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AN EXPERIMENTAL STUDY ON ADVANCEMENT OF DAMPING PERFORMANCE OF FOUNDATIONS IN SOFT GROUND

PART2 EXPERIMENT FOCUSING ON DAMPING AND ANTIVIBRATION PERFORMANCE OF SIDE SURFACE OF FOUNDATION BLOCKS

Shinji ISHIMARU
College of Science and Technology,
Nihon University, Japan

Yukio SHIMOMURA*
Junior College of Nihon University, Japan
Phone&Fax: 81-47-469-5445
E-mail: shimo@arch.jcn.nihon-u.ac.jp

Masashi KAWAMURA
College of Industrial Technology,
Nihon University, Japan

Yoshio IKEDA
Taisei Corporation, Japan

Ippei HATA
Research Institute of Science and Technology,
Nihon University, Japan

Shinya MIWA
Tokyu Construction, Japan

ABSTRACT

To aim at progress of damping performance of foundations that will be built at soft ground, we have proposed an improved foundation work of backfilling a damping material into trenches dug along a foundation supported by improved soil medium. This damping material is a mixture of asphalt with crushed stones and rubber chips (MACSRC) and has itself high attenuation and mitigation performance. Not only to comprehend the attenuation ability of the improved foundation work quantitatively and qualitatively but also to verify the effectiveness of this work, we carried out forced vibration tests for two test blocks, which were constructed by a normal construction work and the above improved foundation work.

According to the experiment results of the blocks by the normal construction work and by the improved foundation work that were excited by the vibration generator, magnitude of amplitudes of the latter became half than the former. Effectiveness in the attenuation performance of MACSRC was confirmed. When the block by the normal construction work was vibrated, the improved foundation work decreased magnitude of amplitude of the adjacent block than the normal construction work. It is expected that MACSRC would exert mitigation ability against earthquakes or other external and internal forces.

Keywords: Mixture of asphalt with crushed stones and rubber chips, Damping and mitigation performance, Improved foundation work, Forced vibration test, Cross interaction.

1. INTRODUCTION

Soil improvement under structures is effective in minimizing fatigue of structures subjected to earthquakes or other external forces. In addition improvement of soil surrounding structures also plays an important role in damping and mitigation performance of structures. To aim at progress of damping performance of foundations that will be built at soft ground, we have proposed an improved foundation work of backfilling a damping material into trenches dug along a foundation supported by improved soil medium. This damping material is a mixture of asphalt with crushed stones and rubber chips (MACSRC) and has itself high attenuation and mitigation performance. Not only to comprehend the attenuation ability of the improved foundation work quantitatively and qualitatively but also to verify the effectiveness of this work, we carried out forced vibration tests for two test blocks, which were constructed by a normal construction work and the above improved foundation work. Here, the normal construction work is a procedure to backfill the dug soil into trenches grubbed along a foundation.

In the experiments, a new test block (Foundation block II) was constructed near the test block that was already existed (Foundation block I). We also dug trenches along Foundation block II and carried out new forced vibration tests focusing on variations of trench conditions and cross interaction effects. Basically, a vibration generator was mounted on Foundation block I. To obtain mitigation ability of the MACSRC, we backfilled the trenches dug along Foundation block II with MACSRC and conducted an experiment of Foundation block I shaked by the exciter. On the last step of the vibration tests, we remounted the vibration generator on Foundation block II whose trenches were paved by MACSRC and vibrated Foundation block II by the exciter to evaluate the effectiveness of the attenuation performance of MACSRC.

From the point of view of taking environmental problems into account, we adopted the rubber chips of recycling materials and mixed them with asphalt and crushed stones.

2. OUTLINE OF EXPERIMENTS AND TEST BLOCKS

A layout of an experimental site is illustrated in Fig. 1. The experimental site is a back lot of the experimental building (Joint Research Center for Environment Protection & Disaster Prevention City) in a campus of Nihon University at Chiba Prefecture in Japan. A new reinforced concrete block (Foundation block II), which is 6m away to east side from the existing test block (Foundation block I), has been built. Foundation block II has been also supported by four soil cement columns and the existing soil layers like Foundation block I. The dimensions of the block are 2.4m x 2.4m x 1.0m. A diameter of a soil cement column is 600mm and its length is 2.5m. The new test block and the soil cement columns are shown in Fig. 2.

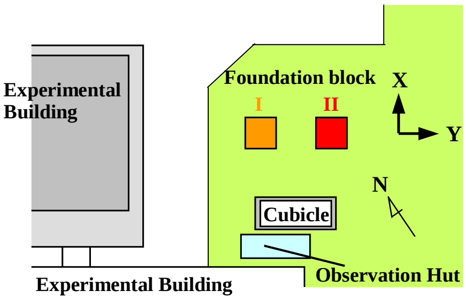


Fig. 1 Layout of the experimental site

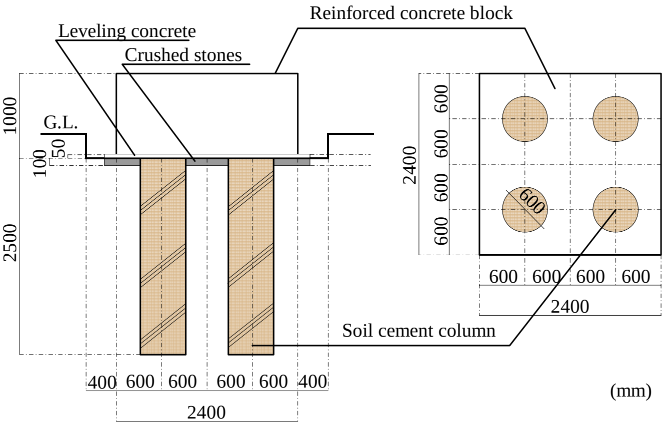


Fig. 2 Test block & soil cement columns

3. MATERIAL TESTING RESULTS

3.1 Soil Cement Column

In order to obtain material characteristics of the soil cement column, sampling and the unconfined compressive strength tests were carried out. We gained test specimens from a new soil cement column whose material age was 28 days. In comparison of the results of the previous material tests (Ishimaru et al., 2004, Ishimaru et al., 2005), the unconfined compressive strengths of all the specimens were slightly small (1.97-3.81MPa) and the deformation moduli (E_{50}) and densities were almost identical with them. Properties obtained by the unconfined compressive strength tests are shown in Table 1.

Table1 Results of unconfined compressive strength tests

		Deformation modulus E_{50} (MPa)	Density ρ (g/cm^3)	Unconfined compressive strength q_u (MPa)
Previous test results	Mean value	1456	1.46	2.86
	Standard deviation	130	0.02	0.59
Present test results	Mean value	1462	1.48	3.77
	Standard deviation	200	0.02	0.67

3.2 Rubber Chips mixed with Asphalt and Crushed Stones

To grasp fundamental material features of a mixture of asphalt with crushed stones and rubber chips (MACSRC) paved into the trenches dug along Foundation block II, we carried out dynamic compressive triaxial tests. Diameters and lengths of the specimens adopted in the above tests are about 100mm and 190mm, respectively. With regard to a solution of environmental problems we selected the rubber chips of recycling materials for the mixture of asphalt with crushed stones.

In the dynamic triaxial compressive tests, the specimens were consolidated by prescribed isotropic stresses and vertical pulsating strains were measured until approximately 0.1 percent strain levels. Examples of hysteresis loops of deviator stresses and axial strains for variations of mixed rates of the rubber chips to crushed stones, whose particle sizes are in the range of 5.0mm to 2.5mm, are shown in Fig. 3. The mixed rate of the rubber chips has been defined by the ratio of the total weight (the rubber chips and the crushed stones) to the weight of the rubber chips.

According to the test results of the mixed rates of the rubber chips, it was found that hysteresis loops of 12.5 percent mixed rates of the rubber chips were relatively stable. It was revealed that the initial secant moduli of 12.5 percent mixed rates of the rubber chips were undiminished and the equivalent damping constants increased, compared with no mixed rates of the rubber chips. Finally, we selected MACSRC of 12.5 percent mixed rate of the rubber chips to backfill the trenches dug along Foundation block II. Blending of MACSRC is illustrated in Table 2. Strain dependence on the equivalent Young's moduli and the equivalent damping constants of the specimens whose mixed rate is 12.5 percent is shown in Fig. 4. Figure 4 represents a result of the experiments for various load levels with 50kPa of confining pressure and 0.1Hz of frequency. In the strain level of 0.01 percent and under, it was found that the equivalent Young's moduli and the equivalent damping constants became about 120 MPa and 20 percent, respectively.

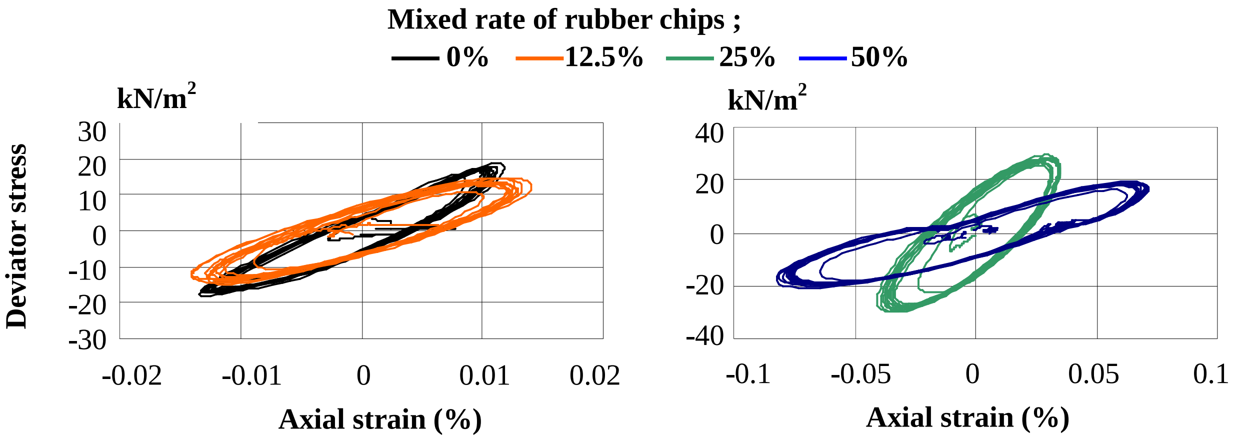


Fig. 3 Examples of hysteresis loops of deviator stresses and axial strains for variations of mixed rates of the rubber chips to crushed stones

Table2 Blending of mixture of asphalt with crushed stones and rubber chips

Mixed rate : 12.5%	Weight ratio rate	Specific gravity	Weight. (gr)
Crushed stones	58.6	2.7	1983.6
Rubber tips	8.4	1.2	283.4
Slow curing	12	2.7	406.0
Fine sand	11	2.7	372.0
Filler	10	2.7	338.0
Total of aggregate	100		3383.0
Asphalt	7.5	1	274.3
Total (aggregate + asphalt)	-	-	3657.3

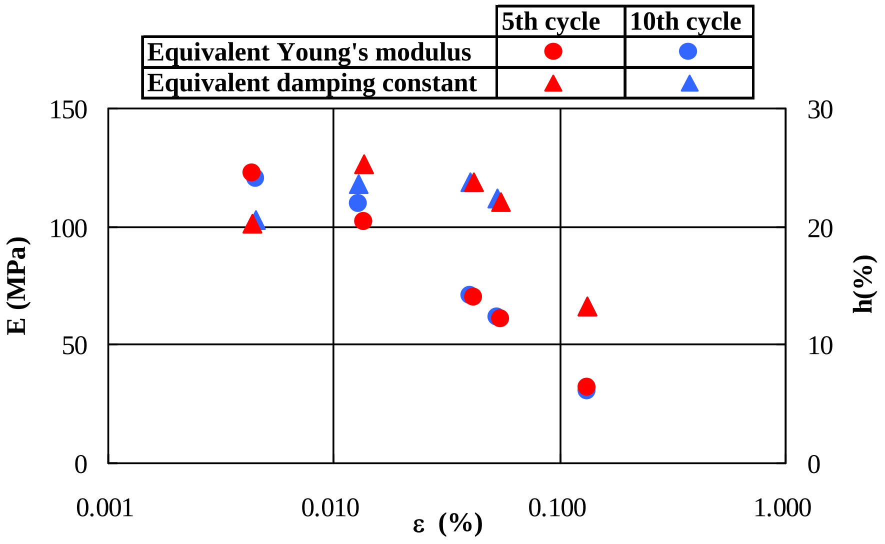


Fig. 4 Strain dependence on the equivalent Young's moduli and the equivalent damping constants of the specimens

4. FORCED VIBRATIONN TEST RESULTS

4.1 Schedule of Tests

We dealt with two test blocks in these experiments. To confirm cross interaction effects and progress of damping performance of the two test blocks, forced vibration tests were carried out under various conditions of the trenches dug along the new reinforced concrete block. Figure 5 shows a schedule of the forced vibration tests. Figure 5 also includes another schedule of the previous experiments. The trenches excavated along Foundation block I, whose width and depth were about 0.4 m and 0.8 m, respectively, were backfilled by the dug soil until the ground surface level, and the backfilled soil was tamped by a rammer. Conditions of the trenches excavated along Foundation block II from Step 4 to Step 6 were the opposite order from Step 1 to Step 3 in Fig. 5. We then backfilled the trenches of Foundation block II with damping devices made of molded rubber rectangular parallelepipeds sandwiched by two steel plates (Step 7). In Step 8, we replaced the damping devices of Step 7 with MACSRC and carried out a forced vibration test to confirm mitigation ability of MACSRC. The vibration generator had been mounted on Foundation block I until Step8. We remounted the exciter on Foundation block I to Foundation block II and conducted an experiment focusing on attenuation performance of MACSRC (Step 9).

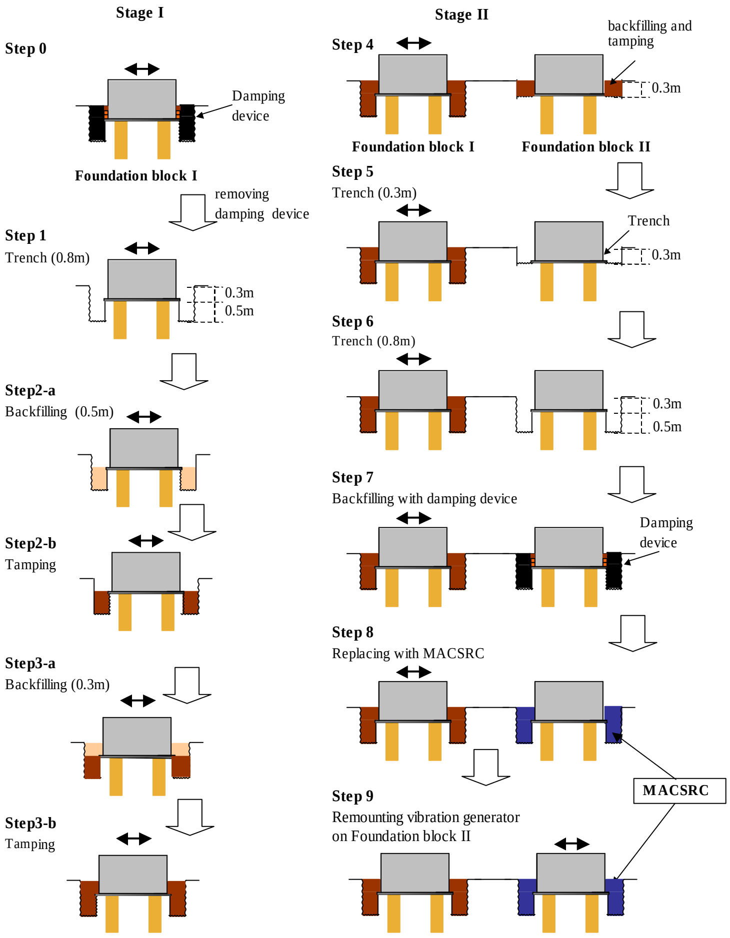


Fig. 5 A schedule of forced vibration tests

4.2 Comparison of Test Results and Pre-analysis Results

To predict peak frequencies and the magnitude of amplitudes of the responses obtained by the forced vibration tests of Foundation block II, simulation analyses were carried out by the axisymmetric FEM model, which referred to the material test results obtained in our companion paper (S. Ishimaru et al., 2005). In the analyses we utilize an analysis model illustrated in Fig. 6. It was assumed that the improved soil medium part under Foundation block II was a cylinder solid that had an equivalent section area of Foundation block II and equivalent properties of the soil cement column and the existing soil layers. To represent looseness and separation between MACSRC and the improved soil medium or soil surrounding Foundation block II, we took loose soil regions into consideration. The equivalent properties of the cylinder solid and soil profiles at the experimental site for the analyses are shown in Table 3 and Table 4. Properties including asphalt and the loose soil regions are illustrated in Table 5. Asphalt properties in Table 5 were referred to the published paper (M. Hirota et.al., 1993, Y. Suzuki et al., 1994).

In these analyses, we took Foundation block II only into account. Results of the simulation analyses were compared with those of the forced vibration experiments in the linear assumption. Amplitude and phase functions of the resonance curves of displacement per unit exciting force for the exciting direction on the upper surface of Foundation block II were evaluated. Experiment results and the simulation analysis results in Step 9 are shown in Fig. 7. The response curve of the experiment for the X-direction had peaks at 8.5Hz and 11.1Hz-12.5Hz. Peaks on the curve of the experiment for the Y-direction appeared at 7.3Hz, 9.7Hz and 12.7Hz. On the other hand, the response curves of the simulation analyses possessed a peak at 10.7Hz only. It was found that results of the simulation analyses were not in agreement with these of the experiment. Overestimating the properties of asphalt and neglecting the cross interaction effects might cause this disagreement.

Magnitude of amplitudes of Foundation block II in Step 9 for the X-direction and the Y-direction at the predominant frequencies decreased about 50 percent and 40 percent compared with those in Step3 (S. Ishimaru et al., 2005) where the trenches grubbed along Foundation block I were backfilled by the dug soil. Therefore it was indicated that MACSRC backfilled into the trenches dug along the block had good attenuation performance.

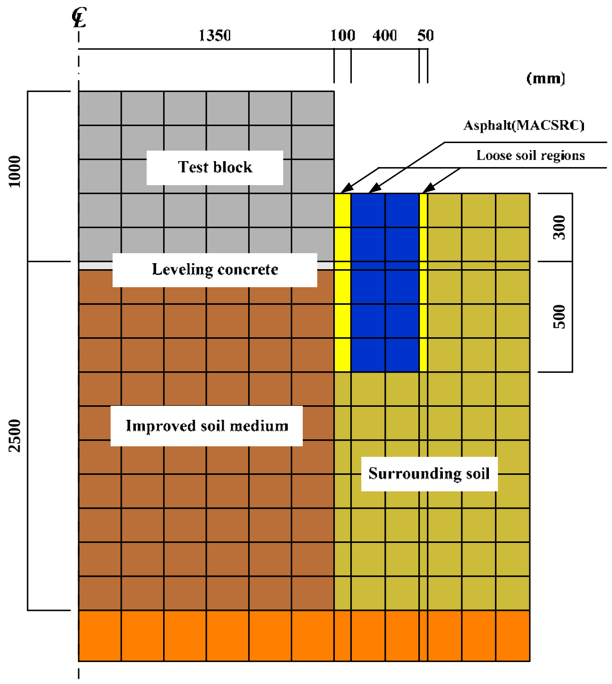


Fig. 6 Axisymmetric FEM model

Table 3 Soil profile of improved soil medium (Lb)

Symbol	ρ (t/m^3)	Vs (m/s)	Poisson's ratio
Lb1	1.5	129	0.25
Lb2	1.5	129	0.25

L1	Lb1	L1
L2	Lb2	L2
L3	L3	L3

Table 4 Soil profile for numerical prediction analysis

Depth (m)	ρ (t/m^3)	Vs (m/s)	Poisson's ratio	Damping ratio	Symbol
1.0	1.4	110	0.311	0.03	L1
2.7	1.4	110	0.311	0.03	L2
5.4	1.6	150	0.451	0.03	L3
10.6	1.7	280	0.372	0.02	L4
14.7	1.7	280	0.478	0.02	L5
21.7	1.7	350	0.465	0.02	L6
27.8	1.8	380	0.461	0.02	L7
38.0	2.0	450	0.466	0.02	L8
45.2	2.0	420	0.461	0.02	L9

Table 5 Properties including asphalt & loose soil regions

Material	Shear modulus G (MPa)	S-wave velocity Vs (m/s)	Density ρ (ton/m^3)	Poisson's ratio	Damping ratio
Foundation block			2.4	0.20	0
Leveling concrete			2.4	0.20	0
Looseness soil regions	2.84	45	1.4	0.31	0.03
Asphalt 1	88.0	200	2.2	0.30	0.15
Asphalt 2	352.0	400	2.2	0.30	0.15
surface subsoil	11.34	90	1.4	0.31	0.03

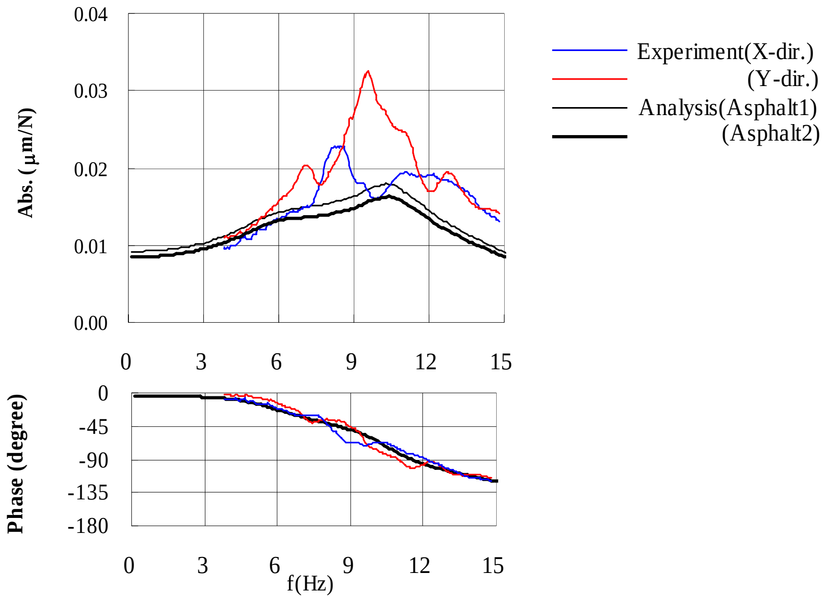


Fig. 7 Amplitude and phase functions of the resonance curves of displacement per unit exciting force for the exciting direction on the upper surface of Foundation block II by experiment and simulation analyses in Step 9

5. FORCED VIBRATION TESTS FOR TRENCHES DUG ALONG NEW TEST BLOCK

While Foundation block I was oscillated by the vibration generator, forced vibration tests (from Step 4 to Step 8) related to various conditions of the trenches dug along Foundation block II were carried out. Amplitude and phase functions of the response displacement curves per unit exciting force for the exciting direction on the upper surface of Foundation block II on Step 4, Step 5 and Step 8 are shown in Fig. 8. Although magnitudes of amplitudes at the peak frequencies were different, the peak frequencies were almost identical on Step 4, Step 5 and Step 8. It means that conditions of trenches dug along Foundation block II only affected magnitude of the amplitudes and did not have an effect on the peak frequencies. The shallower the depth of the trenches became, the smaller the magnitude of the amplitude at the peak frequencies were. Compared with Step 4 and Step 8, from fifteen to thirty percent of decrease in magnitude of amplitudes of Foundation block II on Step 8 was found at the peak frequencies. It is expected that MACSRC would play an important role in progress of mitigation ability of the structures.

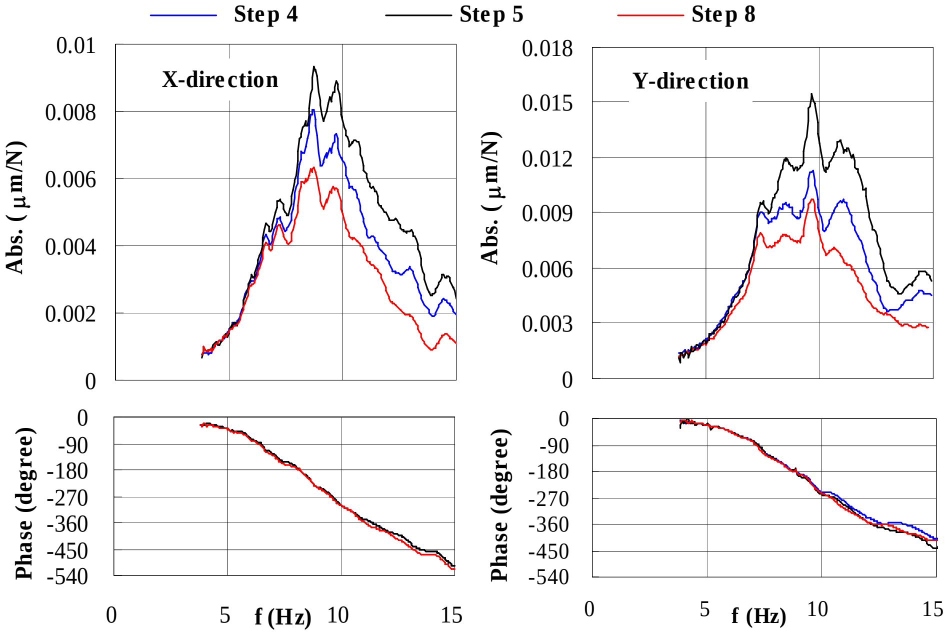


Fig. 8 Comparison of amplitude and phase functions of the response curves of the response displacement per unit exciting force for the exciting direction on the upper surface of Foundation block II on Step 4, Step 5 and Step 8

6. CONVERSE CALCULATION SOIL STIFFNESSES

To examine difference of the dynamic characteristics of the existing test block built by the normal construction work (Step 4) and the new test block constructed by the improved foundation work (Step 9), an identification calculation of soil stiffnesses for sway and rocking components was carried out. When the cross interaction effect between two blocks was neglected, converse calculation soil stiffnesses and equivalent damping constant of the stiffnesses could be estimated by the following equations.

$$\left(\begin{bmatrix} k_H & 0 \\ 0 & k_R \end{bmatrix} - \omega^2 \begin{bmatrix} M & M_H \\ M_H & J \end{bmatrix}\right)\begin{bmatrix} U_f \\ \Theta_f \end{bmatrix} = P\begin{bmatrix} 1 \\ H_P \end{bmatrix} \qquad \text{Eq. 1}$$

$$k_H = \frac{P + \omega^2 M_H \Theta_f}{U_f} + \omega^2 M \qquad \text{Eq. 2}$$

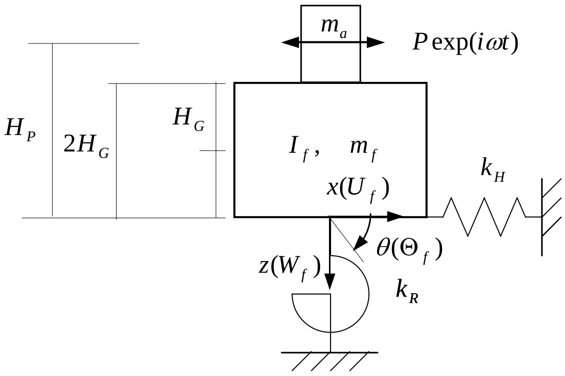
$$k_R = \frac{PH_P + \omega^2 M_H U_f}{\Theta_f} + \omega^2 J \qquad \text{Eq. 3}$$

$$h = \sin\left(\frac{1}{2}\tan^{-1}\frac{k'}{k}\right) \qquad \text{Eq. 4}$$

Here, notations in the above equations are defined in Fig. 9. In Eq. 4, k and k' are real and imaginary parts of the reverse soil stiffnesses, respectively.

Aggregated converse calculation soil stiffnesses and equivalent damping constants for sway and rocking components identified by the test result for the Y-direction are shown in Fig. 10 and Fig. 11, respectively.

The real and imaginary parts of the dynamic converse calculation soil stiffnesses for sway and rocking components of Foundation test block II (Step 9) became larger than those of Foundation block I (Step 4). Compared with those of Foundation block I, increase in the equivalent damping constants of Foundation block II whose trenches were backfilled with MACSRC was also indicated. As a result, effectiveness of the attenuation performance of MACSRC paved into the trenches grubbed along the block was confirmed quantitatively.



$M = m_f + m_a$

$M_H = m_f H_G + m_a H_P$

$J = I_f + m_f H_G{}^2 + m_a H_P{}^2$

displacement of sway mode : U_f

displacement of vertical component : $W_f = 0$

rotational angel : Θ_f

Fig. 9 Estimation of converse calculation soil stiffness & damping constant

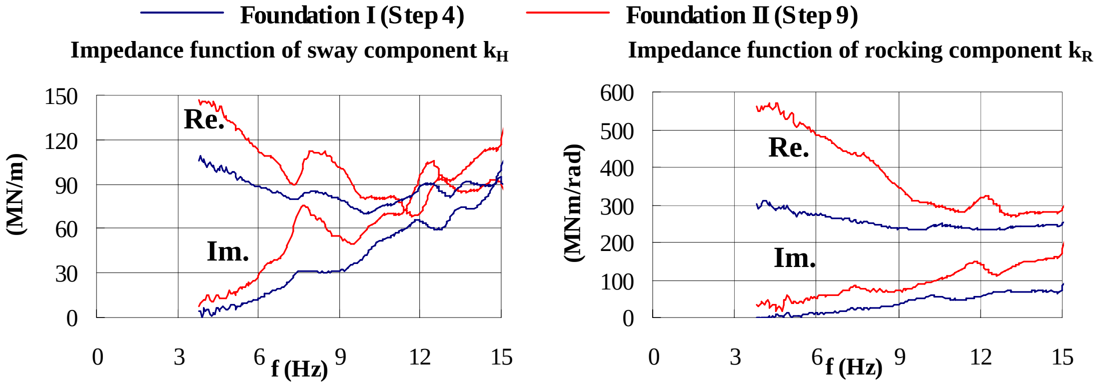


Fig. 10 Dynamic converse calculation soil stiffnesses (sway & rocking)

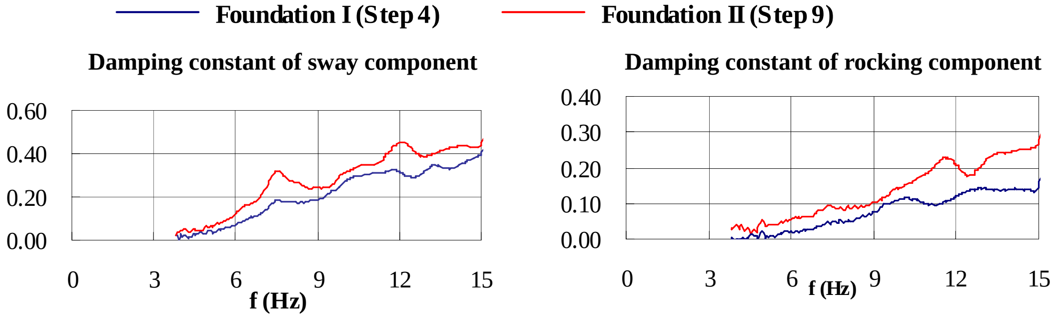


Fig. 11 Equivalent damping constants (sway & rocking)

7. SIMULATION ANALYSIS

After experiments, simulation analysis of Step 9 was carried out by the axisymmetric FEM model, which was illustrated in the previous section. In the simulation analysis, results of the material test were applied to values of an equivalent Young's modulus and an equivalent damping constant of MACSRC. Loose soil regions are taken into account to model looseness and separation between MACSRC in the trenches and the improved soil medium part or soil near Foundation block II in Fig. 6. Properties including the loose soil regions adopted in the analysis are shown in Table 6.

Amplitude and phase functions of the response displacement curves of Foundation block II in Step 9 and the simulation analysis are illustrated in Fig. 12. Although both peak frequencies were slightly different, phase function of the analysis was in good agreement with that of the experiment. Because Foundation block II was dealt with as a single one in simulation analysis of Step 9, analysis results agreed with experiment ones for the X-direction, which would be less affected by the cross interaction.

Table 6 Properties utilized in analysis of Step 9

Material	Shear modulus G (MPa)	S-wave velocity Vs (m/s)	Density ρ (ton/m^3)	Poisson's ratio	Damping ratio
Foundation block			2.4	0.20	0
Leveling concrete			2.4	0.20	0
Loose soil regions	0.000014	0.1	1.4	0.31	0.03
MACSRC	44.4	163	1.68	0.35	0.20
surface subsoil	11.34	90	1.4	0.31	0.03

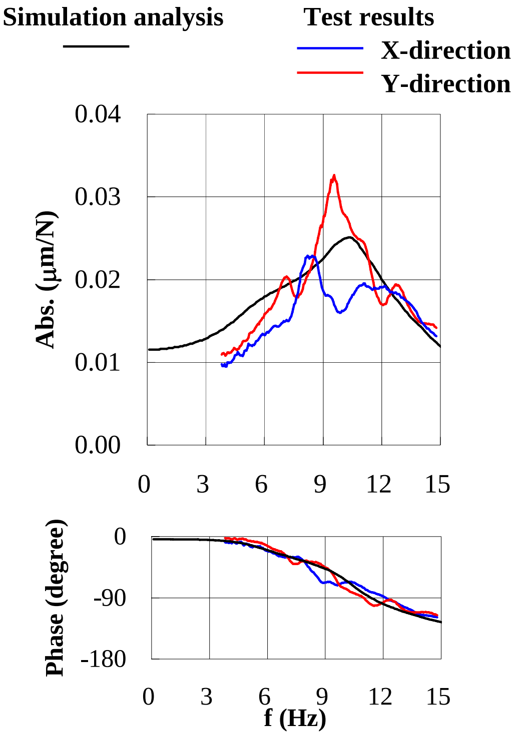


Fig. 12 Comparison of amplitude and phase functions of the resonance curves of the response displacement per unit exciting force for the X-direction on the upper surface of Foundation block II by experiments and analysis of Step 9

8. CONCLUSIONS

The material experiments of MACSRC, as a newly-adopted attenuation ingredient, were carried out to obtain their material properties. Forced vibration tests and their simulation analyses of the two test blocks supported by the improved soil medium were also conducted to grasp fundamental dynamic feature of MACSRC.

The equivalent Young's modulus and the equivalent damping constant of MACSRC of 12.5 percent mixed ratio adopted in the experiment in the low strain level were approximately 120 MPa and 20 percent, respectively.

Compared with the experimental results of the blocks by the improved foundation work and by the normal construction work that were oscillated by the exciter, magnitude of amplitudes of the response displacement function of the former (Step 9) became half than the latter. Effectiveness in the attenuation performance of MACSRC backfilled into the trenches dug along the block was confirmed.

When the block by the normal construction work was shaked by the vibration generator, magnitude of amplitude of the response displacement curve of Foundation block II that paved the trenches with the mixture of asphalt with crushed stones and rubber chips (MACSRC) was about 15-30 percent smaller than that of Foundation block II that backfilled the trenches by the grubbed soil. It is expected that MACSRC would exert mitigation ability against earthquakes or other external and internal forces.

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