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SITE MEASURING AND ANALYSIS OF GROUND VIBRATION INDUCED BY THE LARGE EARTHQUAKE SIMULATION SHAKING-TABLE OPERATION

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Abstract

The large shaking-table operation induced vibration to the free-field is concerned by the nearby users of precise instruments laboratory and refinement processing workshop. In previously researches, theoretical analysis using transfer function method about ground vibration induced by shaking-table operation has not been verified by testing. The present paper focuses on site measuring and analysis of surrounding free-field vibration induced by the large earthquake simulation shaking-table operation. The field vibrations induced by the large shaker were recorded at multiple stations within the steel platen, the reinforce concrete foundation block and the surface of the surrounding soil up to distances of 26 m from the shaker. The results obtained validate that the rigid-body motion pattern of the foundation block for NS excitations of the block have been determined. It has been shown that the foundation of the shaking-table can be simplified as a single-DOF mass-spring-damping model, the foundation soil provides spring restoring force and damping force, the operation of the shaking-table is taken as dynamic loads exerted on the foundation. From the frequency response curve of the foundation obtained with the sweeping-frequency tests for a harmonic force of constant amplitude, the natural frequency of the foundation was determined as 11.8Hz, and this result shown good agreement with the estimated ones as 12.1Hz by using 'Code for design of dynamic machine foundation' combining the geotechnical characteristics of the site. The vibration of reaction foundation block is sufficiently small. For a actual ground motion recorded in a strong earthquake of 60mm,10cm/s and 1.5g corresponding to the maximum displacement, velocity and acceleration that the shaker actuators exert on the foundation, the average rigid-body translation at the top of the block has amplitude of less than 17μm, 0.2mm/s and 5gal respectively, and the latter is less than 0.1%, 0.2%, 0.4% of the former respectively. The vibration attenuation from the foundation to surrounding field versus distance obeys an exponential law, and the measured result is attenuation slowly than estimated ones by the Code. Vibration velocity and acceleration comparison between measured and Code limit value shown that vibration induced by the full load operation of the shaking-table does not have a worse effect on people health and building safety in surrounding field.

Keywords: shaking-table operation, ground vibration, site measuring, mass-spring-damping model, attenuation law

1. Introduction

Opening in the summer of 2013, the newest facility in Earthquake Simulation Laboratory of Institute of Disaster Prevention(IDP) is the biaxial shaking-table. The table is comprised of a 3×3m, 6-ton steel platen with three actuators. It has a stroke of ±100mm, and can reach a peak velocity of 500mm/sec and an acceleration of 1g with a 15 tons payload. A large reinforce concrete foundation block of about 11×11×3.8m and 1060-ton is used for vibration reduction of the shaking-table operation. The shaking-table induced vibration influence to the free-field is a primary area of focus, especially for the nearby users of precise instruments laboratory and refinement processing workshop.

In the previously researches by other people, the measurement of induced ground vibration influence is main focused on the operation of the train and machine, and little research work about the ground vibration induced by shaking-table has been conducted[1,2,3]. Theoretical analysis using transfer function method about the ground vibration influence by operation of shaking-table has been conducted by Huang and Hou[4,5], but the analysis result has not been verified by testing. For this reason, it was necessary to evaluate the ground vibration induced by the operation of earthquake simulation shaking-table as well as to obtain a virtual model for estimate the ground vibration effect induced by shaking-table.

The first objective of the experimental study was to obtain dynamic ground motion data, and by inference geotechnical data, which will prove invaluable in the development of a virtual model of the complete IDP shaking-table including surrounding soil, the reinforced concrete foundation block, the steel platen, the actuators, and the test specimen. The second objective of the study was to obtain magnitude of the ground motion, including the acceleration, velocity and displacement, induced by the operation of the shaking-table. In particular, the dynamic ground motion data would offer experimental information on analysis of the attenuation law of the ground vibration on the soil surrounding the foundation.

2. Force vibration tests of the shaking-table foundation

The force vibration tests of the shaking-table foundation were conducted using the equipment from the Earthquake Simulation Laboratory in Institute of Disaster Prevention, China. The equipment included a biaxial shaking-table, eight Type-941B vibration sensors, one Type-941 signal amplifier and one Type-INV3060 data acquisition instrument.

2.1 Instrumentation of the shaking-table and adjacent foundation block

The foundation block was instrumented with 5 arrangements of 941B acceleration sensors(F2,F3,F6,F7,F8) while platen shaking-table with 2 arrangements of sensors(P1,P5) and with a surrounding soil measuring station beside foundation boundary(S4). The location of the stations is shown in Fig. 1. The distance of station F2 (or F6) to the centre of steel platen is 3 meters.

We suppose a virtual model of the complete IDP shaking-table including surrounding soil, the reinforced concrete foundation block, the steel platen and the test specimen. Assuming that the actuator force the steel platen and test specimen moving while it drive the foundation block vibration, the mass-spring-damping model is reasonable that the lumped mass is afforded by shaking-table foundation while the restoring force and damping force are afforded by foundation soil. The lumped mass afforded by shaking-table foundation block is M, and the equivalent lateral/vertical stiffness afforded by surrounding soil is K_x/K_z while the equivalent lateral/vertical damping ratio afforded by surrounding soil is ζ_x/ζ_z. The virtual mechanics model of the shaking-table foundation is shown in Fig. 2.

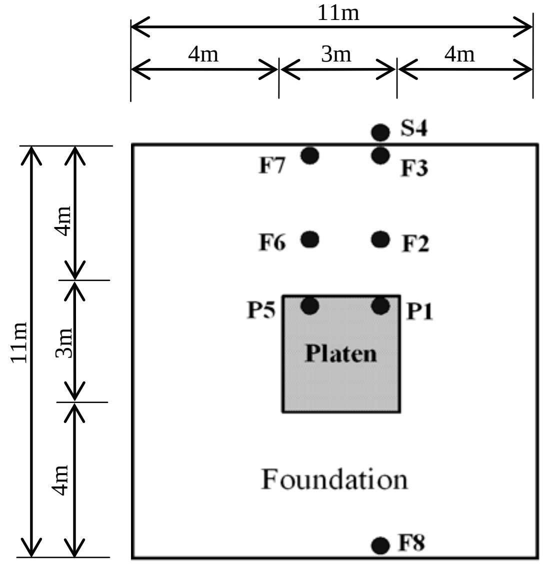

Fig. 1 – Measuring stations arrangement for rigid-body foundation hypothesis

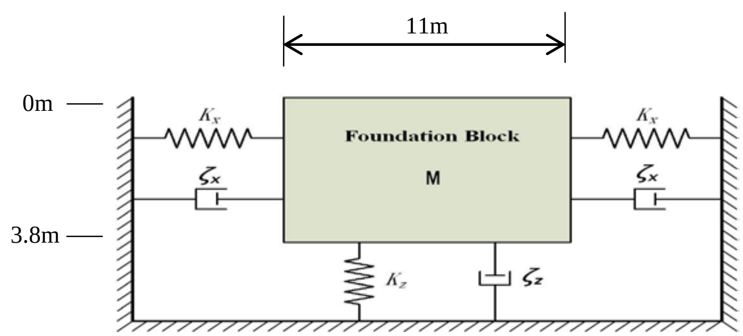

Fig. 2 – Mechanics model of the shaking-table foundation

2.2 Test for the assumption of rigid-body motion pattern of foundation block

The test included excitations in the NS direction with two shaking-table actuators. The forced vibration test use 'actual El Centro ground motion' excitation. The PGA(Peak Ground Acceleration) of each station and cross correlation coefficient for each station to F2 station are shown in Table 1. The cross correlation coefficient is defined by Eq. (1).

$$\rho_{xy}(\tau) = \frac{R_{xy}(\tau) - \mu_x \mu_y}{\sigma_x \sigma_y} \tag{1}$$

where

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t) y(t+\tau) dt \tag{2}$$

while the x(t) and y(t+τ) are the time histories from different stations.

Table 1 – PGA(gal) and cross correlation coefficient

Station No.	**F2**	**F3**	**S4**	**F6**	**F7**	**F8**
PGA	2.38	2.47	2.11	3.01	2.39	1.91
$\rho_{2x}(\tau)$	1	0.99	0.97	0.97	0.98	0.96

The PGA of the foundation is from 1.91 to 3.01gal and the vibration model is a highly linear correlation[6] of each station to F2 station because of all the cross correlation coefficients are bigger than 0.96. So the assumption of foundation moving with a rigid-body is accepted.

2.3 Sweeping-frequency tests for foundation's natural frequency

For conducting the displacement frequency response curve of the foundation forced by the steel platen and shakers, we arranged two stations on the top of the foundation block and the platen. Fig. 3 shows the station arrangement of this test. The foundation station(FS) is arranged a acceleration sensor and the measured acceleration is defined as a, while the platen station(PS) is arranged a displacement sensor and the measured displacement is defined as u_0. The two shaking-table actuators in NS direction produce a sinusoidal force with a rotating frequency f. The sinusoidal force covers frequencies ranging from 7 to 15Hz.

We obtained the displacement response factor as the Eq. (3), and Fig. 4 shows the displacement frequency response curve of this sweeping-frequency tests. The natural frequency of the foundation block is 11.8Hz from the sweep frequency corresponding to the peak displacement response factor.

$$R_d = \frac{u_0}{(u_{st})_0} = \frac{u_0}{P/K} = \frac{u_0}{\mathrm{m}\times\mathrm{a}/K} = \frac{u_0}{\mathrm{a}}\times\frac{K}{M}\times\frac{M}{\mathrm{m}} = \frac{u_0}{\mathrm{a}}\times\frac{M}{\mathrm{m}}\times\omega_{\mathrm{n}}^{2} \tag{3}$$

where 'M' is the mass of the foundation block and 'm' is the mass of the steel platen.

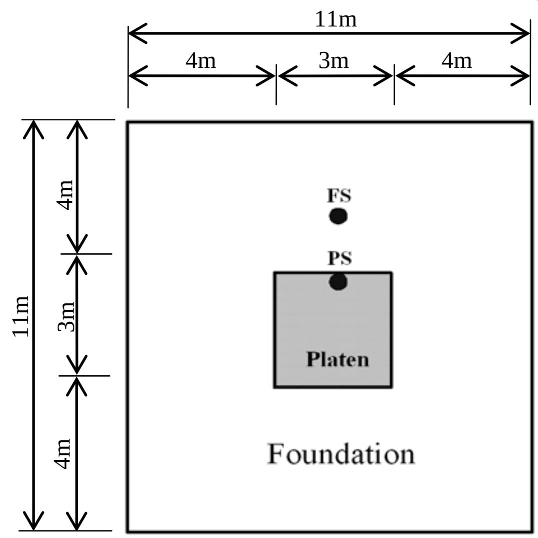

Fig. 3 – Measuring stations arrangement for the sweeping-frequency tests of foundation

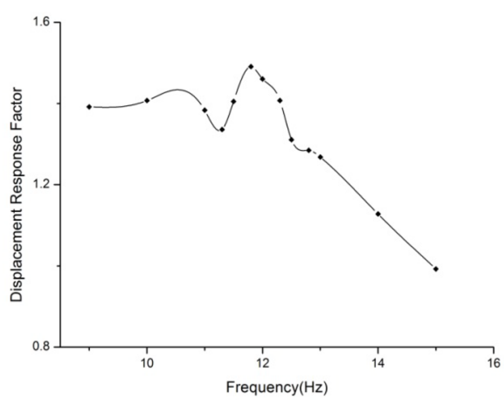

Fig. 4 – Displacement frequency response curve by using sweeping-frequency tests

2.4 Estimate for foundation's natural frequency by 'Code for design of dynamic machine foundation'

The field investigation including several exploratory borings indicates that just sandy soil underlie the site[7]. The characteristic value of bearing capacity of foundation is 200 kPa after CFG piles in foundation treatment. Estimating the dynamic characteristic of foundation block by using 'Code for design of dynamic machine foundation(CDMF)(GB50040-96)'[8], the natural frequency of the foundation is 12.1 Hz while the equivalent damping ratio of the foundation is 0.125. The calculation procedure is as follows:

The shear stiffness coefficient of subsoil is $C_x = 0.7C_z = 2.52\times10^7\ N/m^3$

where $C_z=3.6\times10^7 N/m^3$ is compressive stiffness coefficient of subsoil, from CDMF.

So the shear stiffness coefficient of surface foundation is $K_x' = C_x A = 2.52\times10^7\times121 = 3.05\times10^9\ N/m$

And the shear stiffness coefficient of embedded foundation is $K_x = \alpha_{x\varphi}K_x' = 6.1\times10^9\ N/m$

where $\alpha_{x\varphi} = (1+1.2\delta_b)^2 = 2$ is the improving effect by the foundation depth,

and the $\delta_b = \frac{h_t}{\sqrt{A}} = \frac{3.8}{11} = 0.345$ is the depth ratio of the foundation while the h_t is the foundation depth.

So the equivalent vertical damping ratio afforded by surrounding soil is $\zeta_z = \frac{0.11}{\sqrt{\bar{m}}} = 0.174$

where $\bar{m} = \frac{M}{\rho A\sqrt{A}} = \frac{1.06\times10^6}{2.0\times10^3\times121\times\sqrt{121}} = 0.398$ is the mass ratio of the foundation block and the soil,

so the amended equivalent lateral damping ratio afforded by surrounding soil is $\zeta_{x\varphi} = 0.85\times\beta_{x\varphi}\times\zeta_{x\varphi}' = 0.125$

where original equivalent lateral damping ratio is $\zeta_{x\varphi}' = 0.5\zeta_z = 0.087$, and $\beta_{x\varphi} = 1+2\delta_b = 1+2\times0.345 = 1.69$ is the improving effect by the foundation depth, while 0.85 is a damping ratio reduction factor for block foundation.

So the natural frequency of the foundation is $f = \frac{\omega_n}{2\pi} = 12.1Hz$

where the circular frequency of the foundation is $\omega_n = \sqrt{\frac{K_x}{M}} = \sqrt{\frac{6.1\times10^9\ N/m}{1.06\times10^6\ Kg}} = 75.9 rad/s$

The natural frequency of the foundation estimating by 'Code for design of dynamic machine foundation' is very similar to the result from the displacement frequency response curve by using sweeping frequency tests.

3. Attenuation law of ground motion on field

The force vibration tests for studying the attenuation law of soil surrounding the shaking-table foundation were conducted using the equipment from the Earthquake Simulation Laboratory in IDP, China. The equipment included a biaxial shaking-table, some '941B' vibration sensors, a signal amplifier and a 'INV3060' data acquisition instrument. The bandwidth of the system is from 0.035Hz to 35Hz, while the sampling rate is 1024Hz. The forced vibration tests use 'Wolong ground motion' excitation from 2008 Sichuan Earthquake in China.

3.1 Displacement attenuation law on field

The platen shaking-table was instrumented with one velocity sensor(P1) while foundation block with one velocity sensor(F2) and surrounding soil field with 3 velocity sensors(S3, S4, S5). The mass of the test specimen on the platen is 7-ton. The location of the stations is shown in Fig. 5. The distance of stations marked F2, S3, S4, S5 to P1 is 2m, 4m, 14m, 24m. Displacement data of stations are obtained from the integral of the measured velocity. The PGD (Peak Ground Displacement) of each station is shown in Table 2 and Fig. 6. The test results show that when the table surface's displacements on EW and NS direction are 60mm and 58mm, the ground surface's displacement of the field is only 5-17μm, and the latter is less than 0.1% of the former.

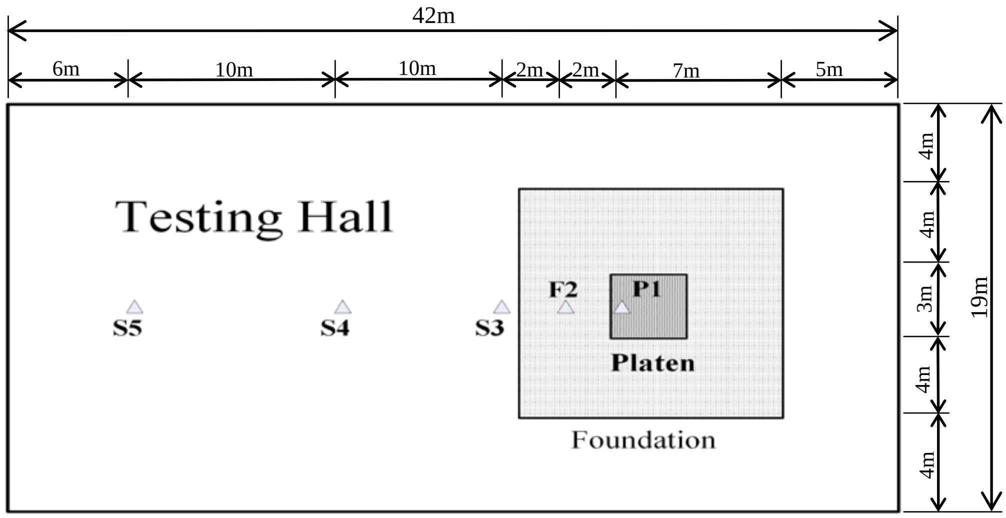

Fig. 5 – Measuring stations arrangement for the displacement attenuation test

Table 2 – PGD(μm) of each measuring station

Station No.	**P1**	**F2**	**S3**	**S4**	**S5**
EW	60130	12.21	7.45	5.88	5.74
NS	57990	16.74	12.42	8.81	5.11

We estimated the vibration displacement of surrounding soil field by the Equation in CDMF[8] (Eq. (4))and by the Equation of Huang[1] (Eq. (5)).

$$\frac{A_r}{A_0} = [\frac{r_0}{r}\xi_0 + \sqrt{\frac{r_0}{r}}(1-\xi_0)]e^{-f_0\alpha_0(r-r_0)} \tag{4}$$

$$\frac{A_r}{A_0} = k_1 \cdot \sqrt{\frac{r_0}{r}} \cdot e^{-f_0\alpha_0(r-r_0)} \tag{5}$$

where $r_0 = \mu_1\sqrt{\frac{A}{\pi}} = 0.8\sqrt{\frac{11\times11}{\pi}} = 4.96m$, while the ξ_0 is 0.25, and α_0 is 1.2×10^{-3}s/m, and f_0 is 12Hz, and k_1 is 1.

Table 3 shown the displacement from the measured and estimated by equation from Code and Huang, and Fig. 7 shown the fitting curves of the measured and estimated. All of them revealed that the equation by Huang is fitting to the measured better. The attenuation law of vibration displacement with distance in NS direction is exponential relationship.

Table 3 – PGD (μm) comparison between measured and estimated

Station No.		**F2**	**S4**	**S5**
EW	**Measured**	12.206	5.876	5.739
	Estimated by CDMF	-	5.316	3.462
	Estimated by Huang	-	5.960	4.023
NS	**Measured**	16.741	8.809	5.112
	Estimated by CDMF	-	7.291	4.748
	Estimated by Huang	-	8.175	5.518

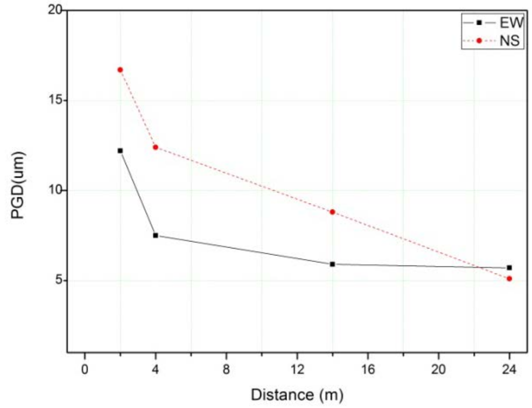

Fig. 6 – PGD attenuation from the foundation to surrounding field versus distance

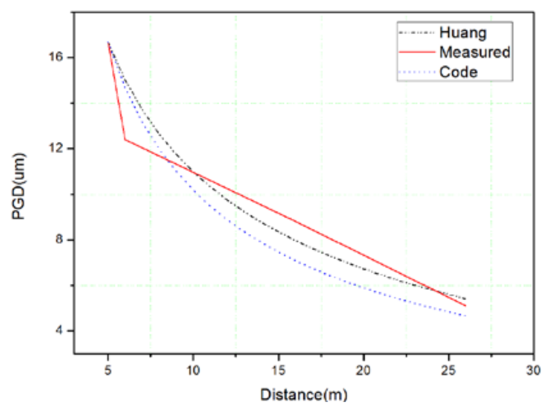

Fig. 7 – Displacement comparison between measured and estimated

Fig.9 shown the time histories of the displacement for the 5 stations at the surface of the field. The PGD of each station and cross correlation coefficient for each station to S2 are shown in Table 4.The time histories of each station are very similar except P1, and vibration model is a highly linear correlation of each station to F2 because of all the cross correlation coefficients are bigger than 0.85. The time lag of S3,S4,S5 is positive while the P1's is negative, and the delay increase with the increasing of the distance to vibration source. This result shows the directional propagation characteristics of waves.

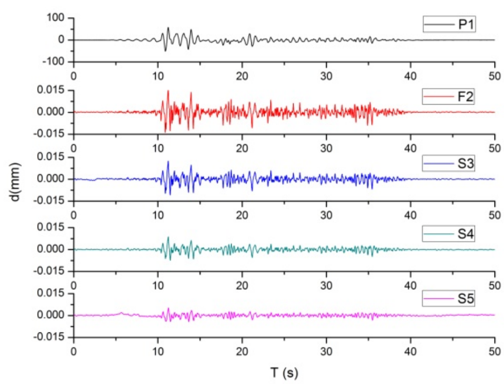

Fig. 8 – Displacement time histories of each measuring station

Table 4 – Cross correlation coefficient of displacement

Station No.		P1	F2	S3	S4	S5
EW	$\rho_{2x}(\tau)$	0.60	1.000	0.95	0.85	0.93
	Time-lag(ms)	-2.92	0	8.78	50.78	28.32
NS	$\rho_{2x}(\tau)$	0.70	1.00	0.98	0.95	0.85
	Time-lag (ms)	-3.90	0	8.79	19.53	46.88

3.2 Velocity attenuation law on field

The platen shaking-table was instrumented with one velocity sensor(P1) while foundation block with two velocity sensors(F2, F3) and surrounding soil field with one velocity sensor(S4). The mass of the test specimen on the platen is 5-ton. The distance of stations marked F2, F3, S4 to P1 is 1.8m, 3.6m, 7.4m. The PGV(Peak Ground Velocity) of each station is shown in Table 5. The test results shown that when the table surface's velocity is 10cm/s, the ground surface's velocity of the field is only 0.08-0.2mm/s, and the latter is less than 0.2% of the former except UD direction.

Table 5 – PGV(cm/s) of each measuring station

Station No.	P1	F2	S3	S4
EW	10.36	-0.0116	-0.0098	-0.0083
NS	-10.60	0.0188	0.0193	0.0170
UD	0.6247	-0.0052	0.0073	-0.0060

3.3 Acceleration attenuation law on field

The platen shaking-table was instrumented with one acceleration sensor(P1) while foundation block with one acceleration sensor(F2) and surrounding soil field with 3 acceleration sensors(S3,S4,S5). The mass of the test specimen on the platen is 7-ton. The distance of stations marked F2, S3, S4, S5 to P1 is 3.5m, 11.5m, 14.5m, 26.5m. The PGA of each station is shown in Table 6. The test results shown that when the table surface's acceleration is 1.5g, the ground surface's acceleration of the field within 15 meters is only 5gal, and the latter is less than 0.4% of the former.

Table 6 – PGA(gal) of each measuring station

Station No.	P1	F2	S3	S4	S5
EW	1162.92	4.07	-1.08	-2.10	0.08
NS	1495.55	4.96	3.46	3.61	1.90
UD	672.99	-5.18	5.37	-6.04	2.40

3.4 Measured results compare to the allowable vibration Codes

Table 7 shown the Code limit value in German Code (DIN4150-3-1999), the result revealed that the measured foundation vibration velocity is much less than the allowable vibration standards[2].

Table 7 – Vibration velocity(mm/s) comparison between measured and Code limit in German

Building type	Limit value	Measured value
Commercial and industrial buildings	20-50	0.08-0.2
Residence buildings	5-20	
Buildings sensitive to vibration	3-10	

Table 8 shown the standard limit value in Chinese Code, the result revealed that the measured vibration velocity is much less than the allowable vibration standards[9].

Table 8 – Vibration velocity(mm/s) comparison between measured and Code limit in China

Environment category	Limit value	Measured value
School and Hospital	0.50-0.26	0.08-0.2
Dormitory	1.00-0.50	
Office	2.00-1.00	
Workshop(non operating area)	5.60	

In general, the limit of PGA of 10m away from foundation is 10gal[4]. In this study, the maximum vibration acceleration in this distance range is only 6gal, which meets the requirements of vibration standards. So the vibration generally does not have a worse effect on people health and building safety in surrounding fields.

4. Conclusions

The results obtained validate that the rigid-body motion pattern of the reaction foundation block for NS excitations of the block have been determined. It has been shown that the foundation of the shaking-table can be simplified as a single-DOF mass-spring-damping model, the foundation soil provides spring restoring force and damping force, the operation of the shaking-table is taken as dynamic loads exerted on the foundation.

It has been shown experimentally that the displacement, velocity and acceleration of reaction foundation block are sufficiently small not to interfere with the building safety in surrounding fields. For a actual strong ground motion of 60mm, 10cm/s and 1.5g corresponding to the maximum displacement, velocity and acceleration that the actuators can exert on the reaction foundation block, the average rigid-body translation at the top of the block has amplitude of less than 17μm, 0.2mm/s and 5gal, and the latter is less than 0.1%, 0.2%, 0.4% of the former respectively.

In the NS direction, the displacement frequency response curve by using sweep-frequency tests method for a harmonic force of constant amplitude shows a broad peak at 11.8Hz, and this frequency can be considered to be the natural frequency of the foundation. Estimating the dynamic characteristic of foundation block by using 'Code for design of dynamic machine foundation' combining the geotechnical characteristics of the site, the natural frequency of the foundation is 12.1Hz while the equivalent damping ratio of the foundation is 0.125. The estimated results with this model agree well with the measured ones.

The vibration attenuation from the foundation to surrounding fields versus distance obeys an exponential law, and the observed displacement is attenuation slowly than estimated result of the Code. Vibration velocity and acceleration comparison between measured and Code limit value show that vibration generally does not have a worse effect on people health and building safety in surrounding fields.

5. Acknowledgements

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7. References

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