Design of the foundation of the 5 x 5 m seismic vibration simulation table

Yingcai Han
Institute of Engineering Mechanics, Harbin, People's Republic of China

ABSTRACT: The dynamic response of the foundation of the 5 x 5 m vibration table for simulating earthquake motion was analyzed by the method of elastic half space-lumped parameters while the method of determining lumped parameters was studied systematically. It was found that, the vibration of footing under dynamic loading could be decreased effectively by increasing the radiation damping of the foundation and it seemed that the mass of foundation could be avoided to increase. Vibration test of the foundation showed that the measured data agreed with the theoretical results.

1 INTRODUCTION

The 5 x 5 m seismic vibration simulation table that installed in Institute of Enginеering Mechanics is the bigest one in China at present. The maximum exciting force of the table was 500 KN in one direction, the table could move in two horizontal directions and in vertical direction. Because the frequency of the exciting force varied in a wide range, the foundation would be in resonance situation sometime. If the design of the footing is not suitable, the strong vibration of the foundation and environment would take place, and the vibration table would not operate normally. Therefore, the systematical study for the design of the foundation was done. The dynamical characteristics of the soil in the site were measured, including dynamical three-axes test and wave velocity measurement; the theoretical analysis and vibrational measurement for the dynamical response of the foundation and its surrounding ground were done.

The soil in the site was yellow powder clay since the surface of ground to 20 m depth, mid-density and plasticity, a little wet. Some solid clay layers appeared under ground about 2m , 7m and 15 m depth. Four holes that was 18 m depth were drilled in the site, no underground water appeared. Four soil cores were taken out from each hole. The main mechanical characteristics of soil were measured and shown in table 1.

In order to examine the reliability of analysis theory for the vibration of foundation, vibrational measurements were done for 11 times for 7 different size foundations in Harbin, Changchuen and Tianshui. The foundations were excited by exciter with resonance method, the measurement results were shown in table 2.

The dynamic response of the foundation was analysed with the method of elastic half space-lumped parameters, considering the influence of soil-foundation interaction. The study was focused on these main problems: the mathematical model of coupled horizontal and rocking vibration of embedded footing, the effect of embedment and modified the radiation damping formula and other lumped parameters. The vibration parameters were inverse-response calculation by means of the measured data, then compared the theoretical curves based on the lumped parameters method with the measured data. The comparision between theoretical curves and measured data shown in table 2 could be found in references (Han,1983a,1985). The research was significant for the dynamical analysis of the offshore rigs, nuclear power station, high buildings and large scale foundation under dynamic loading.

2 DYNAMICAL ANALYSIS OF FOUNDATION

The analysis theory of foundation vibration could be classified into two kinds: ground spring theory and elastic half space theory. D.D. Barkan proposed the ground stiffness coefficient method (Barkan,1962). The mathematical model for dynamic analysis of foundation was simple with this way, but determining the stiffness and damping of footing depended on experience. There was defect in determining damping especially. The advantage of the elastic half space theory was that the radiation damping dissipated through elastic wave was considered. The characteristics of soil were expressed by means of the fundamental parameters, such as shear modulus G, poisson ratio ν and mass density ρ. It is easy comparatively that these parameters were determined. In order to application, the elastic half space was compared to a lumped parameters system(Luco,1982, Richart etc,1970, Lysmer etc,1966).But, the groundsoil was not ideal elastic medium in fact. Generally, soil was divided into layers, nonlinear and non-uniform medium. So that, how to set up the equivalent mass-spring-dashpot model based on the elastic half space theory, through vibration test and theoretical analysis to modified vibrational parameters, become the main problem in foundation dynamics. Finite element method and elastic half space-lumped parameters method were the two analysis method for studying soil-foundation interaction.

2.1 Equation of foundation vibration

The soil under foundation was regarded as elastic half space,and the soil beside the foundation was regarded as the sum of a lot of infinite thin elastic layers. Assume the footing as a absolute rigid body, subjected vertical exciting force $F_z e^{i\omega t}$, horizontal exciting force $F_x e^{i\omega t}$ and rocking moment $T_\varphi e^{i\omega t}$, the vertical, horizontal and rocking vibration of footing were caused.

The coupled influence from vertical vibration was very little, it could be neglected. The influence of coupled horizontal and rocking vibration of foundation was considered. The equations of embedded foundation vibration are:

$$M \ddot{Y} + C_z \dot{Y} + K_z Y = F_z e^{i\omega t} \tag{1}$$

$$\begin{bmatrix} M & \\ & I_\varphi \end{bmatrix} \begin{Bmatrix} \ddot{X}_g \\ \ddot{\varphi} \end{Bmatrix} + \begin{bmatrix} C_x & -C_x h_0 \\ -C_x h_0 & C_\varphi + C_x h_0^2 \end{bmatrix} \begin{Bmatrix} \dot{X}_g \\ \dot{\varphi} \end{Bmatrix} + \begin{bmatrix} K_x & -K_x h_0 \\ -K_x h_0 & K_\varphi + K_x h_0^2 \end{bmatrix} \begin{Bmatrix} X_g \\ \varphi \end{Bmatrix} = \begin{Bmatrix} F_x \\ F_x + T_\varphi + T \end{Bmatrix} e^{i\omega t} \tag{2}$$

where, M = mass of footing;
I_φ = mass moment of inertia about centre of base;
K_z, K_x, K_φ = vertical, horizontal and rocking spring coefficient;
C_z, C_x, C_φ = vertical, horizontal and rocking damping coefficient;
Y, $\dot{Y}$, $\ddot{Y}$ = displacement, velocity and acceleration of vertical vibration;
X_g, $\dot{X}_g$, $\ddot{X}_g$ = displacement, velocity and acceleration of horizontal vibration;
φ, $\dot{\varphi}$, $\ddot{\varphi}$ = angular displacement, velocity and acceleration;
h_0 = highness of center of gravity;
h_1 = distance from the center of gravity of footing to horizontal exciting force.

where, T expressed the additional moment of force that was caused by removing the horizontal resisting force of soil from the side to bottom of footing. That is, the embedded footing was simplified as that one resting on the surface of ground. The expression of T was (Han,1985):

$$T = \frac{1}{2} G_s l^2 (S_{u1} + iS_{u2}) \left[X_g + \left(\frac{2}{3} l - h_0\right)\varphi\right] \tag{3}$$

where, G_s = shear modulus of side soil;
l = embedment depth of footing;
S_{u1}, S_{u2} = resistance function of side soil expressed by Bessel function;
$i = \sqrt{-1}$.

2.2 Determining the lumped parameters

Determining the vibration stiffness and damping of footing is an important substance in studying soil-structure interaction. The key of lumped parameters method is selecting the vibration parameters of foundation correctly. The most important characteristic of soil for determining the stiffness and damping of foundation was shear modulus G. The shear modulus G varied with depth, the larger the value of G was, the deeper the position of soil was in.

When a foundation vibrated slightly, the value of G that calculated based on following formula approached those one that converted from measured shear wave velocity.

$$G = 3260 \frac{(2.97 - e)^2}{1 + e} \sqrt{\bar{\sigma}_0} \ (\text{N/cm}^2) \tag{4}$$

where, $\bar{\sigma}_0$ = effective stress of soil in the typical pointbeneath footing;
e = void ratio of soil in the typical pointbeneath footing.

The elastic half space was compared to a lumped parameters system and a series of calculating formula were obtained. However, soil was divided into some layers generally, the elastic wave would be reflected from the boundary surface between layers, so that the energy of viberation couldn't dissipate as the assumption from theory. Based on a lot of measured data, we knew that the radiation damping of foundation was smaller than that one from theory, it was shown in figure 1(Han,1984). For clay medium, following approximate formulae was recommended. Damping ratio for vertical vibration:

$$D_z = \frac{0.49}{\bar{b}_z} \tag{5}$$

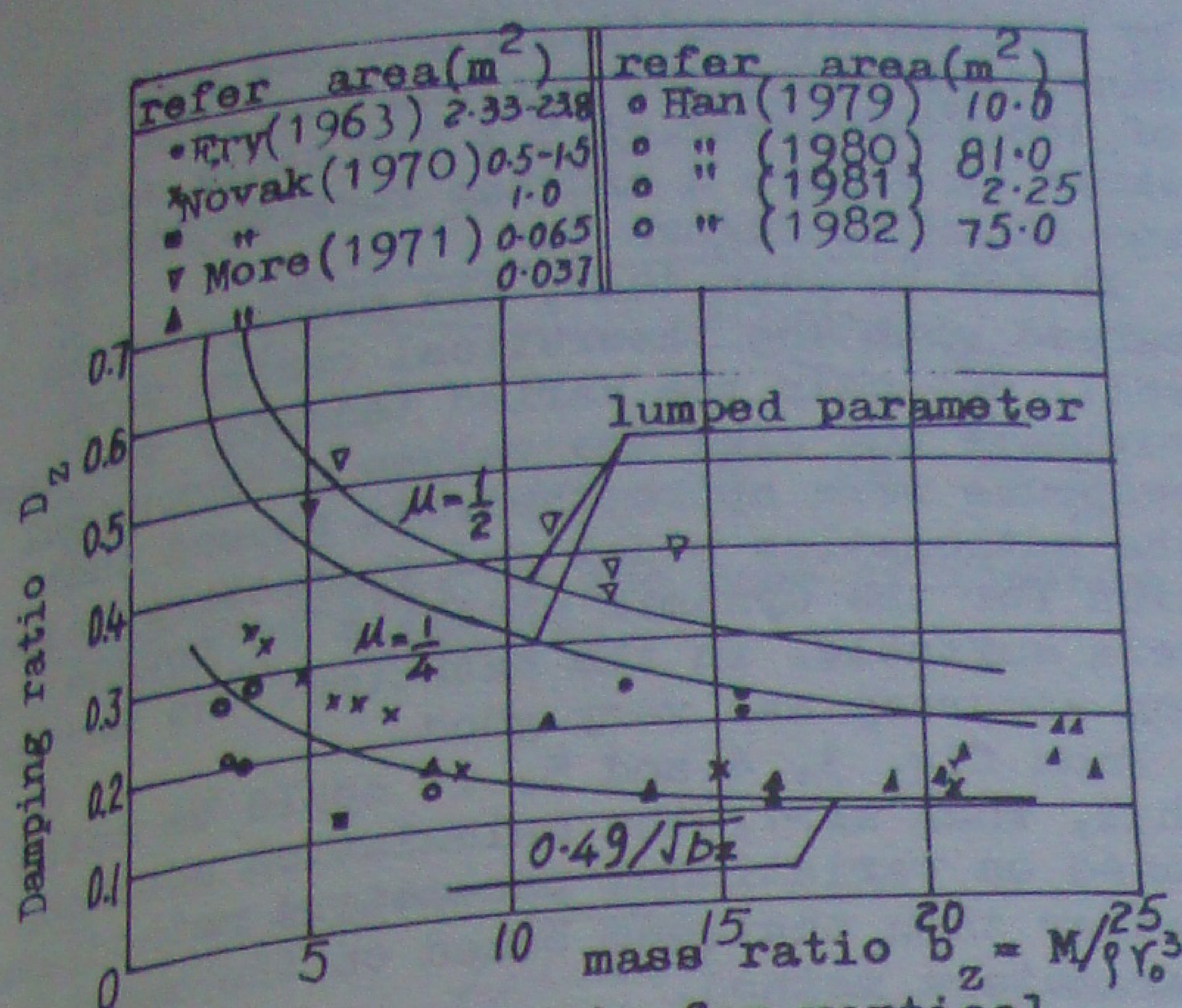

Figure 1. Damping ratio for vertical vibration (clay medium).

where, mass ratio $b_z = M/\rho r_o^3$;

r_o = equivalent radius of footing.

Horizontal and rocking vibration were coupled, the damping ratio of rocking vibration could be calculated like this:

$$D_\varphi = 0.03 + 0.1/\ b_\varphi(1 + b_\varphi/4) \qquad (6)$$

where, mass ratio $b_\varphi = I_\varphi/\rho r_o^5$.

For many times of vibration test, it was shown that the calculated curves by the modified parameters based on equation 4 and 5 agreed with the measured data generally.

2.3 Effect of embedment

The embedment affected the dynamic response of foundation significantly, especially for the coupled horizontal and rocking vibration. The research works about foundation embedment by M. Novk (1971)and R. Whitman (1972) were authoritative. Author of this paper proposed the simplified mathematical model of coupled horizontal and rocking vibration of buried footing (Han,1985). The mathematical model was examined with tests. The foundation in one of the vibration tests was a concrete block with the size of 1.5m x 1.5m x 1.5m . Embedment ratio $\delta = l/r_o$ = 0.00, 0.53, 1.24 and 1.71. Subjected the exciting force $F_x e^{i\omega t}$, the amplitude of the vibforce F_x = 460 N. The results of the vibration test were that, the horizontal amplitude-displacements measured were 127μ,44 μ,9.3$\mu$and 3.7μ (Han,1983b). The test showed that, the stiffness and damping of footing were increased with the embedment obviously, The vibration of foundation was reduced by the embedment.

2.4 Comparison between theoretical calculation and measurement

The shape and size of the foundation of the 5 x 5 m seismic vibration simulation was shown in figure 2. The weight of the footing was 26300 KN. The highness of the center of gravity h_o = 2.33 m. The foundation was subjected the exciting force in three directions and the positions of exciters were shown in figure 2.

Two kinds of the lumped parameters method were used for calculating the vibration of foundation. One of them was that the mass of footing was constant but stiffness and damping were variational parameters, called as variational parameters method, shown by solid line in figure 3, 4 and 5. Another one was that the stiffness and damping of footing were constant but the mass was exchanged, called as constant parameters method,shown by dashed line in figures. The vibrational parameters of the 5 x 5 m table foundation shown in table 3 were calculated based on the latter.The mass density of backfill soil surround the footing $\rho_s = 0.7\rho$ and the formulas of embedment were adjusted correspondingly.

From the shear wave velocity measured in the site, the shear modulus G could be gotten. Then, the values of G, ν and ρ were substituted into the formulas of lumped parameters,and the equation 4 and 5 were made use of , as a result the values in table 3 could be gotten.

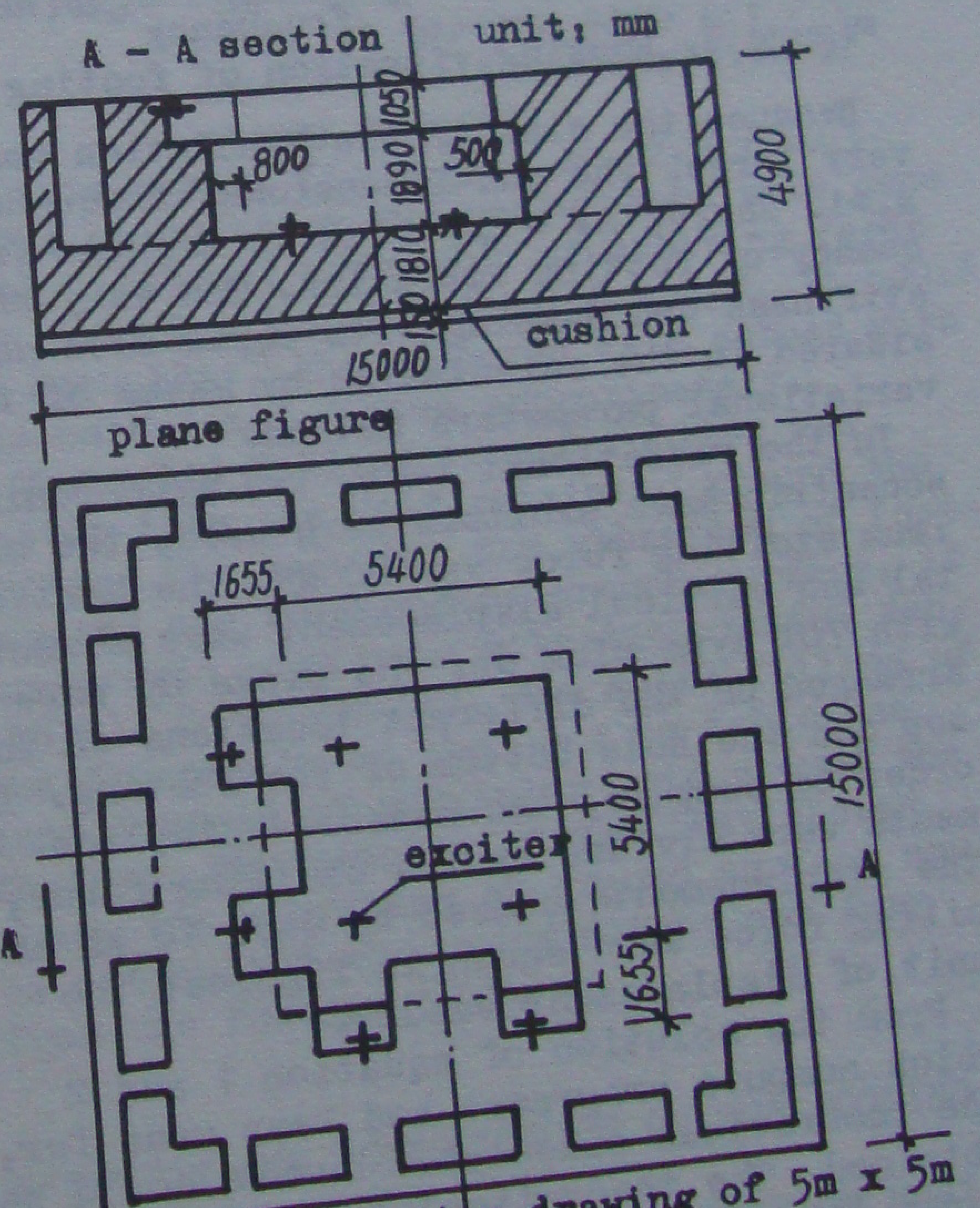

Figure 2. Foundation drawing of 5m x 5m vibration table.

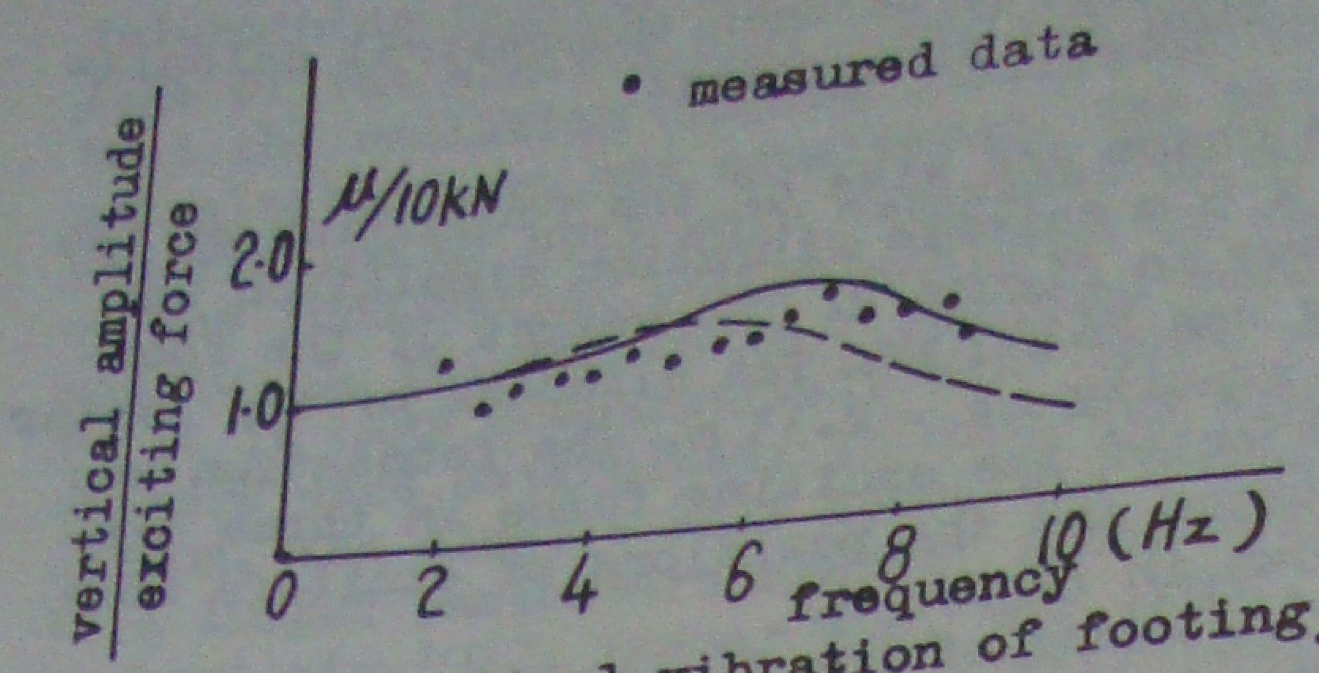

Figure 3. Vertical vibration of footing.

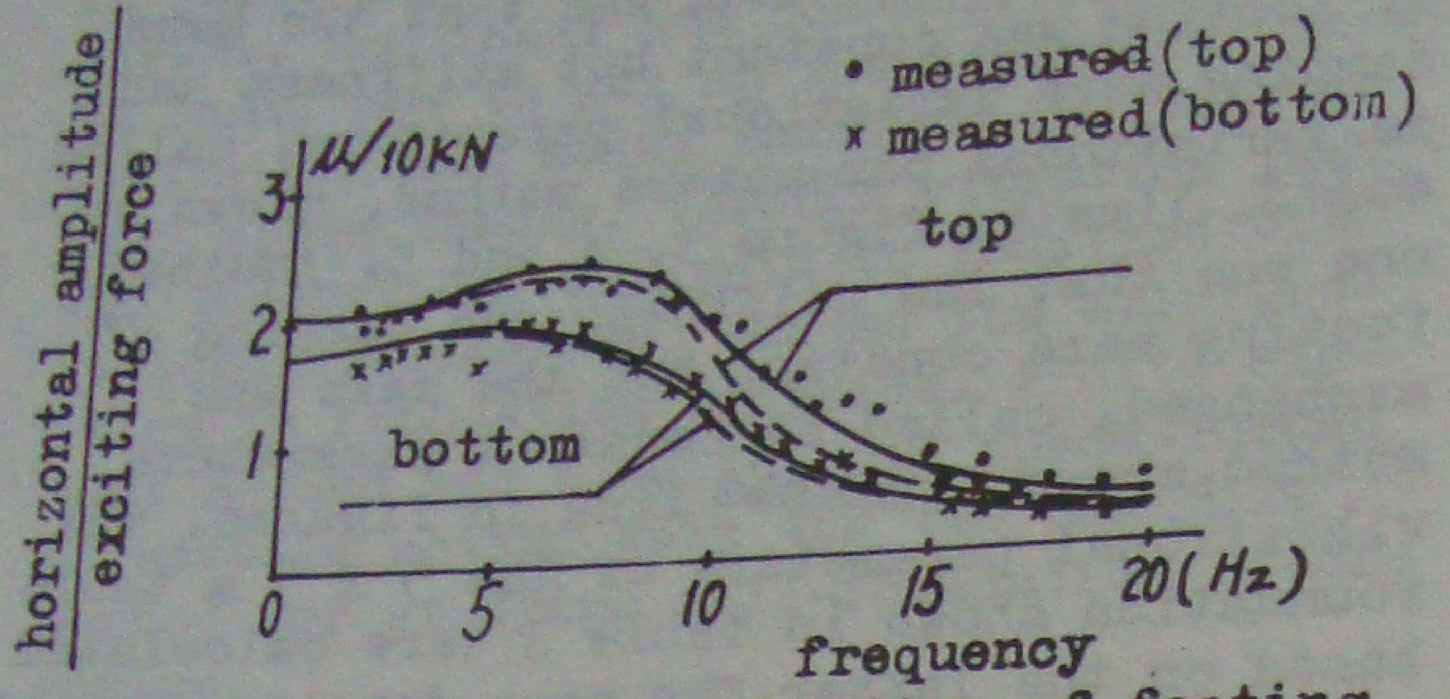

Figure 4. Horizontal vibration of footing.

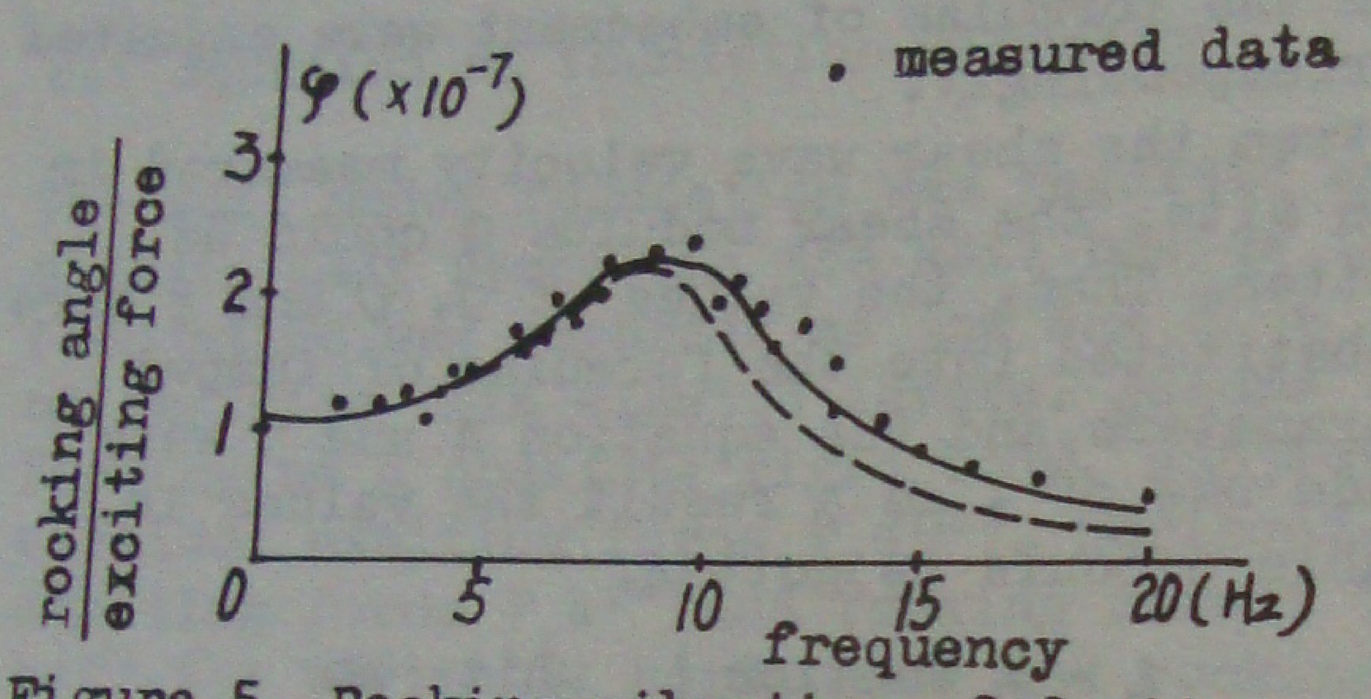

Figure 5. Rocking vibration of footing.

Because the size of the foundation was very large, the non-dimensional frequency $a_o > 1$. Where, $a_o = r_o\omega/v_s$, ω is angular frequency of footing vibration. The vary of stiffness and damping with a_o had been considered in the calculation by means of the variational parameters method.

In the vibrational test, two synchronism eccentric mass exciters were used, the maximum exciting force was 80 KN. The horizontal and vertical displacement were measured with 701 type pick up. The picks up were arranged on the different locations of the top and the hole bottom of the footing. In order to compare, the measured displacements were divided by its exciting force, the displacements caused by each 10 KN exciting force were shown in figures(the unit of displacement was μ).

From the solution of equation 1 and 2 which compute programme had been made for, the theoretical calculated curves could be obtained. The theoretical curves and measured data for vertical vibration of footing was shown in figure 3. The coupled horizontal and rocking vibration were caused by horizontal exciting force, the horizontal displacement on the top and the hole bottom of the foundation of 5 x 5 m table was shown in figure 4 and the rocking vibration was shown in figure 5.

It can be seen that, the measured data agreed with the theoretical curves very well, not only the varied tendency was approximate but also the values of dynamical response were approached. It showed that the mathematics model and parameters selection for the dynamic analysis of foundation were suitable, in the meantime, the measuring accuracy was very good.

From fig. 3, 4 and 5, it could be noted that, when $a_o > 1$, the calculation accuracy based on variational parameters method was better than that one based on the constant parameters method.

3 EFFECT OF MASS OF FOUNDATION

Based on the research of soil-foundation interaction, radiation damping of footing depended on the mass ratio $b_z = M/\rho r_o^3$ for vertical vibration. The less the mass ratio was, the larger the damping of foundation was. For the same mass M of footings, if the equivalent radius r_o of footing is designed as large as poissble, that means the mass ratio to be reduced, the larger radiation damping would be obtained, then the vibration of footing would be reduced. In the meantime, the stiffness of ground would increase with the increasing of r_o. On the other hand, for a constant radius r_o of foundation, if the mass M of footing varies, the dynamic response of the footing would be different. Assume the mass of a foudation with a cavity to be a certain value M_1, $b_z = 2.5$, then the mass was increased to M_2 in the cavity, so that, the mass ratio and damping would change. The dynamic response of the foundation was calculated and shown in figure 6. It could be seen that, with the increasing of the mass of footing, the displacement amplitude of the foundation increased, the acceleration of the foundation reduced and the velocity of the footing was almost constant.

For horizontal excitng force, the situation would be more complex, because the horizontal and rocking vibration were coupled generally. Take the parameters of the foundation of the 5 x 5 m table as a example, its mass was M. Assume the mass of the foundation to exchange to 0.9 M, 0.8 M and 0.7 M, the dynamic response curves were shown in figure 7. It could be seen that, the horizontal displacement amplitude would reduce with the reducing of the mass of the footing in lower frequency range. But in

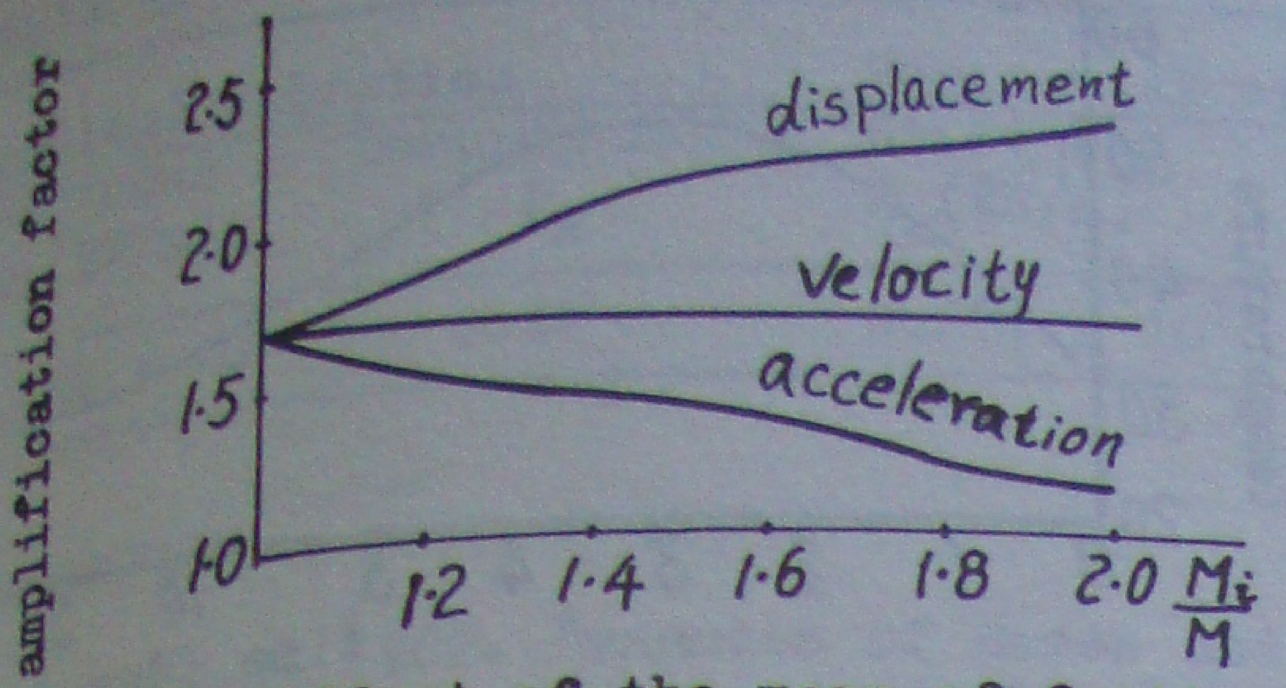

Figure 6. Effect of the mass of footing on vertical vibration.

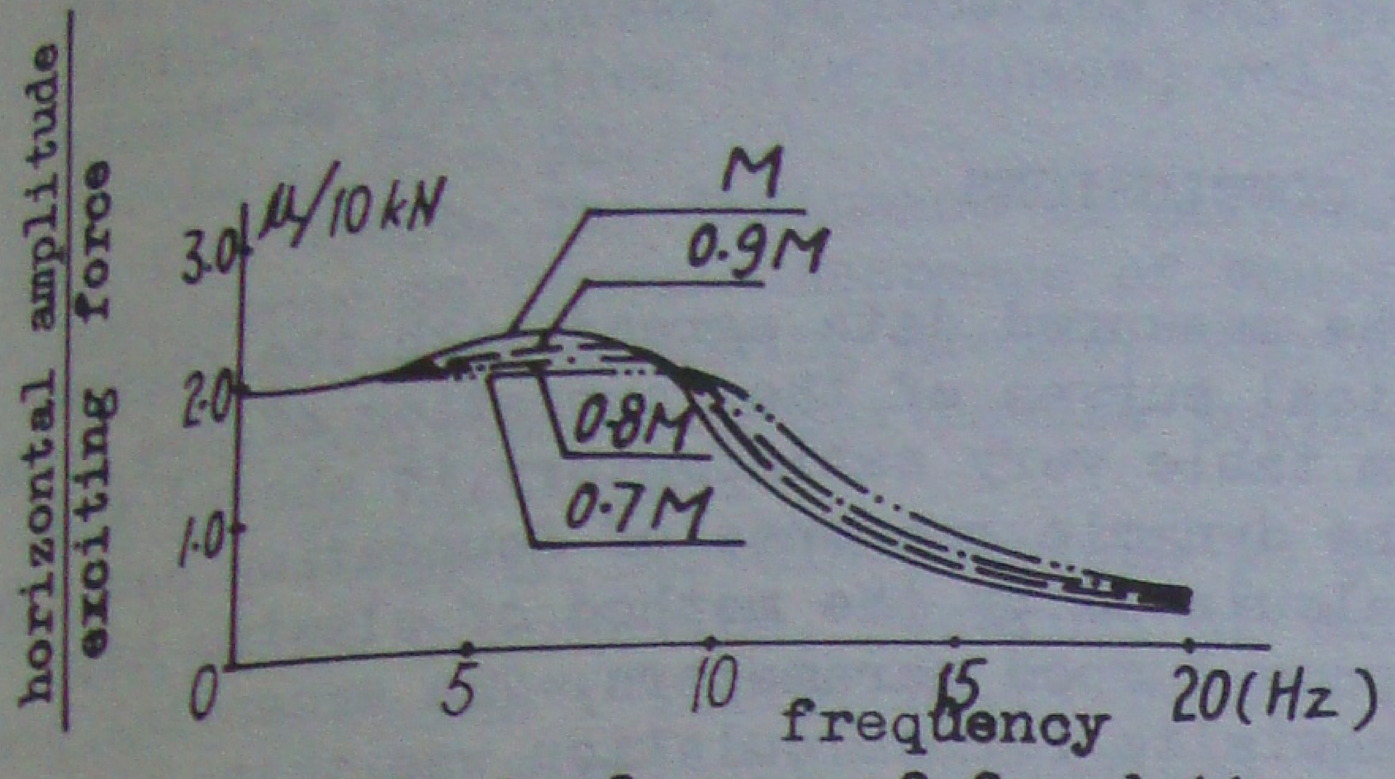

Figure 7. Effect of mass of foundation on horizontal vibration.

higher frequency range, the situation was contrary.

The shape of foundation, including radius r_0 and mass M, should be designed suitably. Considering the soil-foundation interaction, the radiation damping was increased as large as possible and the material of footing was saved as more as posible. From these analysis,we could say that, increasing the mass of footing was not always beneficial to reduce the vibration of footing.

4 DYNAMIC RESPONSE OF SURROUNDING GROUD

Both P-wave and R-wave would attenuat,with the distance from the exciting foundation. But the R-wave attenuation was slower than P-wave did. Therefore, the influence of the exciting footing on the surrounding ground depended upon the attenuation of R-wave mainly, while the influence of P-wave should be considered suitably.

In the vibration test of the foundation of the 5 x 5 m table, the horizontal and vertical displacement amplitudes on the ground with different distance away from the footing were measured. The calculated curves and measured data were shown in fig. 8 and 9 for vertical and horizontal vibration separately. The calculated curves were obtained based on following expression:

$$W = W_1 \beta \sqrt{\frac{r_0}{r}\left[1-\xi_d\left(1-\frac{r_0}{r}\right)\right]} \cdot e^{-f\alpha(r-r_0)} \qquad (7)$$

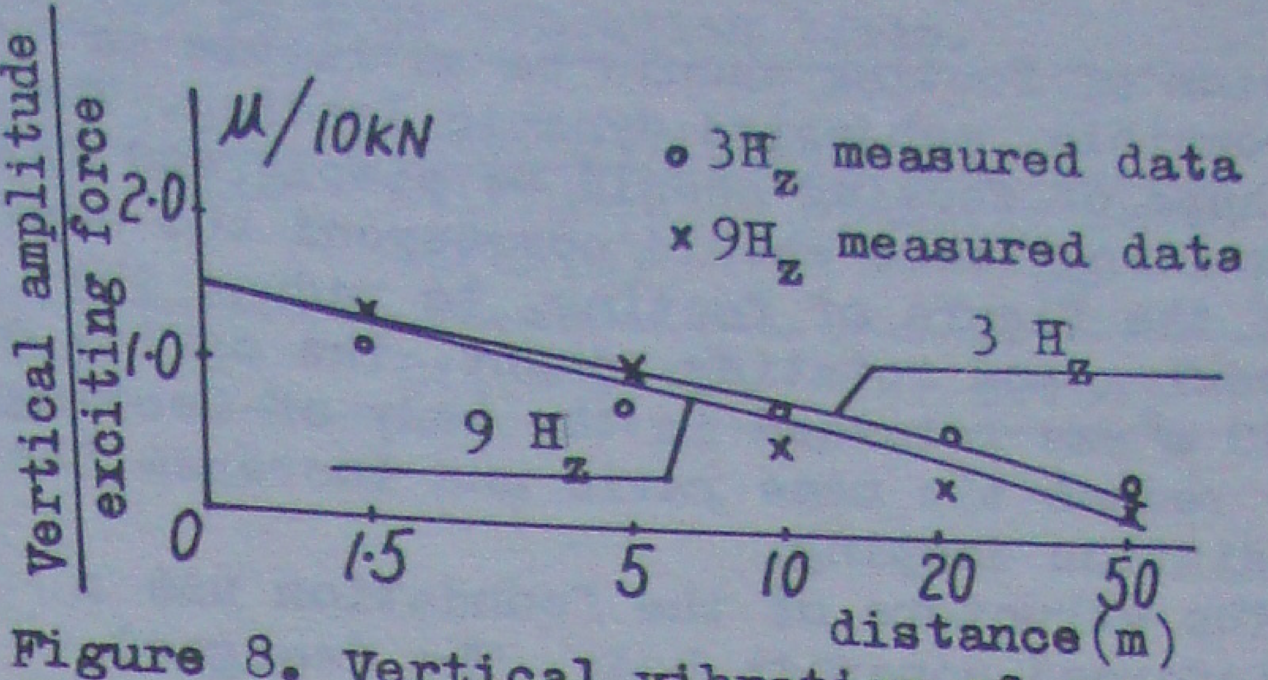

Figure 8. Vertical vibration of surrounding ground of foundation.

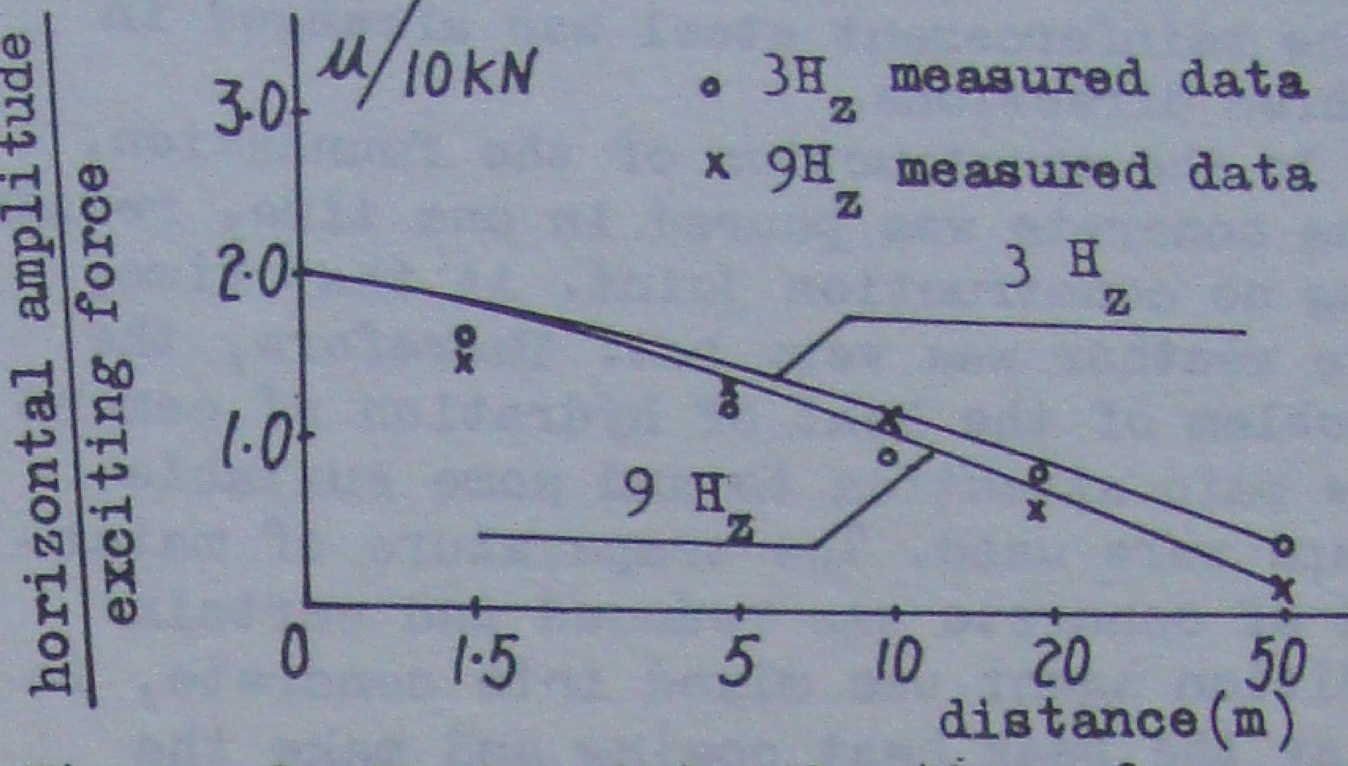

Figure 9. Horizontal vibration of surrounding ground of foundation.

Where, W = amplitude of surface of ground to distance r from the centre of foundation;

W_1 = amplitude of footing;

β = coefficient for influence of loading, for nature surface of ground $\beta = 1$;

f = excitation frequency;

ξ_d = coefficient of influence of P-wave, it depends upon r_0;

α = coefficient for absorption of energy of soil.

In this paper, $\xi_d = 0.25$, $\alpha = 2.0 \times 10^{-3}$.

The calculation and measurement were done with different frequency of exciting force 3 H_z and 9 H_z shown in fig. 8 and 9. It could be seen that, the measured data agreed with the calculated curves approximately.

The solid filling around footing was better than the void retaining around the footing for reducing the vibration of footing and its surrounding ground surface, it was proved with some vibration tests(Han, 1983b). Consequently, the solid filling of the foundation of the 5m x 5m table was made instead of retaining void around the footing. The results of the test showed that, the vibration of ground surface could be attenuated to a very slight one away from the footing 50 m.

5 DESIGN AND CONSTRUCTION OF THE FOOTING

As a reaction mass, the foundation must be designed to a rigid block and the deformation of footing should be as little as possible, subjected dynamic loading. The shape of footing should be simple and the exciting force should correspond the centre of the figure of footing, to reduce the rocking and rotating moment. The cavity of 140 m^3 was retained in the body of footing, to reduce the mass ratio and increase the radiation damping.

The structure of the foundation was a reinforced concrete body. The designed grade of concrete was 250*. The reinforcement ratio was more than 0.3 % somewhat and the reinforcement steel was arranged in three directions.

In the construction of the foundation, the concrete was poured in one time, retaining no construction joint. At that time, the weather was very hot. Therefore, the problem of the heat of hydration of cement was paid attention to and some suitable steps were used. The temperature of material of concrete was reduced and certain addition agent was mixed into concrete, to delay the peak heat coming and make the strength of concrete increasing. The temperature inside the concrete of the footing was measured and shown in fig. 10. It showed that the temperature varied with time after the concrete had been poured.

The estimation of the vibration of the 5m x 5m table foundation could be done, based on its vibration test. When the table is in operation, the horizontal displacement amplitude would be 0.15 mm and acceleration 0.0 55 g by the maximum exciting force in one direction.

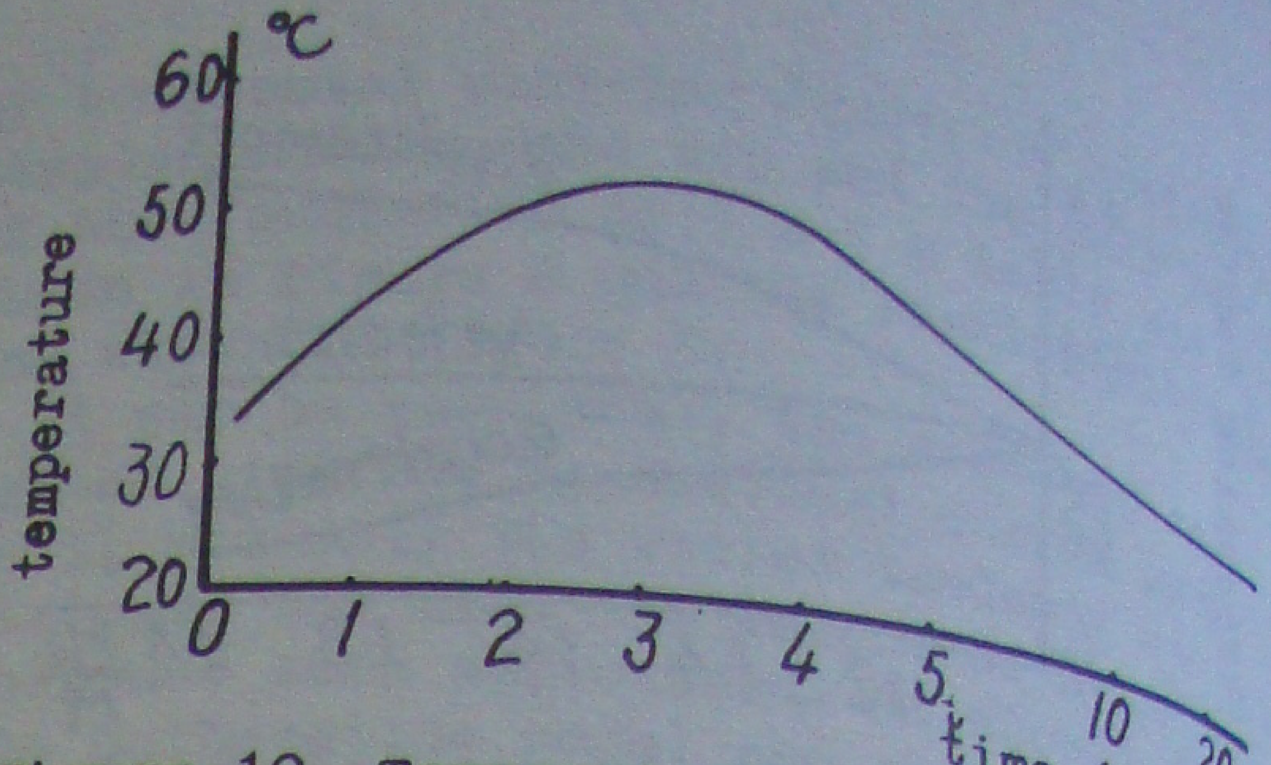

Figure 10. Temperature curve measured after pouring concrete.

6 CONCLUSIONS

The measured data agreed with the theoretical curves of the foundation of the 5m x 5m table very satisfactory,it showed that the dynamic response of foundation could be calculated by the method of elastic half space-lumped parameters. The essential prerequisite for calculation was that, the shear modulus G of ground soil should be determined correctly, the effect of embedment should be determined and the formulae of damping should be modified.

The suitable geometry shape of footing should be designed,reducing the mass ratio and increasing the radiation damping.

The solid filling around the footing was better than the void retaining around the footing.

Table 1. The main mechanical characteristics of the soil in site.

Depth of soil (m)	Unit weight (g/cm)	Void ratio (e)	Shear wave velocity V_s (m/s)	P-wave velocity V_p (m/s)
0.0 - 2.0	1.89	0.78	185	314
2.0 - 5.0	1.71	0.95	179	519
5.0 - 12.0	1.95	0.68	256	1530
12.0 - 18.0	1.93	0.65	377	1530

Table 2. Dynamic response measurement of foundations

Position of foundation	Size of footing (m)	Backfill	Frequency* (H_z)	Date (year, month)
Harbin	3.0 x 3.0 x 1.5	no	H : 14, V : 21	1980,6
Harbin	3.4 x 2.9 x 1.5	slag	H : 19, V :22	1980,11
Changchuen	12.5 x 6.5 x 3.7	crushed stones	V :8.5	1982,9
Harbin	4.6 x 2.7 x 1.1	non-disturbed	H : 15	1981,8
Harbin	1.5 x 1.5 x 1.5	soil $\rho_s = 0.8\rho$	H : 12.5, V : 21	1981,9
Tianshui	12.0 x 8.8 x 4.8	soil $\rho_s = 0.75\rho$	H : 8.5	1983,6
Harbin	15 x 15 x 4.9	soil $\rho_s = 0.70\rho$	H : 6.5, V : 5.5	1984,8

* 'H' means horizontal, 'V' means vertical.

Table 3. Constant parameters of the foundation of the 5m x 5m vibration table.

Vertical vibration		Horizontal vibration		Rocking vibration	
Stiffness K_z(KN/m)	Damping ratio D_z	Stiffness K_x(KN/m)	Damping ratio D_x	Stiffness K_ϕ(KN.m)	Damping ratio D_ϕ
0.954×10^7	0.42	0.687×10^7	0.67	0.454×10^9	0.18

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