Study on Earthquake Response Reduction of Direct Foundation Using Composite Geomaterial

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SUMMARY:
In recent earthquakes in Japan, there were many kinds of damages to soil-foundation, which negatively affected the function of the whole structure. While, by uplifting or sliding at the foundation bottom and nonlinear effect of surrounding soil called dynamic nonlinear interaction, a possibility of reducing the earthquake response of building has been reported. So it is necessary to improve the aseismic capacity of soil-foundation. Cement-mixed soil improvement is cited as one of measures against these ground damage. However, soil cement often exhibits brittleness with the increase in the strength, and results in decreasing the aseismic capacity.
To address these subjects, we develop an artifical geomaterial with high toughness (composite geomaterial). And we are intended to develop new earthquake response reduction foundation using composite geomaterial. This paper discusses properties of composite geomaterial on laboratory studies. Then earthquake response behaviours of buildings are discussed by shaking table tests.

Keywords: Nonlinear soil-structure interaction, Earthquake response reduction, Direct foundation, Composite geomaterial, Friction isolation, Shaking table test

1. GENERAL INSTRUCTIONS

In recent earthquakes in Japan, there were many kinds of damages to soil-foundation such as liquefaction, damage of footing beam and pile, settlement of ground around foundation, which negatively affected the function of the whole structure [AIJ (2011)]. While, as a dynamic interaction of the direct foundation structure during large earthquake, uplifting or sliding at the foundation bottom and nonlinear of surrounding soil are occurred. By these effects, a possibility of reducing the earthquake response of a building has been reported [Miyamoto (2006), Kishimoto et al. (2009) and AIJ (2006b)]. So it is necessary to improve the aseismic capacity of soil-foundation.
Cement-mixed soil improvement is cited as one of the measures against these ground damage. The soil cement is often used for reinforcement against earthquakes in Japan [AIJ (2001) and The Building Center of Japan (2002)], because there was little damage of buildings on the cement improved soil at the Hyogoken Nanbu Earthquake (1995) [AIJ (2006a)]. However, soil cement often exhibits brittleness with the increase in the strength, and results in decreasing the aseismic capacity.
To address these subjects, it is effective to develop an artificial soil having known mechanical properties and toughness against large deformation, then to understand the soil-foundation behavior during large earthquakes, and to enhance the aseismic capacity of the superstructure and the soil-foundation as a whole. By this way, the aseismic capacity of the structures is improved and the function is maintained even after large earthquakes.
Focusing on the ductility of fibers and the elasticity of rubber-chips, authors have developed an artificial geomaterial compound, which is a mixture of soil slurry, cement, rubber-chips, and fibers and stable in a large strain region. And composite geomaterial are used as bearing stratum for building, backfill soil around foundation and improved soil around piles [Shimamura et al. (2011a-c) etc.].
This paper discusses the shearing mechanism and the properties of the compound based on laboratory studies. Authors performed the unconfined compression test and the cyclic simple shear test as

laboratory tests. Then earthquake response behaviours of buildings are discussed by shaking table tests. The foundations are surrounded by different backfill composite soils and supported on a hard soil considering different contacted conditions. The shaking table tests were conducted under the condition of 1g.

2. SUMMARY OF COMPOSITE GEOMATERIALS

This paper discusses the shearing mechanism and the properties of the compound based on laboratory studies. Authors performed the unconfined compression test and the cyclic simple shear test as laboratory tests.

2.1. Materials

The physical properties of the materials used in this study are presented in Table 1. Cement, rubber-chips and fibers were added to the basic soil slurry, collected from soil recycling plants. Two kinds of rubber-chips were used. Rubber-chips are made from the high damping rubber using base isolators, and the diameter is from 1 to 5 millimeters. Slag cement was chosen for the cement because of its long-term stability and our experience. The nylon fibers cut out short were used as fibrous materials.

Table 1. Material properties

Materials	Properties
Soil Slurry	Density = 1.50±0.02g/cm^3 Sand fraction*1 = 40±2.5% Slump flow = 400±50mm
Cement	Slag cement*2 Density = 3.04g/cm^3
Rubber chips	a) Scrap tire rubber Density = 1.1g/cm^3 Particle size = 1-5mm
	b) High damping rubber Density = 1.1g/cm^3 Particle size = 5mm under
Fibers	Nylon fiber

*1 The grain size is 74μm-2mm
*2 Japanese Industrial Standard (JIS) R 5211

2.2. Composition

The compositions of the test samples are shown in Table 2. The samples were prepared with the cement content of 75 kilograms in one cubic meter of soil-cement slurry, and two levels of rubber-chips content of 0 and 300 kilograms in one cubic meter of soil-cement slurry mixed with rubber-chips and fibers.

Table 2. Material properties

No.	Cement	Rubber-chips				Fibers	Unit weight
		Scrap tire		High damping rubber			
	Kg/m^3**1	kg/m^3**2	%**3	kg/m^3**2	%**3	%**4	g/cm^3
1	75	0	0	0	0	0	1.54
2	75	300	27	0	0	5	1.38
3	75	0	0	300	27	5	1.38

**1 Cement / One cubic meter of slurry with soil and cement
**2 Rubber-chips / One cubic meter of composite geomaterials
**3 Rubber-chips (volume) / Composite geomaterials (volume)
**4 Fibers (volume) / Composite geomaterials (volume)

3. LABORATORY TESTS

3.1. Unconfined Compression test

According to the Japanese Geotechnical Society (JGS) standard [JGS (2000)], the unconfined compressive strength, q_u, is defined as the compressive stress at which an unconfined cylindrical specimen of soil will fail in a simple compression test. The test then started by applying a constant axial strain of 1% per minute. The load and deformation values were recorded as needed for obtaining a reasonably complete load-deformation curve. Samples were used the tests within 28 days after preparation. Specimen sizes were 5 centimeters in diameter and 10 centimeters length. We defined the strain at maximum compressive stress (unconfined compressive strength), q_u, on these tests as the failure axial strain, ε_f.

3.2. Cyclic simple shear test

As shown in Figure 1, cyclic simple shear testing apparatus used in this study of advanced Kjellman-type [Hara et al. (1977)]. In order to accurately evaluate the shear modulus, G, and damping ratio, h, over a wide range of shear strain, γ, say from 0.001% (10^{-5}) to that at the peak of the order of 10% (10^{-1}), the testing apparatus was adopted. A cylindrical specimen was laterally confined by Teflon coated low friction rings, was subjected to cyclic simple loading at small level. The relation between shear stress, τ, and shear strain was determined. The loading method was stress controlled and strain controlled (γ>1%). The loading of sine wave of 11 cycles was applied continuously for each step in an undrained condition, and the vertical stress, σ_v, was 100 kilopascals. We adopted three levels of loading frequency of 0.1, 1.0, 3.0 Hz. Samples were used the tests within 28 days after preparation. Specimen sizes were 10 centimeters in diameter and 3 centimeters length. The samples were adhered to upper loading plate and shaking table by epoxy resin adhesive. We defined the shear modulus at very small strain level ($\gamma \approx 0.001\%$) as the initial shear modulus, G_0 on these tests.

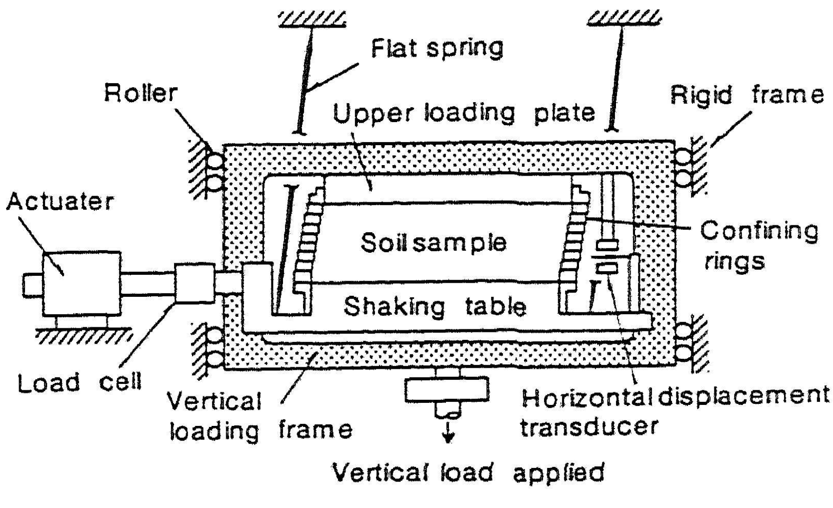


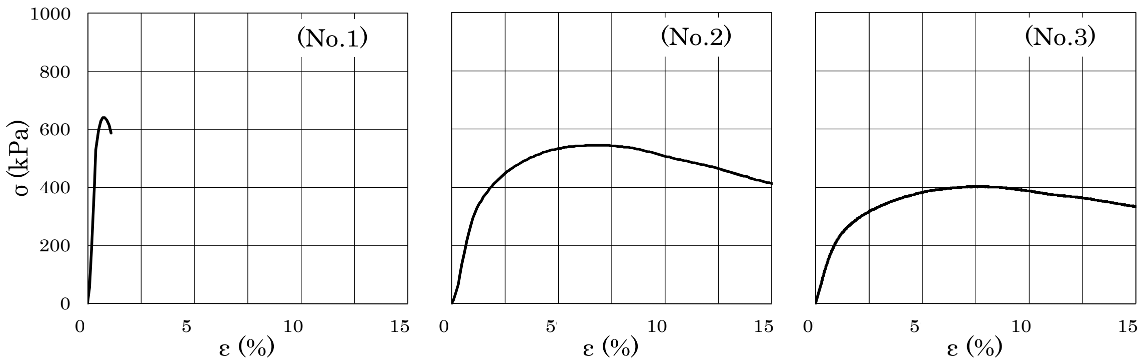
Figure 1. Schematic view of cyclic simple shear testing apparatus

4. RESULS OF LABORATORY TESTS

4.1. Unconfined Compression test

Figure 2 illustrates the relations between axial strain, ε, and compressive stress, σ, of the tests. Sample No.1 that is usual soil cement shows that the relation between axial strain and compressive stress that is highly brittle. The failure axial strain of sample No.1 was about 1 %, and when 1 % was exceeded, the specimen was fractured in brittleness as shown in Photograph 1(a). However, in sample

No.2 to which scrap tire rubber-chips and fibers were added, and in sample No.3 to which high damping rubber-chips and fibers were added, failure axial strains have increased with the addition of them and were about 8 %. The deterioration of strength of sample No.2 in a high strain region after peak strength was small, and the shape of the specimen was maintained though it was transformed by 15 % or over as shown in Photograph 1(b). Characteristics of sample No.3 were same as those of No.2.



(a) No.1 (b) No.2 (c) No.3

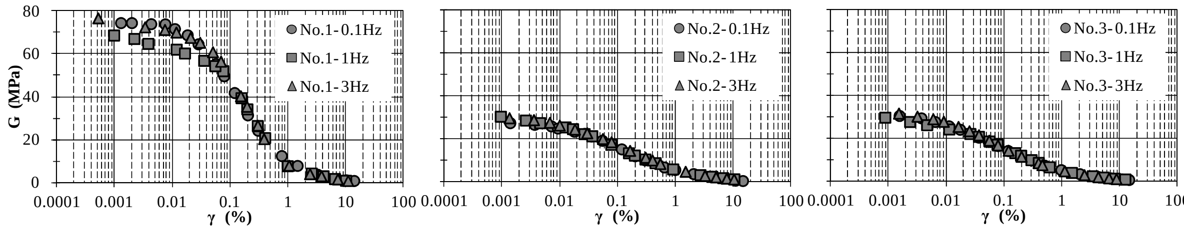
Figure 2. Stress - strain curves

(a) No.1 (ε<2%) (b) No.2 (ε>15%) (c) No.3 (ε>15%)

Photograph 2. Failure conditions of specimens after unconfined compression test

4.2. Cyclic simple shear test

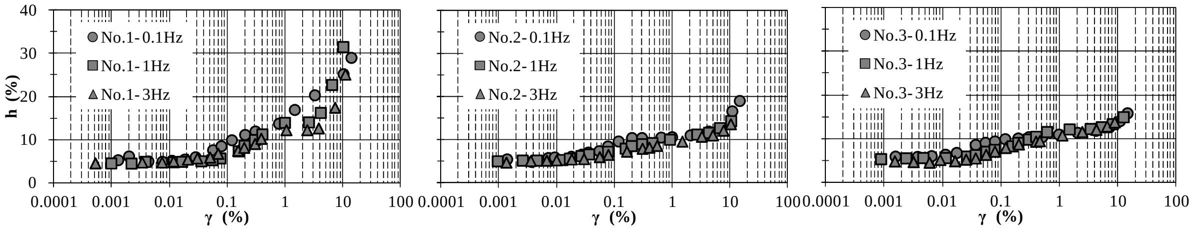
Figure 3 shows the relations between shear modulus, G, and shear strain, γ. In each sample, shear moduli were decreased nonlinearly with increasing shear strain in all frequencies. The initial shear modulus, G_0, of sample No.1 was about 75 megapascals. However, in sample No.2 to which scrap tire rubber-chips and fibers were added, and in sample No.3 to which high damping rubber-chips and fibers were added, initial shear moduli have decreased with the addition of them and were about 30 megapascals. In the frequency range of these tests (0.1-3Hz), shear moduli were not affected to frequencies.



(a) No.1 (b) No.2 (c) No.3

Figure 3. Shear modulus vs. shear strain

Figure 4 shows the relations between damping ratio, h, and shear strain. As for each sample, damping ratios were increased nonlinearly with increasing shear strain in all frequencies. As for sample No.2 and sample No.3, damping ratios reached about 15 % in the very large strain level. Whereas damping ratios of sample No.1 showed large value in the large strain range (γ>1%). We consider the factor as follows. Specimens of sample No.1 were fractured in the super-large strain rage. Therefore, fractions were increased in failure plane. In the frequency range of these tests (0.1-3Hz), damping rations were not affected by a frequency dependent.



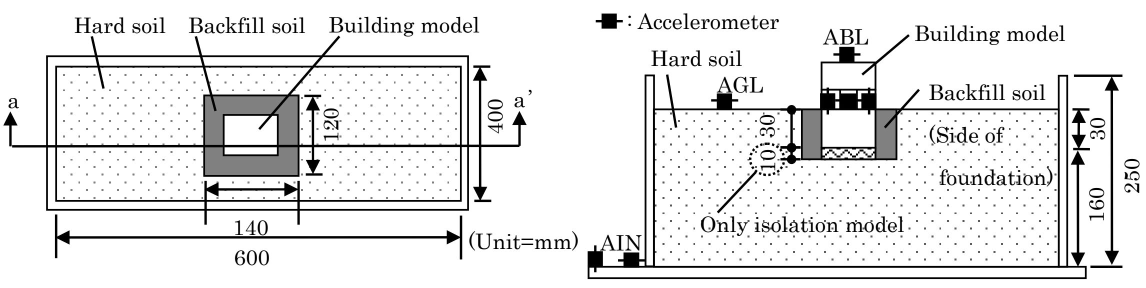
(a) No.1 (b) No.2 (c) No.3

Figure 4. Damping ratio vs. shear strain

5. SHAKING TABLE TEST

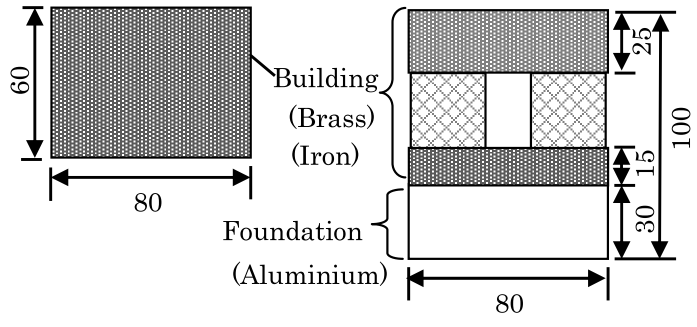
5.1. Summary of shaking table tests

We performed the shaking table tests in order to compare earthquake response behaviors of buildings with different backfill soils around the foundations which are supported on a hard soil, with different contact conditions between the foundation and the supporting soil. The shaking table tests were conducted under the condition of 1 g. Figure 5 shows the plan and the sectional side view of the experimental model. The soil container made of steel has 600 millimeters long, 400 millimeters wide and 250 millimeters high. The hard soil was made of soil-cement slurry, and the amount of cement addition was 75 kilograms in one cubic meter of soil-cement slurry (sample No.1). The thickness of backfill soil enclosing the foundation is 30 millimeters. Accelerometers were located at top of building model, top of foundation, surface of hard soil (ground surface) and base plate of the container box. Figure 6 shows the plan and the side view of the building model. The upper and lower parts of building model are made of brass (density: 8.4g/cm^3), middle parts are iron (density: 7.9g/cm^3), and the parts of foundation are aluminium (density: 2.7g/cm^3).



(a) Plan (b) Sectional side view (section a-a')

Figure 5. Plan and sectional side view of the experimental model

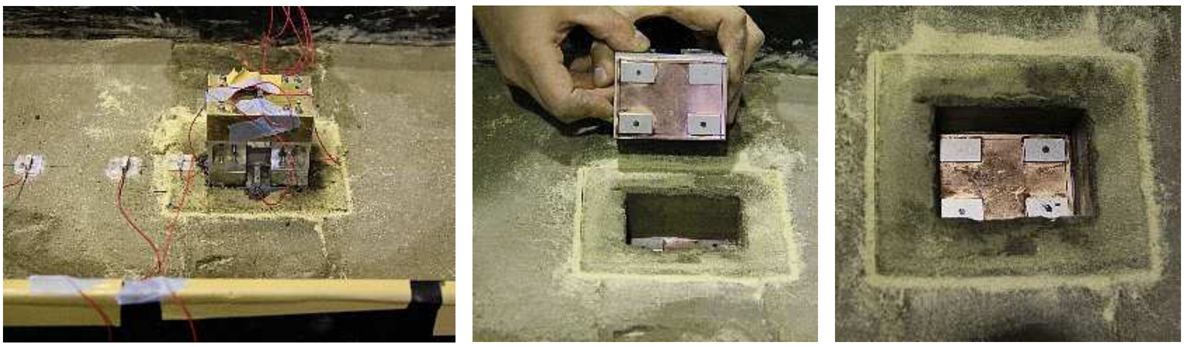


(a) Plan (b) Side view

Figure 6. Plan and side view of building model

5.2. Contact condition between foundation and supporting soil

In these tests, we compared earthquake response behaviors of buildings with different contact conditions between the foundation and the supporting soil. Contact conditions were made into three kinds. In the model of "Non-slip", the foundation was adhered to the supporting soil by epoxy resin adhesive on the assumption that the case where the foundation is not slipped by earthquakes. In the model of "Slip", the foundation was not adhered to the supporting soil on the assumption that the case where the foundation is slipped by large earthquakes. Moreover, in the model of "Isolation", the foundation was floated about 10 millimeters from the supporting soil by neodymium magnets on the assumption that the case where the friction between the foundation and the supporting soil is zero (see Photograph 2).



(a) Experimental model (b) Bottom of foundation (c) Top of supporting soil

Photograph 2. Experimental model and neodymium magnets attached

5.3. Backfill soil (Surrounding soil)

For the horizontal acceleration response reduction of building by the backfill soil (surrounding soil), we compared earthquake response behaviors of buildings with different backfill soils around the foundations which are supported on a hard soil. We tested three cases of specimen. In Case-1, the property of the backfill soil was same as sample No.1 of hard soil. In Case-2, the foundation was backfilled by the soil with the property of sample No.2 compounded scrap tire rubber-chips and fibers. In Case-3, the foundation was backfilled by the soil with the property of sample No.3 compounded high damping rubber-chips and fibers.

5.4. Input earthquake motion

These tests with different input accelerations were conducted in the direction of long side of the container box. The input earthquake motion was the published wave (hereafter KOKUJI wave). The published wave simulated by fitting the acceleration spectra published by the government. The phase characteristics of the published wave were taken from the records of Hachinohe, JMA Kobe, etc. and a random, respectively. In this experiment, we used JMA Kobe (1995NS) phase. Figure 7 shows acceleration time history and maximum acceleration of KOKUJI wave (large level). A small level of shaking was adjusted to 1/5 levels of the acceleration.

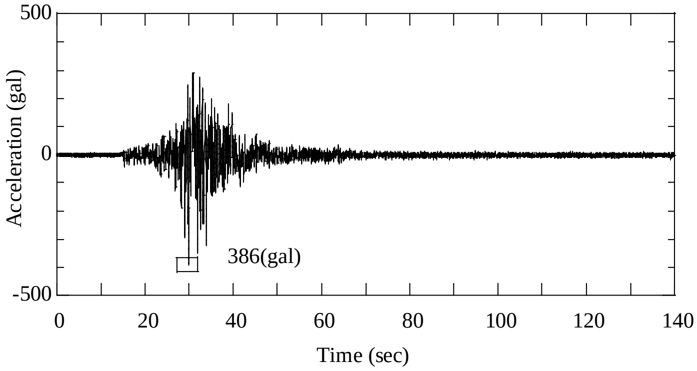


Figure 7. Acceleration time history and maximum acceleration of KOKUJI wave (JMA Kobe phase)

6. RESULTS OF SHAKING TABLE TEST

We compared rations of acceleration Fourier spectrum at the top of building model to that of the ground surface (ABL/AGL). Therefore, we compared earthquake response behaviors of buildings with different backfill soils around the foundations which are supported on a hard soil, with different contact conditions between the foundation and the supporting soil, and with different levels of input earthquake motion.

6.1. Comparison by difference contact conditions between foundation and supporting soil

Figure 8 shows rations of acceleration Fourier spectrum for the case of surrounding soil to Case-3. Shaking level was large. We analyzed the influences that the difference of contact condition gave to the building response. We compared on three kinds of contact conditions, "Non-slip", "Slip", and "Isolation". The maximum amplification ratio becomes small in order of "Isolation" < "Slip" < "Non-slip". Moreover, the frequency at maximum amplification ratio also becomes low in the order. Therefore, it was confirmed that earthquake response of building was decreased by decreasing input energy from bottom of foundation and by increasing absorption of seismic wave energy in surrounding soil.

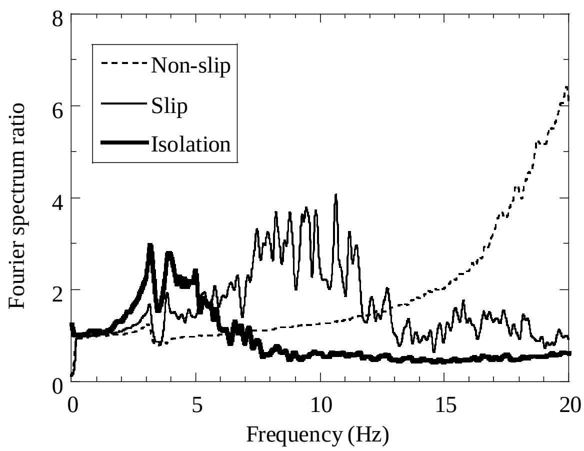
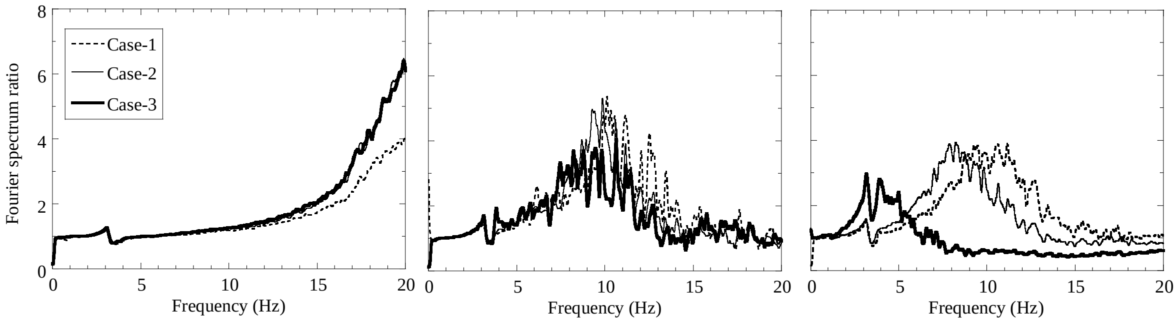


Figure 8. Fourier spectrum ratios (ABL/AGL)

6.2. Comparison by difference backfill soils

Figure 9 shows rations of acceleration Fourier spectrum for each models of contact condition. Shaking level was large. We analyzed the influences that the difference of backfill soil gave to the building response. We compared on three kinds of Backfill soils, Case-1, Case-2, and Case-3. In the model of "non-slip", the maximum amplification ratio is reduced most in Case-1. However, in other models ("Slip" and "Isolation"), the maximum amplification ratio is reduced most in Case-3. Moreover, the frequency at maximum amplification ratio becomes low in order of Case-3 < Case-2 < Case-1, which results from the mixing rubber-chips and fibers. Also, change of the amplification seen near 3Hz on figure is influence of rocking input motion by pitching of shaking table.

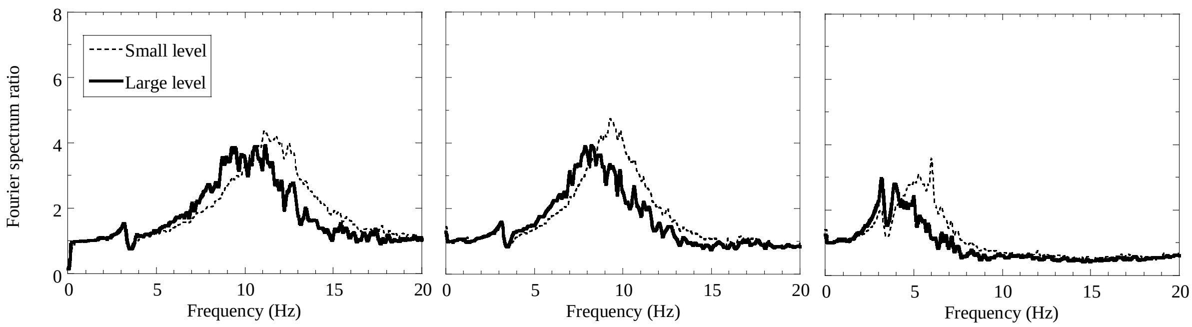


(a) Non-slip (b) Slip (c) Isolation

Figure 9. Fourier spectrum ratios (ABL/AGL)

6.3. Comparison by difference levels of input earthquake motion

Figure 10 shows rations of acceleration Fourier spectrum for each cases of backfill soil. Contact condition was "Isolation". We analyzed the influences that the difference of input motion level gave to the building response. In all cases (Case-1, Case-2, and Case-3), maximum amplification rations of the large level of shaking are smaller than that of the small level of shaking, and frequencies at the maximum amplification ratios of the large level of shaking are lower than that of small level of shaking. Therefore, it was shown that the influence of the nonlinear interaction between the foundation and the backfill soil (surrounding soil) was large in the large level of shaking.



(a) Case-1 (b) Case-2 (c) Case-3

Figure 10. Fourier spectrum ratios (ABL/AGL)

6.4. Influence by rocking motion of building

We examined the influence of rocking motion of building on earthquake response of building in the case of large input motion. The angular acceleration of building, $\ddot{\theta}$ (rad/s^2), was evaluated to divide difference of the vertical acceleration of the both ends of foundation by width of building (0.08 m) (see Figure 11). The horizontal acceleration of top of building generated from rocking motion, $\ddot{\theta}$H, was evaluated to multiply the angular acceleration of building by height of building, H. And we compared ratios that were evaluated to divide Fourier spectrum of the angular acceleration of top of building by Fourier spectrum of acceleration of the ground surface ($\ddot{\theta}$H /AGL).

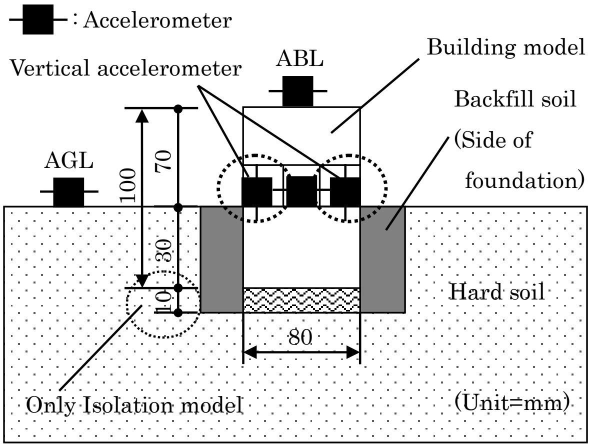


Figure 11. Accelerometer layout sketch

Figure 12 shows rations of acceleration Fourier spectrum for the case of surrounding soil to Case-3. Shaking level was large. We analyzed the influences that the difference of contact condition gave to angular acceleration of top of building, $\ddot{\theta}$H. Corresponding to change in Figure 8, predominant frequency becomes low in order of "Isolation" < "Slip" < "Non-slip". The rate of rocking component to building response became large by the model of "Slip" and "Non-slip".

Figure 13 shows rations of acceleration Fourier spectrum for the model of contact condition to "Isolation". Shaking level was large. We analyzed the influences that the difference of backfill soil gave to angular acceleration of top of building, $\ddot{\theta}$H. From comparison with Figure 9(c), Case-1, Case-2, and Case-3 of the rate of rocking component to building response were comparable. In especially these experiments, the predominant frequency in the case of Case-3 with which the foundation was isolated overlapped with the frequency in which shaking table pitches, and the rocking component was large.

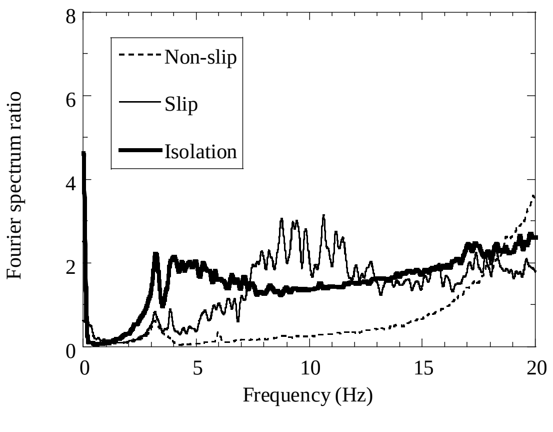


Figure 12. Fourier spectrum ratios ($\ddot{\theta}$H /AGL)

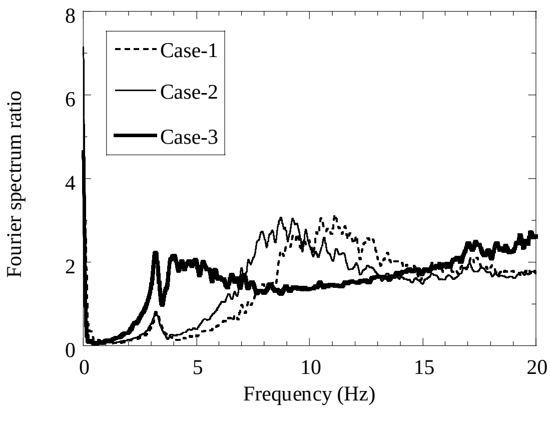


Figure 13. Fourier spectrum ratios ($\ddot{\theta}$H /AGL)

7. CONCLUSIONS

Finally, we conclude with a description of the experimental results.

(a) The composite geomaterial which is a mixture of cement, rubber-chips (sample No.2 and No.3), and fibers, is a high toughness geomaterial compared with a usual soil cement (sample No.1) from laboratory tests.
(b) The earthquake response of building is greatly influenced by contact condition between foundation and supporting soil. And the earthquake response of building is decreased by decreasing input energy from bottom of foundation and by increasing absorption of seismic wave energy in surrounding soil.
(c) By applying the composite geomaterial to backfill soil around foundation, the earthquake response reduction of building in case of large earthquake can be expected.
(d) When contact conditions of foundation are set to "Slip" and "Isolation", the horizontal response of building is remarkably decreased and the natural frequency shifts to the low frequency range, but the rocking component of foundation is increased. Therefore measures against the rocking motion of structure by rotation input are needed.

In the near future, we conduct the experiments repeatedly, and try further research of mechanical properties and shear mechanisms. We also advance the analytical examination. Therewith, we advance the development of more high-performance composite geomaterials.

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