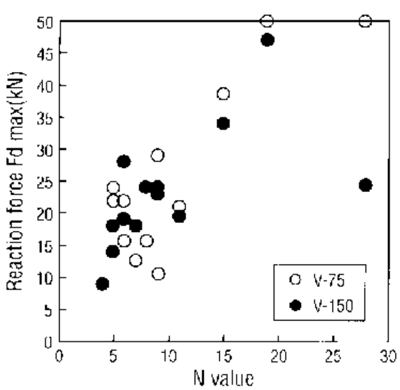


Fig. 8 Relation between pile tip reaction force and N values

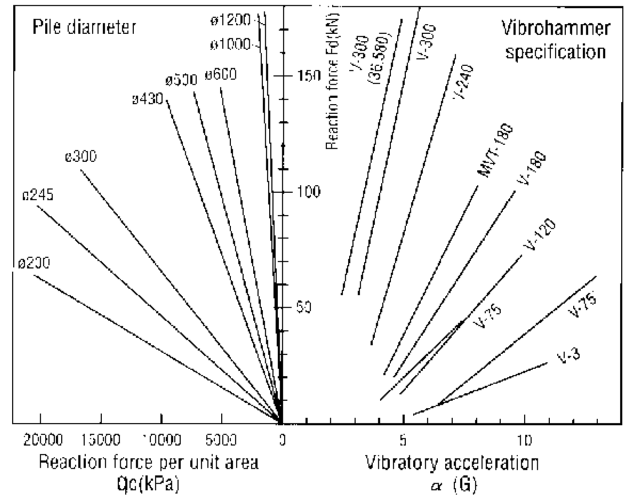


Fig. 9 Relation between vibrohammer specifications and α ~ Fd ~ qc

CONCLUSIONS

In this paper, the vibratory characteristics of vibro-driven piles was discussed, based on the monitoring results at four reclaimed sites.The main conclusions of this paper are summarized as follows;

1. The vibratory characteristics of vibro-driven piles was systematically elucidated on the basis of four case histories of monitoring field data.
2. The linear relation between the pile tip reaction force and the vibratory acceleration in free penetration state indicates that the pile tip reaction force (Fd) can be represented as the force of inertia plus the pile weight minus the vibromotive force as in Eq. (1).
3. A formulation of the relation between pile tip reaction and vibratory acceleration was presented, followed by the method for determining their parameters.
4. By means of the application of the above relation, a chart was proposed for selecting the suitable specifications of vibrohammer for a particular type of ground.

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