

## Change of Dynamic Interaction Characteristics between Soil and Large-Scale Shaking Table Foundation during Reinforcement Work

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### ABSTRACT

The change of Dynamic characteristics of large-scale shaking table foundation were measured at the various stages of reinforcement works to extract the dynamic interaction effects. The availability of the impulsive excitation test in place of the step-sweep sinusoidal excitation test is also presented.

### 1 INTRODUCTION

Many studies to verify experimentally the effects of dynamic interaction between soil and foundation have been carried out in recent years. Most of the dynamic tests, however, have been conducted using comparatively small-scale foundation models. It is preferable to use foundations as large as possible in order to minimize the effects of the local irregularities of soil properties which inherently exist in actual soil.

Valuable experimental results for both dynamic soil-structure interaction and dynamic characteristics of the surrounding soil have been presented by making use of the large-scale shaking table foundation of National Research Institute for Earthscience and Disaster Prevention in Tsukuba, formerly National Research Center for Disaster Prevention of Japanese Governmental Agency (Ogawa et al. 1977). In 1988, the limit performance of this shaking table was improved and reinforcement works of the foundation began just after the improvement. The drives of this shaking table have been possible during the reinforcement works. In course of the reinforcement works, the embedment conditions, the configuration and the weight of the foundation have been changed. At various stages of the reinforcement works, the excitation tests of the foundation have been performed by driving the shaking table. The change of dynamic characteristics of the foundation and the surrounding soil at each stages of the work has been measured.

The objective of this study is to measure the change of dynamic characteristics of the foundation and to extract the interaction effects from the observed results. Also, by comparing the results due to the sinusoidal and impulsive excitation

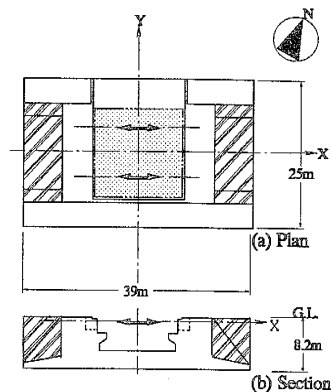


Fig.1 Shaking table foundation.

tests, the availability of the impulsive excitation test is presented. The results of the dynamic responses of the surrounding soil have been reported in another paper (Wakui et al. 1990).

## 2 OUTLINES OF SHAKING TABLE FOUNDATION, EXPERIMENT AND MEASUREMENT

The foundation is made of reinforced concrete with base area of  $39 \times 25 \text{m}^2$  and embedded in the soil by 8.2m as shown in Fig. 1. Soil profiles are shown in Table 1. In the reinforcement works, concrete mass of about  $1,200 \text{m}^3$  was cast between the buttresses of both sides of the foundation as indicated by hatched line of Fig. 1. The weight of foundation itself increased from 8,200 tons to 11,700 tons after the reinforcement works.

The shaking table is driven horizontally by four actuators and the excitation force that the shaking table exerts on the foundation is measured by oil pressure gauges.

Figs. 2(a) to (f) show the six states of the foundation when the excitation tests were performed. The first stage corresponds to the state before the reinforcement works; the second to the state when the surrounding soil was removed; the third to the state when the concrete was cast; the fourth and the fifth to the states when the sides of the foundation were half and fully backfilled, respectively; and the sixth to the state when sheet piles were taken out. The backfill soil is loose and the shear wave velocity of the soil is estimated to be about 50m/sec.

The dynamic response of the foundation during the excitation tests have been measured by displacement meters, accelerometers and earth-pressure gauges. Fig. 3 shows the location of accelerometers and the displacement meters ( $T = 1 \text{sec}$ ,  $\zeta = 70\%$ ) set on the foundation and the surrounding soil.

## 3 COMPARISON OF RESONANCE CURVES DUE TO STEP-SWEEP AND IMPULSIVE TESTS

In the impulsive excitation tests, the impulsive force was generated by driving the shaking table in the form of step function. Figs. 4(a) and (b) show the time histories of the excitation force and the horizontal response of the foundation observed at the point S0.

Figs. 5(a) and (b) show the comparison of the horizontal and vertical frequency-response curves obtained from the results of impulsive and step-sweep sinusoidal excitation tests. Fairly good agreement between two results can be seen in the frequency range more than 2 Hz. Therefore, the impulsive excitation test may be recommended to be adopted in place of the customary used step-sweep sinusoidal test. The main advantage of

Table 1 Soil profile

Depth (m)	Soil	$V_s$ (m/sec)	
		0	400
0-10	Clay & Silt		
10-15	Sand		
15-20	Silt		
20-25	Sand		
25-30	Sand		
30-35	Silt with Sand		
35-40	Sand		
40-45	Sand with Gravel		

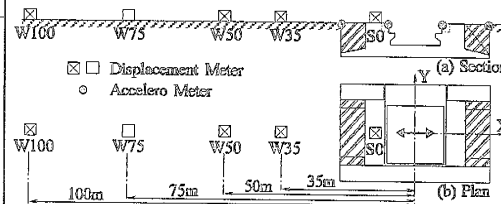


Fig.3 Location of seismometers.

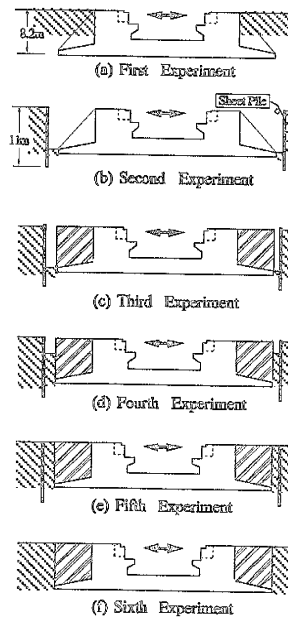


Fig.2 Six stages of excitation tests.

the impulsive excitation test is less time consuming than the conventional method.

#### 4 DYNAMIC CHARACTERISTICS OF SHAKING TABLE FOUNDATION

By comparing the experimental results of six stages of the foundation shown in Fig. 2, we can extract the effects of various factors on the dynamic characteristics of the foundation. It should be noted that all of the comparison are made for the results observed at the point S0.

##### 4.1 Effect of constraint of Soil

Figs. 6 (a) and (b) show the comparison of the horizontal and vertical frequency-response curves for the first and the second experiments. These results are normalized by unit excitation force. The difference of these curves can be considered to be the effect of constraint of soil at the sides of the foundation. It is clear from these results that the constraint of soil at the sides of the foundation decreases the horizontal and vertical responses which is caused accompanied by the rocking motion of the foundation. It is also noticed that the constraint of soil decreases remarkably the resonant frequency of the rocking motion.

##### 4.2 Effect of Added Concrete Mass

Figs. 7 (a) and (b) show the comparison of the horizontal and vertical frequency-response curves for the second and third experiments. The difference of these curves may be interpreted as the effects of the added concrete masses. The foundation weight of the third state is about 30% larger than the second state. It is noticed that the effects of added concrete masses appear only on the vertical response of the foundation. As being expected, it is also seen that the added masses decrease remarkably the resonant frequency of the rocking motion.

The effect of added masses may also be seen by comparing the first and sixth experiments, whose results are shown in Figs. 8 (a) and (b). A slight shift of the resonant frequency of the rocking motion is also noticed from Fig. 8 (b). The main reason that the

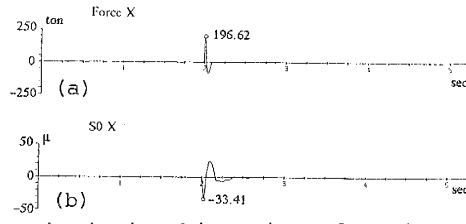


Fig.4 Time histories of excitation force and horizontal displacement at S0. (The 5th test)

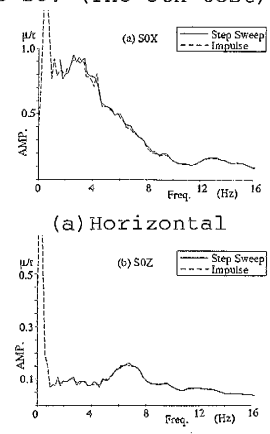


Fig.5 Comparison of frequency-response curves.

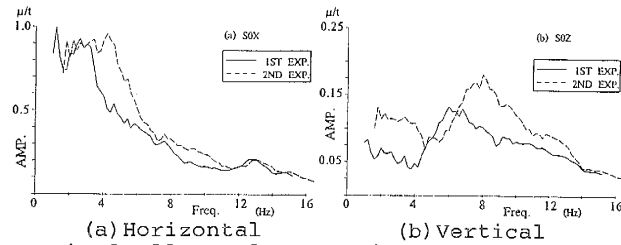


Fig.6 Effect of constraint of side soil.

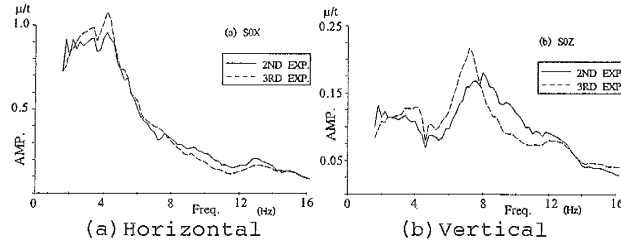


Fig.7 Effect of added concrete mass. (Comparison of 2nd and 3rd tests.)

effect of added masses is less than the case shown in Fig. 7 is that the increase of mass in the sixth state is only 8% larger than the first state.

#### 4.3 Effect of Embedment Depth

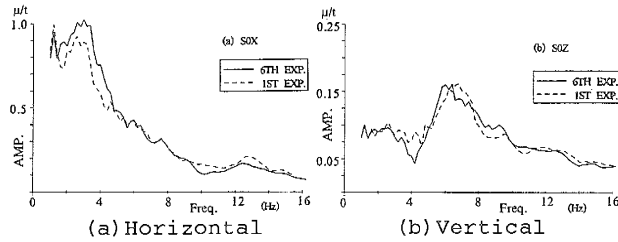
In Figs. 9(a) and (b), the frequency-response curves for the third, fourth and fifth experiments are shown simultaneously. From these results, we can see that with increase of the embedment depth the horizontal and rocking responses of the foundation tend to decrease. It should be noted that the embedment effects appear only around 4 to 6 Hz for the horizontal response but are more pronounced for the rocking response.

#### 4.4 Effect of Sheet Piles

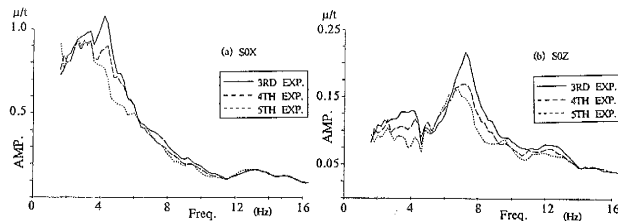
The sixth experiment was performed soon after the sheet piles were taken out. Figs. 10(a) and (b) show the comparison of the frequency-response curves for the fifth and sixth experiments. The difference of these two curves may be interpreted as the effects of the sheet piles. Since the difference is very small, we can say that the effect of the sheet piles is negligible.

#### 4.5 Deformation of Foundation

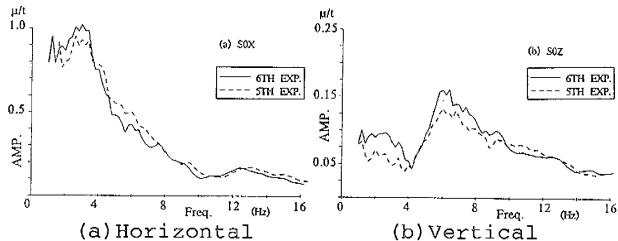
It has been generally pointed out from the theoretical studies that the deformation of foundation become remarkable with increase of frequencies (Iguchi and Luco 1982). Perhaps, one of the most interesting subjects is to observe the deformation of the foundation experimentally. Figs. 11(a) to (c) show the deformation curves of the foundation during a half cycle of harmonic vibrations for  $f = 6, 8$  and  $10\text{Hz}$  of the fifth experiments. The deformation curves are drawn by using the observed results of accelerometers shown in Fig. 3. These results indicate that for higher frequencies more than  $f = 8\text{Hz}$ , the foundation may not be considered to be rigid as far as this foundation is concerned.



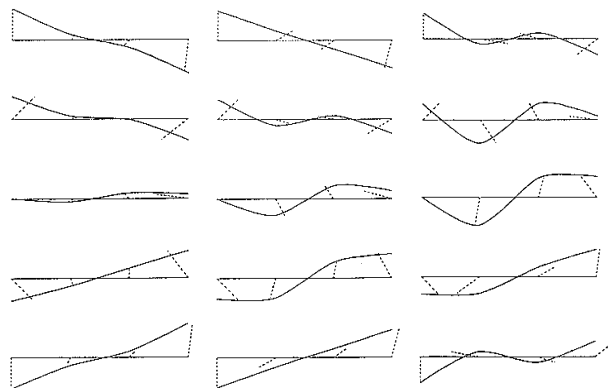
(a) Horizontal (b) Vertical  
Fig.8 Effect of added concrete mass.  
(Comparison of 1st and 6th tests.)



(a) Horizontal (b) Vertical  
Fig.9 Effect of embedment depth.



(a) Horizontal (b) Vertical  
Fig.10 Effect of sheet piles.



(a) 6Hz (b) 8Hz (c) 10Hz

Fig.11 Deformation curves of foundation during a half cycle of vibration (5th test).

5 SOIL RIGIDITY AND RADIATION DAMPING

The dynamic effects of soil may be represented by complex soil springs in which the real and imaginary parts correspond to the rigidity and the radiation damping of soil, respectively. Fig. 12 shows a foundation-spring-dashpot model.  $K_H$  and  $K_R$  of this figure represent the horizontal and rocking spring constants, and  $C_H$  and  $C_R$  are the damping coefficients. These constants are defined at the base of the foundation, in which the effects of constraint of soil at the foundation sides are included. These values can be obtained under the assumption that the foundation is rigid and by using the horizontal and vertical responses observed at the point S0.

In Figs. 13(a) and (b) the spring constants and damping coefficients for the first and second states are shown versus the frequency of excitation. It is seen from these figures that the results are remarkably frequency dependent. Due to the constraint of soil at the foundation sides, the spring constants and damping coefficients for the first state become larger than those of the second state except the rocking damping coefficient in small range of frequencies. Drastic change may be seen for the rocking spring constant. It should be noted that the horizontal spring constant is not affected by the constraint at the foundation sides in lower frequencies.

Figs. 14(a) and (b) show the results for the second and third states. Since there is no constraint of soil at the foundation sides for both cases, similar results are obtained for both states.

The effect of embedment depth on the spring constants and the damping coefficients are shown in Figs. 15(a) and (b). Due to loose backfill soil, the effect of embedment depth does not clearly appear. The tendency, however, that spring constants and the damping coefficients increase with increase of the embedment depth can be slightly seen from the figures.

Figs. 16(a) and (b) show the comparison of the spring constants and the damping coefficients for the first and sixth states. Both cases are affected by the constraint of soil at the sides of the foundation. Observing these results, the followings can be presumed: (1) Since the backfill soil was not enough compacted in the sixth state, large difference was produced between two states. (2) The radiation damping from the side of the foundation into soil is estimated to be very small for this foundation. In other words, almost all the energy radiate into soil from the base of the foundation. (3) The constraint of soil at the foundation sides has a greater influence on the rocking motion than the horizontal component.

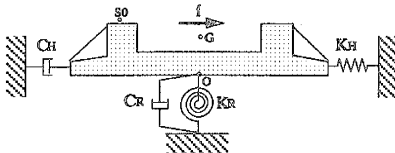
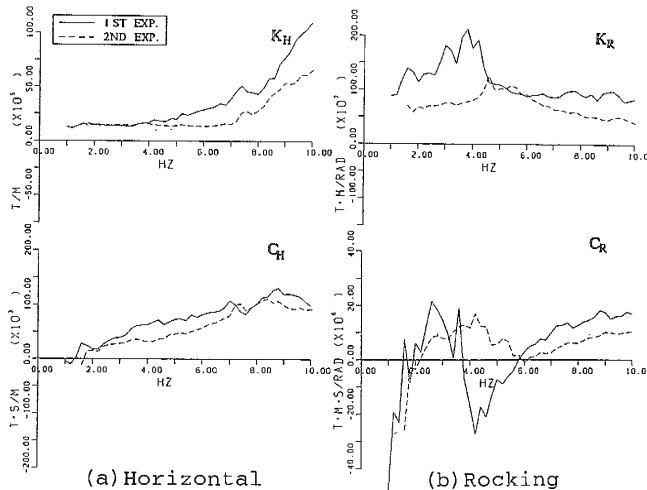


Fig.12 Soil-foundation model.



(a) Horizontal (b) Rocking  
 Fig.13 Spring constants and damping coefficients of soil. (Effect of constraint of side soil)

## 6 CONCLUSIONS

(1) The impulsive excitation test can be used in place of the customary used step-sweep sinusoidal test.

(2) The constraint of the side soil of foundation has effect mainly on the rocking response of the embedded foundation.

(3) Added mass of foundation tends to increase the horizontal displacement of the foundation and changes the resonant frequency of the rocking motion.

(4) Deformation of the foundation becomes remarkable for higher frequencies more than 10Hz.

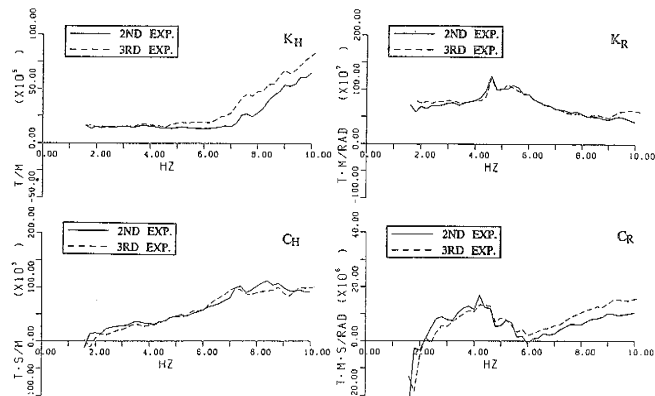
(5) Even when the backfill soil is loose, the embedment effects may appear on the dynamic response of the foundation.

## ACKNOWLEDGEMENTS

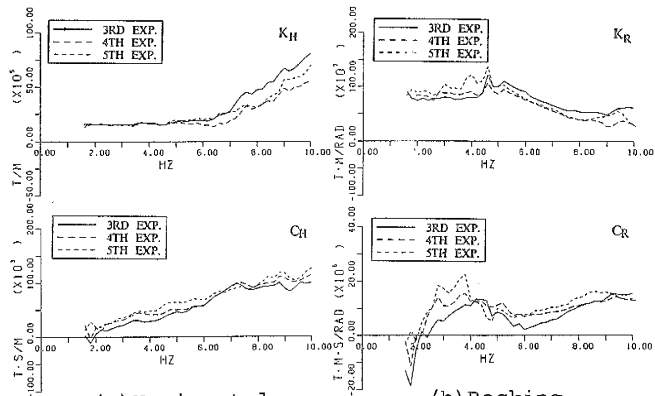
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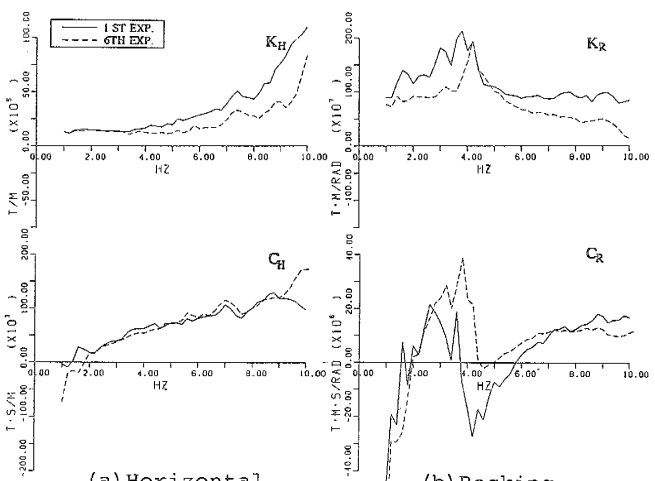
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(a) Horizontal  
Fig.14 Spring constants and damping  
coefficients of soil.



(a) Horizontal  
Fig.15 Spring constants and damping  
coefficients of soil.



(a) Horizontal  
Fig.16 Spring constants and damping  
coefficients of soil.