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STANDING WAVE TRAPPED IN A GROUP OF HIGHLY HOMOGENEOUS BUILDINGS

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Abstract

Since it is difficult to observe Structure-Soil-Structure Interaction (SSSI) between many structures, most of the previous studies based on experiments and measurements have been conducted on SSSI between two structures. However, previous studies based on numerical methods and studies of vibration testing using reduced models have shown a tendency toward a larger number of structures exciting stronger SSSI. So, experimental study of SSSI between many structures is needed.

In this study, we will show the results of microtremor measurement in apartment groups in which four to six highly homogeneous buildings are arranged at narrow intervals where standing waves seems to be excited by the buildings' responses to the ground vibration. If the buildings do excite ground vibration, it greatly affects the dissipation of the systems' vibration energy when multiple buildings are arranged narrow intervals, and it can also be an evidence of previous studies of SSSI. So, we consider that it is significant for the seismic design of structures to reveal whether or not buildings' responses can excite ground vibration.

We will show that the response of apartment groups can excite such a standing wave by vibration tests of a reduced model using H-section steels (width: 400mm × height: 400mm). In these vibration tests, results that cannot be explained without considering such standing waves are obtained. The results show that standing waves can be excited in a building group similar to the reduced model.

Keywords: structure－soil－structure interaction; standing wave; microtremor measurement; vibration test

1. Introduction

The fact that the response of a building to ground vibration affects vibration itself is well known as Soil-Structure Interaction (SSI). The phenomenon in which ground vibrations excited by SSI propagate to nearby structures can have remarkable effects on the response of the structures (this phenomenon is called Structure-Soil-Structure Interaction (SSSI)). This fact is also known [1]. Since appropriate SSSI evaluation is thought to be useful for the seismic design of structures and countermeasures against environmental vibration problems, many studies on SSSI have already been conducted.

Since it is difficult to measure SSSI between many structures, most of the previous studies based on vibration measurements on real-scale structures have been conducted on SSSI between two structures [2, 3, 4]. On the other hand, previous studies based on numerical methods [5, 6] and previous studies based on reduced model tests [6, 7] have shown that as the number of structures in a system increases, SSSI tends to be stronger. Therefore, experimental study of SSSI between many structures is needed.

In this study, we will show the results of microtremor measurements with systems in which four to six highly homogeneous buildings are arranged at narrow intervals and the effects of SSSI seem to be remarkable. In addition, we will discuss the characteristics of the microtremor wave field like this by using the microtremor array exploration technique and vibration tests of the reduced model.

2. Microtremor measurements at apartment groups and free field

2.1 Method

Fig. 1 shows a map of the apartment groups and the nearby area that is free of other objects, which we refer to as the free field throughout the rest of this study, for microtremor measurement. Fig. 2 and 3 show details of the sensor (accelerometer) arrangements of the microtremor measurements. We measured the microtremor of apartment groups at the center of the first floor of each apartment for 20 minutes with a 200 Hz sampling rate (Fig. 2), and we measured the microtremor in the free field with a large triangular array (L-array) and a small triangular array (S-array) for 30 minutes with a 200 Hz sampling rate (Fig. 3).

When we processed the microtremor data for the apartment groups, we regarded the sensors to be installed parallel to the *x* axis (we ignored the positional displacement of the sensors in the *y* direction) and we regarded the sensor arrangement as a linear array. Then, we transformed the data of this linear array from time and 1-D space domain to frequency and 1-D wavenumber domain with the maximum likelihood method (MLM) [8] to get information about the phase-lag between the apartments. The concept of this data processing is shown in Fig. 4. When we imaged the characteristics of this F-K spectrum, we used the normalized F-K power spectrum defined by the next equation. We did this because we did not want to focus on the power differences between the different frequencies, and we wanted to focus on the wave number of the maximum power point at each frequency.

$$\overline{P}(f_c,k)=\frac{P(f_c,k)}{\max[\delta(f-f_c)P(f,k)]} \tag{1}$$

Where, $\overline{P}(f_c, k)$ is the normalized F-K power spectrum where the frequency is f_c and the wavenumber is k, $P(f, k)$ is the F-K power spectrum where the frequency is f and the wavenumber is k, $\max[g]$ is the maximum value of the function g, and δ is delta function.

When we processed the data for the microtremor of the free field, we transformed the data from the time and 2-D space domain to the frequency and 2-D wavenumber domain by MLM to get information about the direction of arrival.

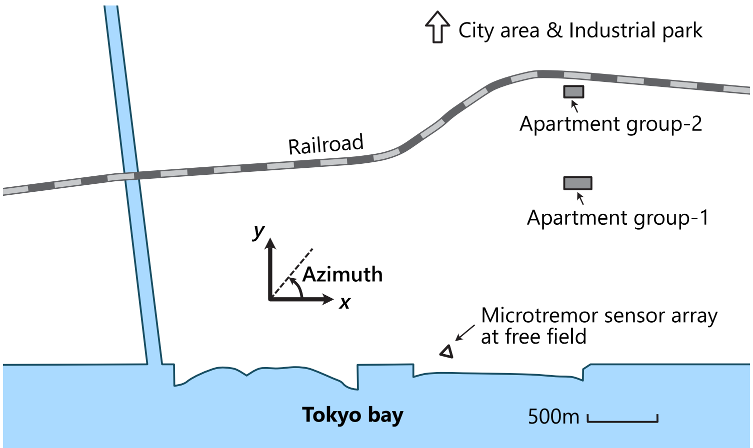
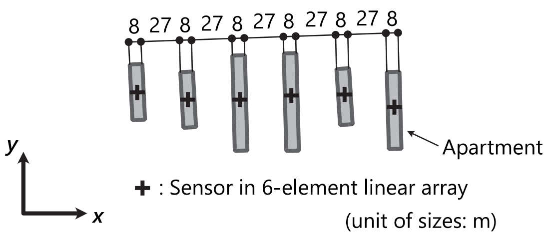
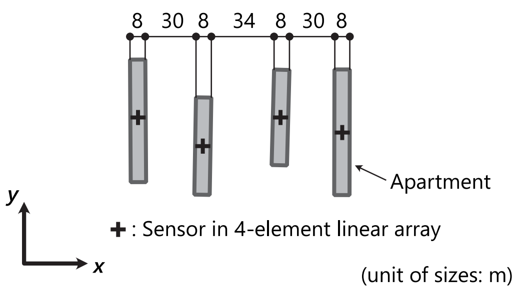


Fig. 1 – Map of sites to explore microtremor



(a) Apartment group-1



(b) Apartment group-2

Fig. 2 – Measurement plan of apartment groups

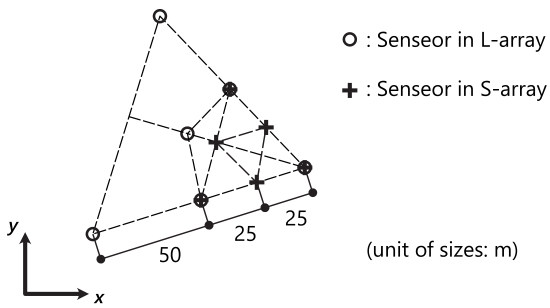


Fig. 3 – Microtremor sensor array in the free field

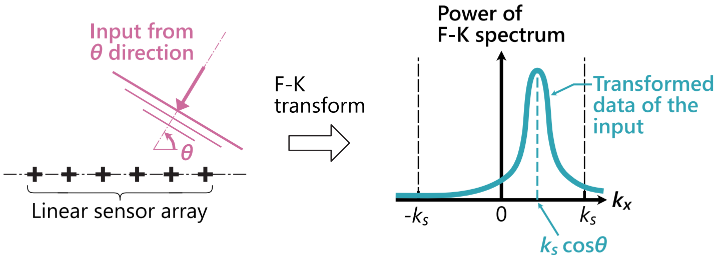
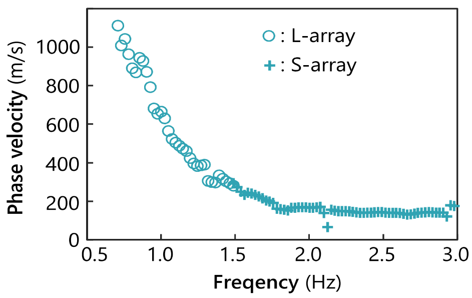


Fig. 4 – Pattern diagram of data processing for linear arrays

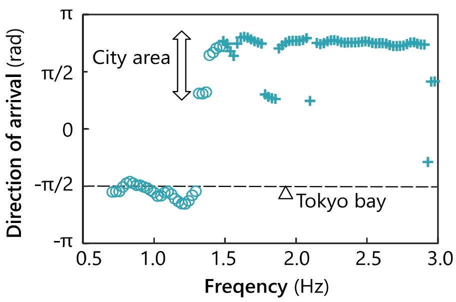
2.2 Results

Fig. 5 shows results of F-K analysis for microtremor measurements in the free field by MLM. Figure (a) shows a smooth dispersion curve and the smoothness of the curve confirms the reliability of the measurement results. Figure (b) shows that the component with Tokyo Bay as the vibration source is strong at around 0.7―1.3Hz, and the components from the urban area, industrial park, or railway (see also Fig. 1) as the vibration source is strong at around 1.3―3Hz.

Fig. 6 shows the results of F-K analysis for microtremor measurement at the apartment groups by MLM. In this figure at around 0.7―2.5Hz, there are two peaks of the normalized F-K power spectrum. One peak is stronger than the other peak and the other peak is at a nearly symmetrical position to the strong peak relative to the axis with zero wave number. That is, standing waves are generated.

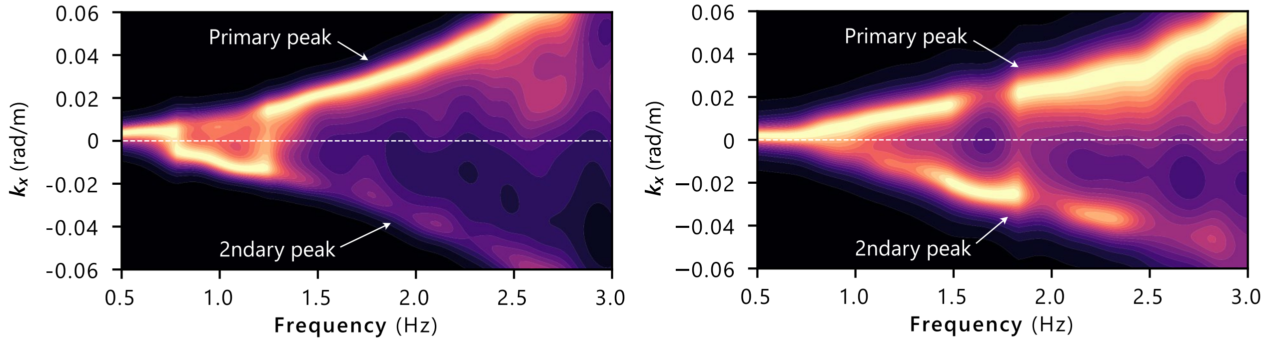


(a) Phase velocity



(b) Direction of arrival

Fig. 5– Results of F-K analysis for the free field



(a) Apartment group-1 (b) Apartment group-2

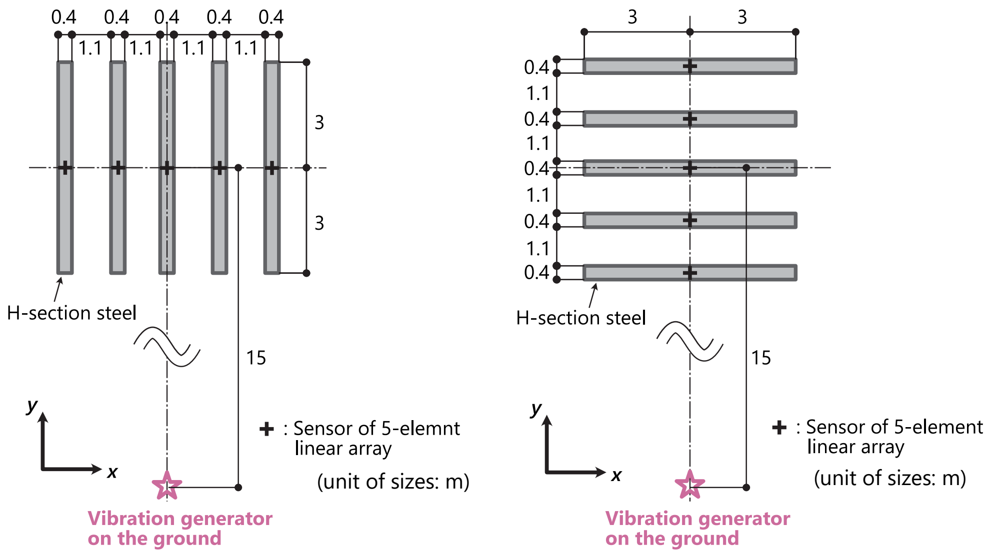
Fig. 6– Normalized F-K power spectrum at apartment groups (using *y* component)

3. Vibration tests of the reduced model

3.1 Method

In the vibration tests of the reduced model, we regarded an H-section steel (width: 400mm × height: 400mm) as an apartment included in the apartment group and arranged the H-section steels on the ground. Then, we installed a vibration exciter (force rating 490 N, frequency range 0.1 Hz－1 kHz) at a point sufficiently distant from the reduced model. We excited ground vibration using a linear chirp (3－30 Hz) and measured the response of the ground and the H-section steels. Then we processed the measured data by F-K analysis as with the data processing for the microtremor at the apartment groups.

Fig. 7 shows the arrangement of H-section steels, the exciter, and the sensors (accelerometer). We performed the vibration tests with and without the H-section steel in the arrangement of Plan *x* and *y* shown in Fig. 7 and compared the results. Excitation was performed only in the vertical direction. Table－1 shows the cases of the vibration tests.



(a) Plan *x* (b) Plan *y*

Fig. 7 – Plans for the vibration test of the reduced model

Table 1 – Cases of the vibration test of the reduced model

Case	Plan	H-section steel
x-f	*x*	Without
y-f	*y*	Without
x-s	*x*	With
y-s	*y*	With

Table 2 – Parameters of apartment groups and reduced model

	Actual buildings: Apartment group		Reduced model: H-section steel	Model / Actual buildings
	1	2		
W (t)	about 2,000 to 3,000		1.2	about 5×10^{-4}
L (m)	about 50	about 70	6	about 0.1
B (m)	8		0.4	0.05
d (m)	27	30	1.1	about 0.04
Number of elements	6	4	5	about 1
Target wavenumber (rad/m)	±0.06		±1.2	20
Soil stiffness	Unknown		Unknown	-
Foundation structure	Pile		Mat	-
Input type	Microtremor input		Linear chirp (3－30Hz)	-

Where, *W* is mass of the target for measurement, *L* is the horizontal length of the long side of the target for measurement, *B* is the horizontal length of the short side of the target for measurement, *d* is the interval of apartments or H-section steels

Table－2 shows a comparison of the parameters between the apartment complex and the reduced model. As shown in the table, the soil conditions and the foundation structure are different, in addition, the similarity rule is also not satisfied, so the apartment complex and the reduced model are not similar systems. However, we consider that it is possible to grasp qualitative trends even with such reduced models with insufficient similarity.

3.2 Results

Fig. 8 shows the results of the vibration tests for the reduced model. In the case of *x*-f (Fig. 8 (a)), the peaks of the normalized F-K power spectrum appear near the zero wavenumber. On the other hand, in case *x*-s (Fig. 8 (b)), the peaks of the normalized F-K power spectrum appear at a non-zero wavenumber. Furthermore, there are symmetrical peaks in Fig. 8 (b) relative to the axis with zero wave number. The symmetrical peaks like this are also shown in the results of the F-K analysis of the microtremor measurement at the apartment groups (Fig. 6).

In case *y*-f and *y*-s (Fig.8 (c), (d)), there is a single dominant peak at each frequency. This characteristic is different from the characteristics shown in the results of the microtremor measurement at the apartment groups shown in Fig. 6. From the above, in these vibration tests, it is considered that the response of H-section steels in case *x*-s is most similar to the microtremor at the apartment groups.

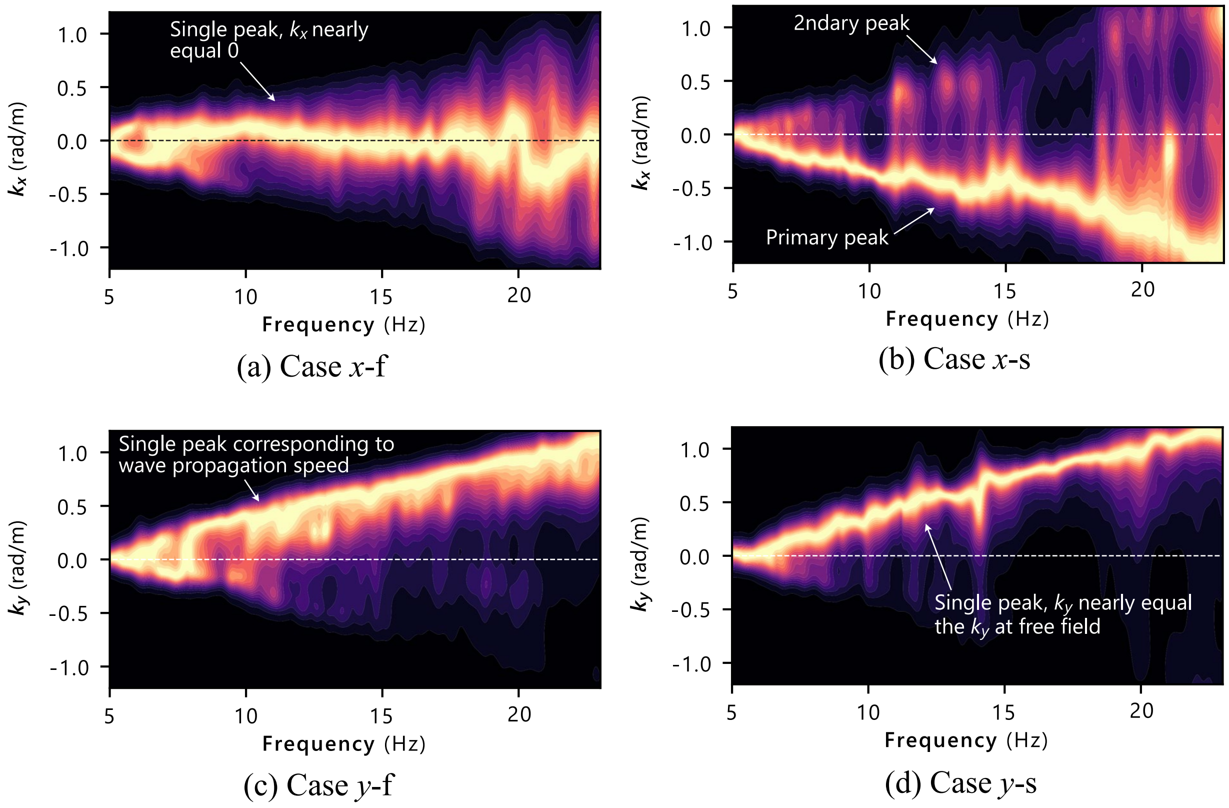


Fig. 8 – Normalized F-K power spectrum of the vibration test of the reduced model (using vertical component)

4. Discussion

The two symmetric peaks of the normalized F-K power spectrum that appeared in the data of the microtremor at the apartment groups (Fig. 6) and in the vibration test case *x*-s (Fig. 8 (b)) can be explained by one of the following two hypotheses: One is is the idea that there is a weak vibration source opposite the strong vibration source to the linear array. This is shown in Fig. 9. The other is the idea that the source itself is single and the secondary peak is caused by the wave excited by the response of the structures. This is shown in Fig. 10.

The former idea (Fig. 9, hypothesis-1) is inconsistent with the direction of the arrival of the microtremor in the free field, and it is also inconsistent with the fact that case *x*-s has two symmetrical peaks of the normalized F-K power spectrum though there is only one vibration source. Because the direction of arrival of the microtremor for apartment groups may be different from the direction in the free field, the idea is not always inconsitent with the result of microtremor measurement. However, both the sea and the urban area (or industrial parks, railways) are stable vibration sources, and just as the free field is sandwiched between these sources, the apartment groups are also sandwiched between these sources. So, we consider that it is unnatural that the direction of arrival for the microtremor at apartment groups is different from the direction in the free field in all frequency ranges from 0.5 Hz to 3 Hz.

The latter idea (Fig. 10, hypothesis-2) is consistent with the direction of arrival of the microtremor in the free field, and can explain the difference between case *x*-s and case *x*-f. In case *y*-f and case *y*-s, there is only a single peak at each frequency in the normalized power spectrum, so these cases seem to be inconsistent with hypothesis-2. However, this characteristic of case *y*-f and case *y*-s can be explained as a result of the superpositon of the excited waves shown in Fig. 10 (b) and the original input emphasize the components in the same direction of travel. So, we consider that hypothesis-2 is more consistent with the actual phenomenon than hypothesis-1.

In a system where the phenomenon shown in Fig. 10 is remarkable, it is considered that some amount of input energy is trapped in the group of structures. We consider that the standing waves trapped in the group of structures like this affect not only microtermor response but also earthquake response.

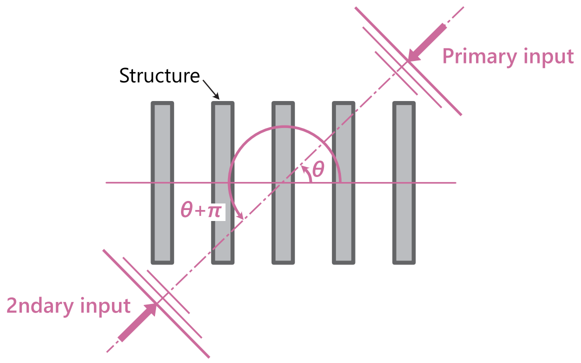
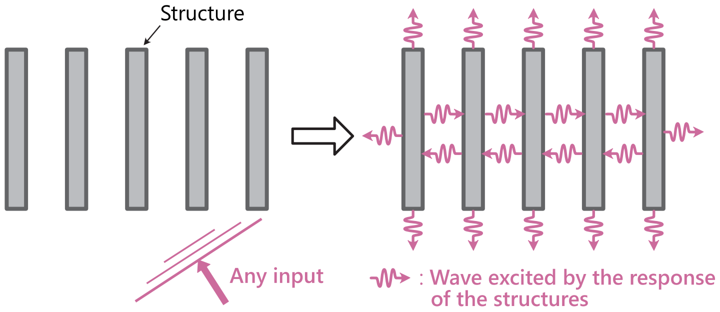


Fig. 9 – Hypothesis-1 for explaining the two symmetric peaks of the normalized F-K power spectrum



(a) Input (b) Response

Fig. 10 – Hypothesis-2 for explaining the two symmetric peaks of the normalized F-K power spectrum

5. Conclusion

In this study, we have shown the results of microtremor measurement in apartment groups where the standing wave seems to be excited by their responses to ground vibration. Then, we have shown that the standing wave can be excited by the response of groups of buildings to ground vibrations by vibration tests of a reduced model.

We consider that evaluating the effects of this standing wave may enable to more reasonable evaluation for the damping ratio of a building as a fixed base structure. This is because this standing wave is expected to affect the vibration energy dissipation of the building group. We also consider that adjusting the building interval according to the wavelength of this standing wave may make it possible to minimize the seismic response of building groups.

In the future, we would like to directly detect this standing wave in full-scale buildings. We also want to investigate the effect of this standing wave on the seismic response of buildings.

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