SEISMIC OBSERVATION SYSTEM FOR A BUILDING AND SURROUNDING GROUND IN KOMABA RESEARCH CAMPUS

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ABSTRACT

Recently, the Institute of Industrial Science of the University of Tokyo has been moved from Roppongi Campus to Komaba Research Campus. In the relocation, a seismic observation system was newly set up in the institute's building, on the ground surface, and in a borehole. The observation system has collected records from 20 seismic events. On the basis of these records, soil and building responses were analyzed. The results showed general characteristics of the seismic response in the urban area of Tokyo, particularly, the site amplification due to sediments over Tokyo Formation. A particular soil anisotropy was found around 4.2 Hz due to soil-structure interaction. Three-dimensional linear elastic dynamic analysis (FEM) of the building was conducted to simulate the actual response of the structure under seismic loads. In the future, more observation records will be collected and they may provide the details of the site and building response characteristics.

INTRODUCTION

The seismic response of structures has been one of the most important topics in earthquake engineering and numerous studies have been carried out. However, seismic observation systems of actual structures are still rather scarce, and hence, the seismic records from actual structures together with free field motion nearby have significance importance to examine analytical models.

Recently, the Institute of Industrial Science (IIS) of the University of Tokyo has been moved from Roppongi Campus, located in the central part of Tokyo to Komaba Research Campus, located in the western part of Tokyo. During the relocation, a seismic observation system was set up in the institute's new building and its surrounding ground. This system consists of nine three-component accelerometers and four one-component accelerometers. Three three-component accelerometers were placed at different depths bellow ground level (–10 m, –18 m and –55 m) while the others were set up on the ground surface, and on the basement and upper floors of the building. The system can also retrieve seismic records from seismometers at the Chiba Experiment Station (Katayama et al., 1990) of the University of Tokyo, located in 30 km east of Komaba site.

This paper introduces this new observation system and discusses on the soil and building responses based on the seismic records and microtremors.

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SOIL PROFILE OF KOMABA SITE

Komaba Research Campus is located in the western part of Tokyo, 40 m above the sea level. In 1996, before construction of new Komaba research campus, boring surveys were conducted at six places. The deepest survey, at that time, was up to 20.7 m and six different layers of soil were identified as shown in Table 1. In October 2000, accelerometers were buried and another boring survey was conducted up to 55 m in depth. The soil profile obtained from these boreholes as well as the results of standard penetration test (SPT-N) and PS logging tests are shown in the Fig. 1.

Although the soil profile and SPT N-values of each one of the initial six boreholes are not shown here, they match fairly well the survey results shown in Fig. 1, suggesting that the soil layers are quite uniform and simple.

Table 1. Boring survey results

Height above sea level (m)	Depth GL– (m)	Type of soil	SPT N-value (mean)	Geological time	Name of stratum
40.7 39.5	0.0 –1.2	Fill	2 - 4 (3)	Holocene	Fill
36.0	–4.7	Volcanic cohesive soil	3 - 13 (6)	Pleistocene	young Kanto loam
28.0	–12.7	Volcanic cohesive soil	1 - 26 (6)		old Kanto loam
22.0	–18.7	Gravel	4 - 37 (17)		Tokyo Formation
20.0	–20.7	Gravel	≥ 60		Tokyo Gravel Bed
		Fine sand	29 - 60 (≥ 60)		Kazusa Group

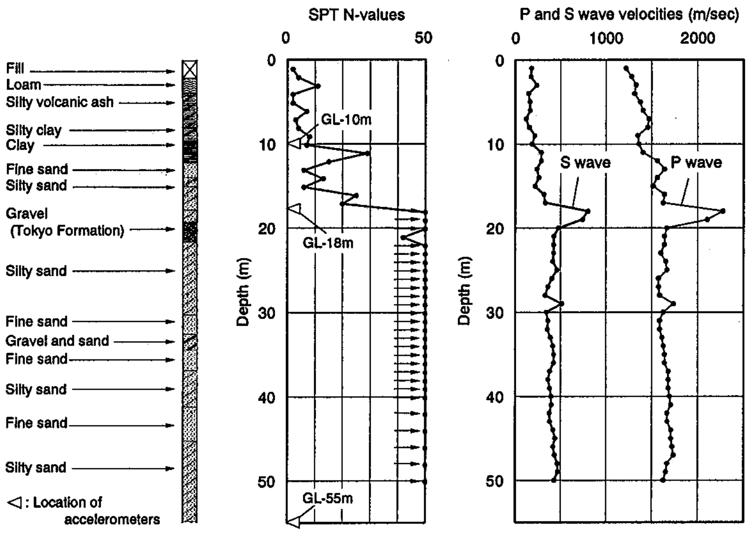


Figure 1. Soil profile, Standard Penetration Test (SPT) N-values and P and S wave velocities

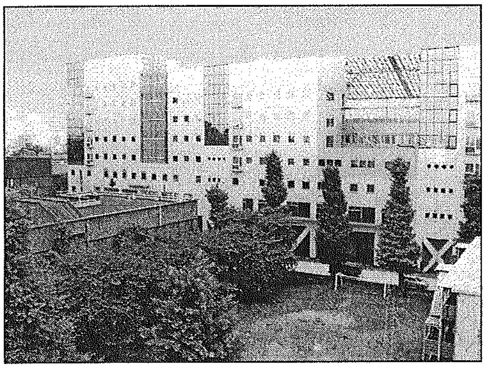
STRUCTURAL CHARACTERISTICS OF THE INSTITUTE OF INDUSTRIAL SCIENCE BUILDING

The new building of the Institute of Industrial Science is 218 m long, 48 m wide. The first two stories (the base and first stories) are moment-resisting steel reinforced concrete frame structures (SRC). From the second story to the top of the structure is a combination of concentrically braced and moment-resisting steel frames. The building is composed of two wings (east and west), both oriented north and south. The two wings are separated from each other, having an open space in between. The two wings are linked by several simply-supported bridges. Each wing is composed of two structures separated by an expansion joint. For administrative purposes both wings are sub-divided into blocks B, C, D, E, and F. The expansion joint is located between blocks D and E (Fig. 2). The west wing is eight-story high, while the east wing is six-story high. The first story's height is 7.25 m while the other inter-stories height is 4 m. The building has a common glass roof designed in such a way that it does not interfere with the independent vibration of the two wings.

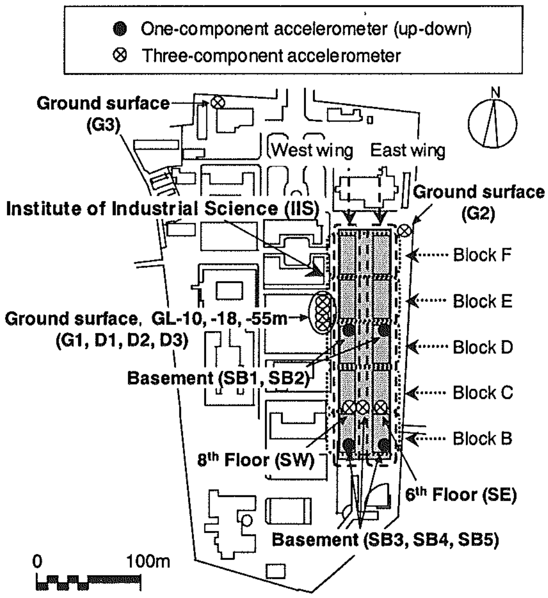
The building's foundation is composed by foundation beams linking the caps of clustered piles of reinforced concrete. The piles are founded at a depth of 20 m in the Tokyo Gravel Bed, on which the most of the high-rise buildings in Tokyo are founded.

SEISMIC OBSERVATION SYSTEM

The seismic observation system consists of nine three-component accelerometers and four one-component accelerometers, with acceleration range 0 - 2000 cm/sec^2, frequency range 0.1 - 30 Hz, and sampling frequency of 100 Hz.

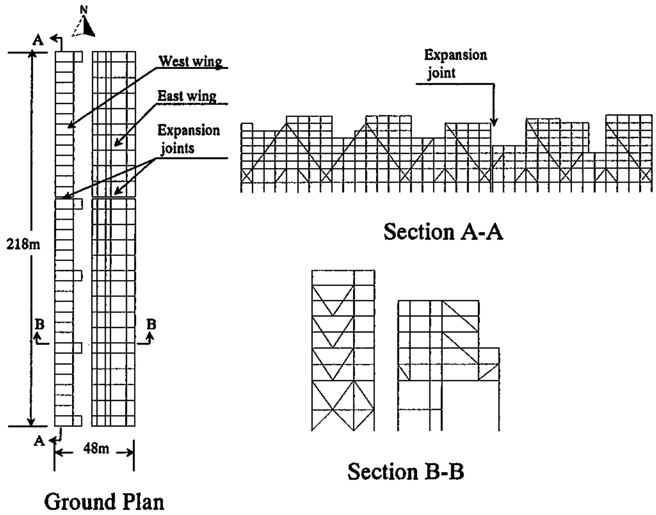


(a) Photograph of the IIS building



(b) Location of accelerometers

Figure 2. New IIS building and location of accelerometers



(c) Structural plan and sections

Figure 2.(cont.) New IIS building and location of accelerometers

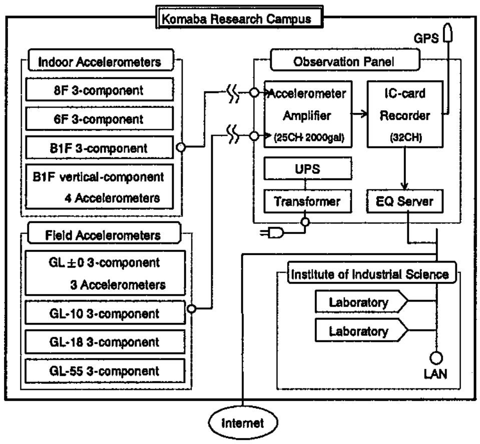


Figure 3. General scheme of the observation system

The locations of accelerometers placed in the downhole, on the ground surface and on the building floors are shown in Fig. 2. There are three three-component accelerometers placed on the ground surface and another three three-component accelerometers buried at different depth levels (–10 m, –18 m, and –55 m). The accelerometer located at 18 m below the ground surface is in the Tokyo Formation stratum, which is a stiff gravel layer. The deepest instrument is placed in the Kazusa Group stratum.

Figure 3 shows a schematic diagram of the observation system. The signals captured by the accelerometers are sent to an observation panel, where they are amplified and stored in a digital format which can be accessed through a Local Area Network (LAN). The system is also capable of retrieving records from a seismometer array set up in the Chiba Experiment Station (Katayama and Sato, 1982; Katayama et al., 1990). Based on this observation system and the Chiba seismometer array, it is possible to study the wave propagation and site amplification characteristics in Tokyo area. The information on the Chiba array is available in Katayama et al. (1990), Lu et al. (1992) and Yamazaki and Turker (1992).

On the basement of the building, four one-component (up-down) accelerometers and one three-component accelerometer were placed. Also, two three-component accelerometers were placed between blocks B and C on the eighth and sixth floor of the west and east wing, respectively. This observation system will provide valuable information on the dynamic response characteristics of the soil and structure under seismic excitation.

EARTHQUAKE RESPONSE OF SOIL AND STRUCTURE

The observation system started its operation in April 2001 and it has already recorded 20 earthquake events with Peak Ground Accelerations (PGA) ranging from 2 cm/sec^2 to 54 cm/sec^2. Microtremors were also measured at locations of ground surface accelerometers (G1, G2, and G3) and accelerometers on different floors of the building (SE and SW). Based on the seismic records and microtremors the dynamic response characteristics of the soil and structure were studied.

Soil amplification evaluated from earthquake records

The amplification of peak acceleration was evaluated from the 20 recorded events at depths of 0 m (ground level), –10 m, –18 m, and –55 m in the three boreholes separated 3 m from each other (Fig. 2). The amplification ratios for the three components, North-South (NS), East-West (EW) and Up-Down (UD), for each event are shown in Fig. 4 by normalizing the peak accelerations by those at –55 m.

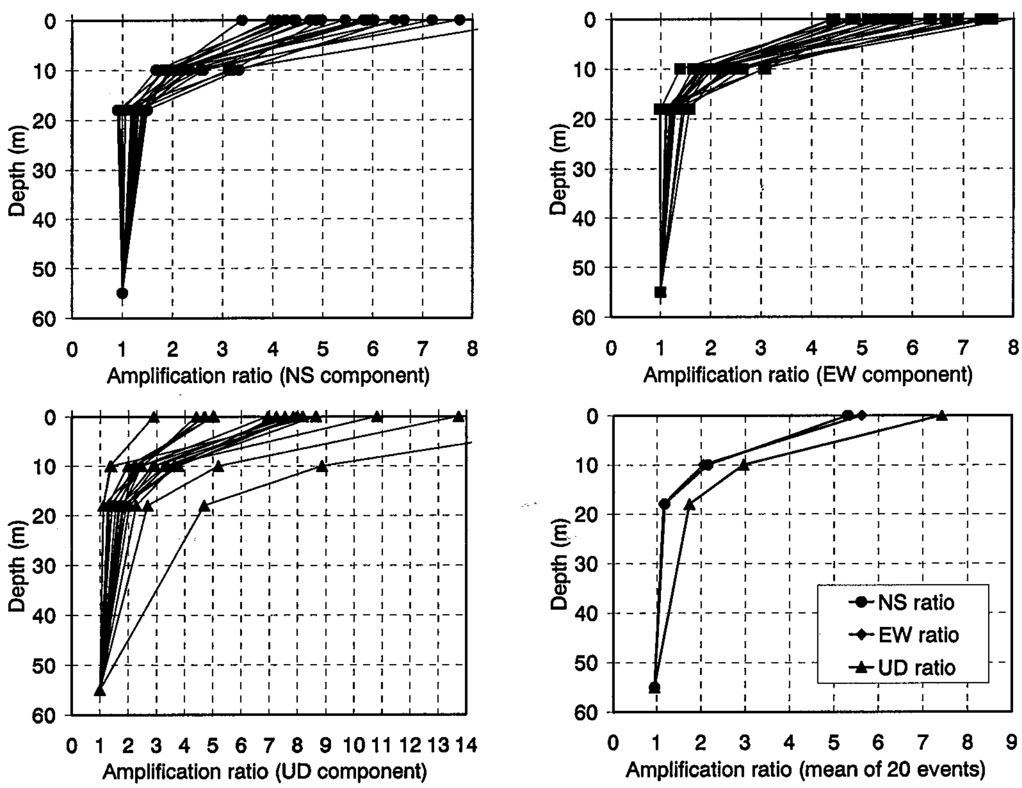


Figure 4. Amplification ratios of peak acceleration

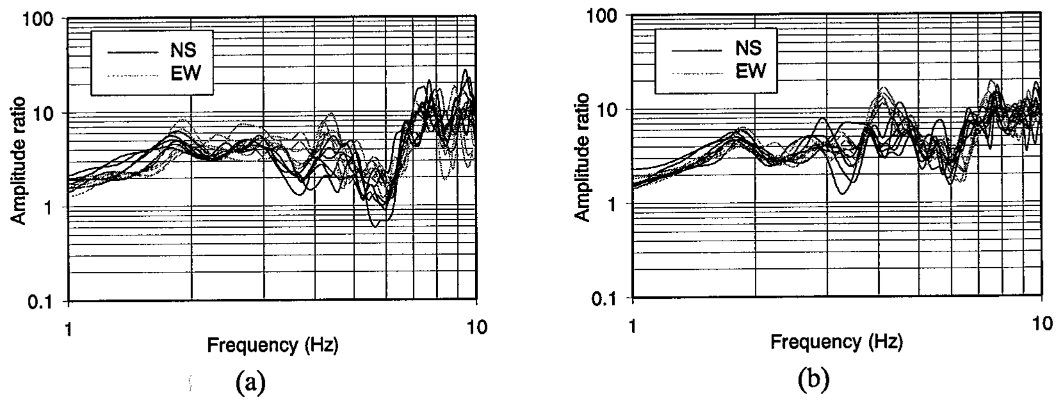


Figure 5. Fourier spectral ratios of the seismic records for the NS and EW components: (a) between G3 and D3 and (b) between G1 and D3.

The amplification is significant in the first 18 m below the ground surface. From the soil profile and SPT N-values shown in Fig. 1, the stiffness of the soil above the Tokyo Formation stratum seems to be much softer than that of this layer. For the layer between -18 m and -55 m, the both horizontal components show rather similar amplification while in the first 18m layer, the north-south component shows larger scatter than the east-west component does. However, the average of the amplification ratios for the 20 events were almost equal for the two horizontal components at all the depths (Fig. 4). It is noticed that the amplification ratio of the vertical component in terms of peak acceleration is larger than those of the horizontal components for all the depths. But, in general, the amplification of peak acceleration is rather uncertain because it is affected by pulse-like peaks and the occurrence time of the peaks may be different.

Soil amplification characteristics were further investigated in terms of the ratio of Fourier spectra of a record at –55 m and that on the ground surface. The Fourier spectra were smoothed using a Parzen window with bandwidth 0.4 Hz. Figure 5(a) shows the Fourier spectral ratios for six events (see Table 2) computed based on the records from accelerometer G3 (ground surface far from the building) and D3 (buried at –55 m). All the analyses from now on are based on the six events shown in Table 2. They were selected because their PGA values in both horizontal directions are comparatively large (larger than 5 cm/sec^2) in the dataset of 20 events.

It can be seen that the Fourier spectral ratios of both horizontal components are quite similar up to 7 Hz. Figure 5(b) shows the Fourier spectral ratio for 6 events to the two directions (NS and EW), computed based on the records from accelerometer G1 (ground surface) and D3 (buried at –55 m), both located at the west side of block E. In this case, the Fourier spectral ratio is seen to be different around 4.2 Hz for the two horizontal components. Similar tendency was also observed in the Fourier spectral ratio computed from accelerometers G2 (located close to the north-east corner of block F) and D3, which are not shown here. It should be noted that the accelerometers G1 and G2 are placed at 11 m and 15 m, respectively from the building while accelerometer G3 is far away from it. The anisotropy observed around 4.2 Hz seems to be due to the effect of the existence of the building. However, the real causes of this phenomenon have not been proved yet and computer simulation of the soil-structure system should be carried out for further investigation.

Microtremor observation

Microtremors were measured on the building floors and on the ground surface at the places where the accelerometers are located. The instrument used for the microtremor measurement is a SPC-35N (Tokyo Sokushin Co.). The velocity records are high-pass filtered, amplified and converted to a digital format using a 16 bit AD converter for storage in a personal computer. A sampling frequency of 100 Hz was used. The measurements were carried out during in the day and night on different dates. The total time length (day and night) of microtremor measurements at each place was of 13 minutes.

The Fourier spectra were calculated for the microtremor records using the same procedure as for the seismic records. The H/V spectral ratio method (Nakamura, 1989) was used to evaluate site response characteristics, where H and V are the smoothed Fourier spectra for the horizontal and vertical components, respectively. This method has also been used for strong motion records (Maruyama et al., 2000) and its stability was explained by Yamazaki and Ansary (1997) based on the attenuation relations of the velocity response spectra for the horizontal and vertical components of seismic motion.

Figure 6 shows the horizontal and vertical Fourier spectra of microtremors measured next to the location of the accelerometer G3, and their ratio. Note that in this study, the horizontal Fourier spectra were obtained as the resultant (product) of the two horizontal components (Arai and Tokimatsu, 1998). Each microtremor record was analyzed for several time windows of 20.48 sec length, and thus, the stability of microtremors with time was checked. In the figure, each thin line represents one of these time windows and the thick line is the average of them.

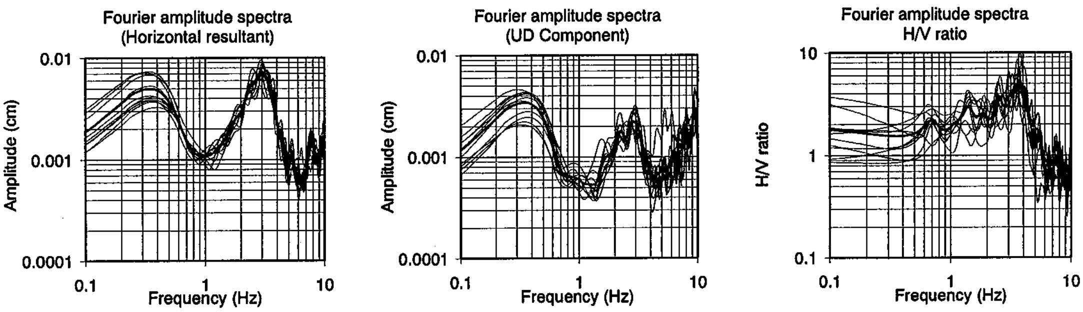


Figure 6. Fourier spectra and H/V ratios of 10 time windows and their average of microtremors at the location of accelerometer G3

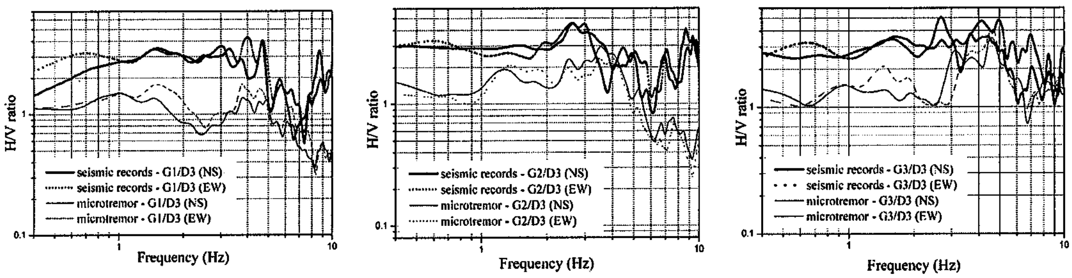


Figure 7. H/V Fourier spectral ratios of seismic ground motions and microtremors at the locations of accelerometers G1, G2, and G3

Based on the H/V ratio, the predominant frequency of the ground at the location of accelerometer G3 is found to be around 3.7 Hz (Fig. 6). The H/V Fourier spectral ratios for all the seismic records at the three accelerometers deployed on surface (G1, G2, and G3) were also calculated. Figure 7 compares the average H/V ratios for the seismic motions and microtremors recorded at G1, G2 and G3 for the two horizontal directions.

In the figure, it is observed that the general trend of H/V ratios of strong motion records and microtremors are similar. However, the amplitude ratio of microtremor is smaller than that of seismic records. It was noted that the fundamental frequency of the ground according to the H/V ratio for the seismic records is less than that of microtremor for the both horizontal directions at G2 and G3 locations. The fundamental frequencies of the ground at G1 location obtained from seismic records and microtremors are close to each other. By comparing H/V ratios of microtremors in the north-south direction with those in the east-west direction at G1, G2, and G3 locations, it can be seen that microtremors did not reflect the soil's anisotropy detected in the seismic records (Fig. 5). This is probably explained by the fact that the vibration level of microtremor is much smaller than that of seismic motion, and the vibration (response) of the building has smaller effects on the microtremor of the ground close to the building.

Building's response

Based on the records of the accelerometers SE set up on the sixth floor of the east wing, on the eighth floor of the west wing, and on the ground surface, the fundamental frequency of the building was evaluated. Using the same procedure as for the soil response analysis, the Fourier spectra for all the six events were computed. Additionally, microtremors were measured on the building floors at the same locations of the accelerometers SE and SW.

Figure 8 shows the Fourier spectral ratio of the seismic records and microtremors between the eighth floor and ground surface for the west wing and the Fourier spectral ratio between the sixth floor and ground surface for the east wing. Good agreement is observed between microtremors and seismic events in term of the fundamental frequency although the levels of shaking are quite different between seismic records and microtremors. The minor discrepancy in the level of amplification at the fundamental frequency between microtremors and earthquakes is considered due to the fact that the sources of microtremors are of various kinds, and it is very likely that those sources were different at the different moments at which microtremors were measured. The fundamental frequency of the west wing (8 story) is obtained as about 2.6 Hz (period = 0.39 sec) and 2.1 Hz (period = 0.48 sec) to the NS and EW directions, respectively, and 2.7 Hz (period = 0.37 sec) and 2.1 Hz (period = 0.48 sec) for the east wing (6 story) to the NS and EW directions, respectively.

Structural modeling of IIS Building

The building of the Institute of Industrial Science (IIS) was modeled by three-dimensional finite elements using a structural analysis program, SAP2000 (Computer and structures Inc., 2000). The linear elastic dynamic problem is solved in the time domain by means of a combination of the mode superposition and incremental methods (Wilson, 2000). The structural damping is assumed to be of Rayleigh type. As explained before, the building is composed by four "independent" superstructures, and thus independent models were used for each one of the four superstructures.

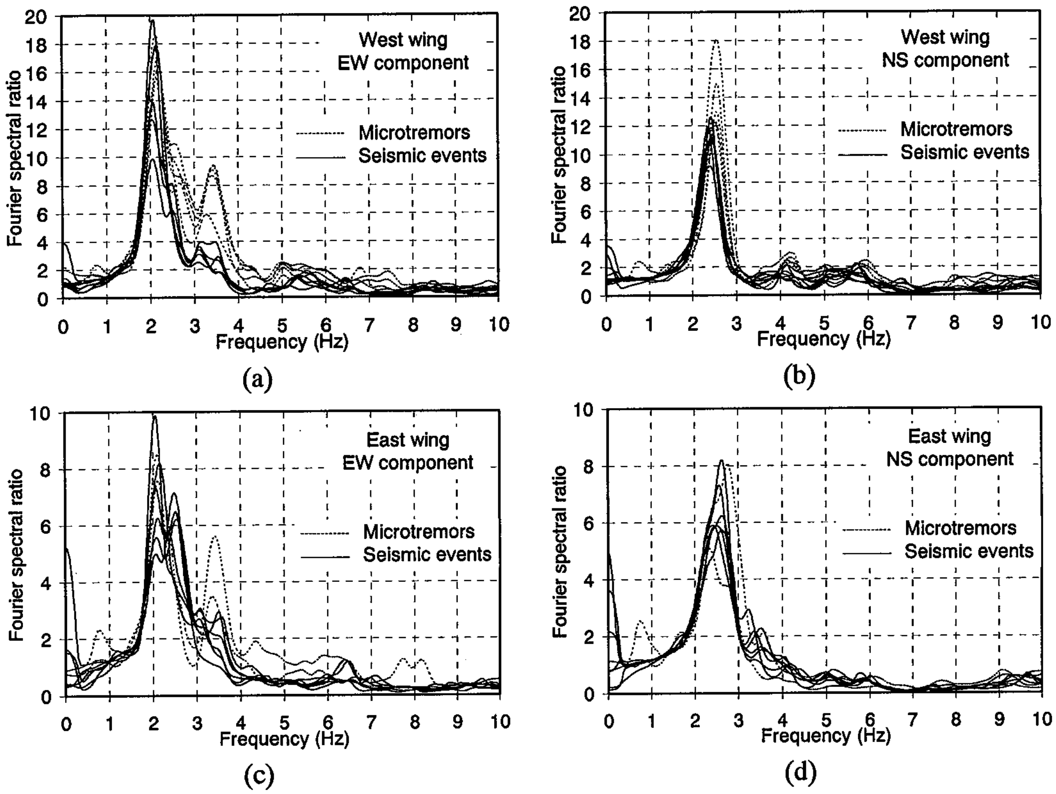
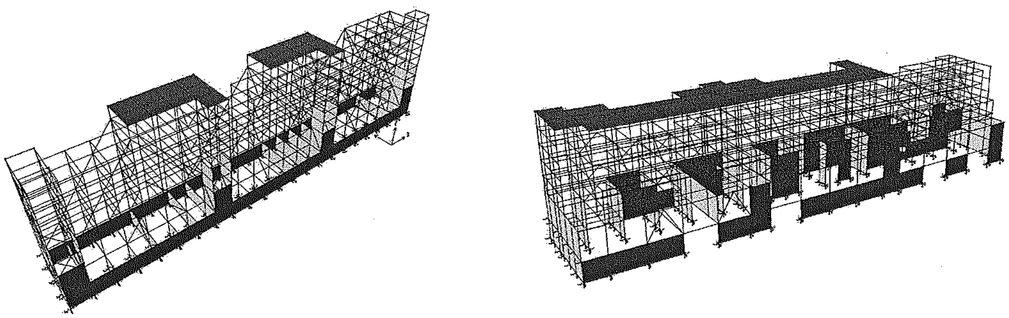


Figure 8. Fourier spectral ratios between the 8th floor of the west wing SW or 6th floor of the east wing SE and ground surface for the 6 seismic events and microtremors to the horizontal directions: (a) West wing to the EW direction, (b) West wing to the NS direction, (c) East wing to the EW direction, and (d) East wing to the NS direction.

Figure 9 shows a 3D view of the model for the west and east wings (blocks B, C and D only). The model was set up based on the structural drawings and the loads acting on it were assumed to be the same as those used in the design. Although it is possible to make a good model based on the "actual" dimensions and material properties of the structure, it is very difficult to estimate the actual structural properties (e.g. mass, stiffness, damping), and even more difficult to assure the dynamic response predicted by a model matches the actual response. The seismic observation system set up in the IIS building as well as on the ground surface and in the borehole offers to us a very good chance to investigate which are the most important structural variables and their effects on a model. Table 2 shows basic information on the events used in this analysis.

In the model, the modal damping was assumed to be 2% for all the modes of vibration because it is a steel structure and the seismic events that have been recorded are rather small. The building was initially modeled with a fixed-base. However, the model with this assumption was found to be stiffer than the actual structure, from the result of the seismic observation. Since soil-structure interaction seemed to affect the actual building's behavior, the authors have decided to introduce the soil effects in the model.



(a) (b)

Figure 9. Three-dimensional finite element model: (a) Blocks B, C, and D of the west wing, and (b) Blocks B, C, and D of the east wing.

Table 2. Characteristic of the earthquake events used in the analysis

Event (yymmdd)	Magnitude in the JMA scale	Recorded peak acceleration (cm/sec^2)					
		Ground surface G1		West wing: 8thflr SW		East wing: 6thflr SE	
		NS	EW	NS	EW	NS	EW
010524	4.3	–12.31	–8.55	–7.19	–5.90	–5.76	4.42
010625	4.0	–43.03	54.05	29.72	–21.51	–23.73	24.31
010720	4.8	9.30	13.51	12.89	12.69	–9.16	–10.74
010726	4.2	22.29	–24.80	13.02	16.78	–13.84	–9.38
011117	4.5	–16.94	24.06	15.17	–12.32	11.15	11.08
011219	3.8	–5.85	8.28	–6.24	9.58	–5.27	–9.56

The effect that the soil has on the structural response was modeled by means of massless supporting springs. The stiffness values of those springs were computed according to the methodology proposed by Gazetas (1991). Table 3 shows three of the six algebraic expressions to compute such stiffnesses. The values of these stiffnesses were adjusted by trial and error following the ATC-40 methodology (Applied Technology Council, 1996). According to this methodology, the dynamic soil behavior is simplified and generalized using the strength and stiffness envelope shown in Figure 10.

The acceleration time history responses obtained from the model for the six seismic events at the locations of the accelerometers were analyzed using the Fourier spectra. The ratio between the Fourier spectrum on the 8th floor or the 6th floor of the building (from the model) and that on the ground surface was computed. Figure 11 shows the comparison between the Fourier spectral ratios from the records and from the model analysis.

Good agreement was achieved in term of the fundamental frequency for the two buildings (east and west wings) between the observed records and model. However, the structural model generally overestimates the level of amplification. This is more evident from the results of the east wing model. It could be explained based on the fact that in the model the effect of the soil was modeled only by mass-less springs, and thus, the effect of radiation damping was not considered. Additionally, it should be keep in mind that the actual structure has very complex boundary conditions that were not considered in the model so long as it was modeled as a set of independent structures. For instance, the bridges linking the east and west wings are believed to affect the response of the blocks, but their effects were not included.

Table 3 Surface stiffnesses and stiffness embedment factors for a rigid plate on a semi-infinite homogeneous elastic half-space (adapted from Gazetas, 1991)

Stiffness parameter	Rigid plate stiffness at surface	Embedment factors
Vertical translation	$\frac{GL}{1-\nu}\left[0.73+1.54\left(\frac{B}{L}\right)^{0.75}\right]$	$\left[1+0.095\frac{D}{B}\left(1+1.3\frac{B}{L}\right)\right]\left[1+0.2\left[\frac{(2L+2B)}{LB}d\right]^{0.67}\right]$
Horizontal translation	$\frac{GL}{2-\nu}\left[2+2.5\left(\frac{B}{L}\right)^{0.85}\right]$	$\left[1+0.15\left(\frac{2D}{B}\right)^{0.5}\right]\left\{1+0.52\left[\frac{\left(D-\frac{d}{2}\right)16(L+B)d}{BL^2}\right]^{0.4}\right\}$
Rocking	$\frac{G}{1-\nu}I_x^{0.75}\left(\frac{L}{B}\right)^{0.25}\left(2.4+0.5\frac{B}{L}\right)$	$1+2.52\frac{d}{B}\left[1+\frac{2d}{B}\left(\frac{d}{D}\right)^{-0.20}\left(\frac{B}{L}\right)^{0.50}\right]$

G, L, B, D, d, I_x and ν are the soil's shear modulus, plan dimensions of the foundation (L>B), elevation below the ground surface of the foundation basemat, average height of the sidewall that is in "good" contact with the surrounding soil, moment of inertia of the foundation and the Poisson's ratio of soil, respectively.

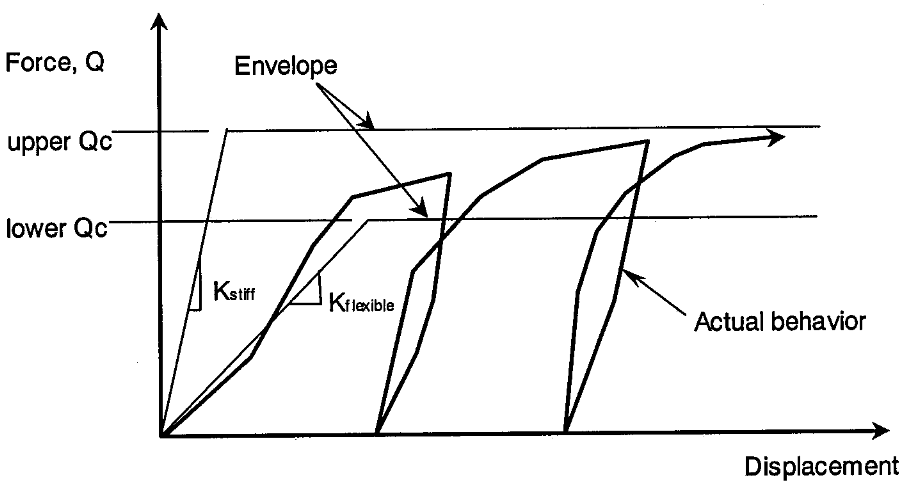


Figure 10. Basic force-displacement envelope for soil components (adapted from ATC-40, Applied Technology Council, 1996)

Another very important variable that is difficult to estimate is the structural damping. As mentioned before, the damping ratio of 2% used in the model for all the modes of vibration, but the damping ratio computed based on the smoothed Fourier spectral ratio from microtremor using the transfer function method (McVerry, 1979) suggests that the structural damping ratio might be in the order of 8%. However, this result must be also considered very carefully because the method was applied to the smoothed Fourier spectral ratio. The second peak exhibited by the model is due to the effect of the higher modes in the "isolated" structural model.

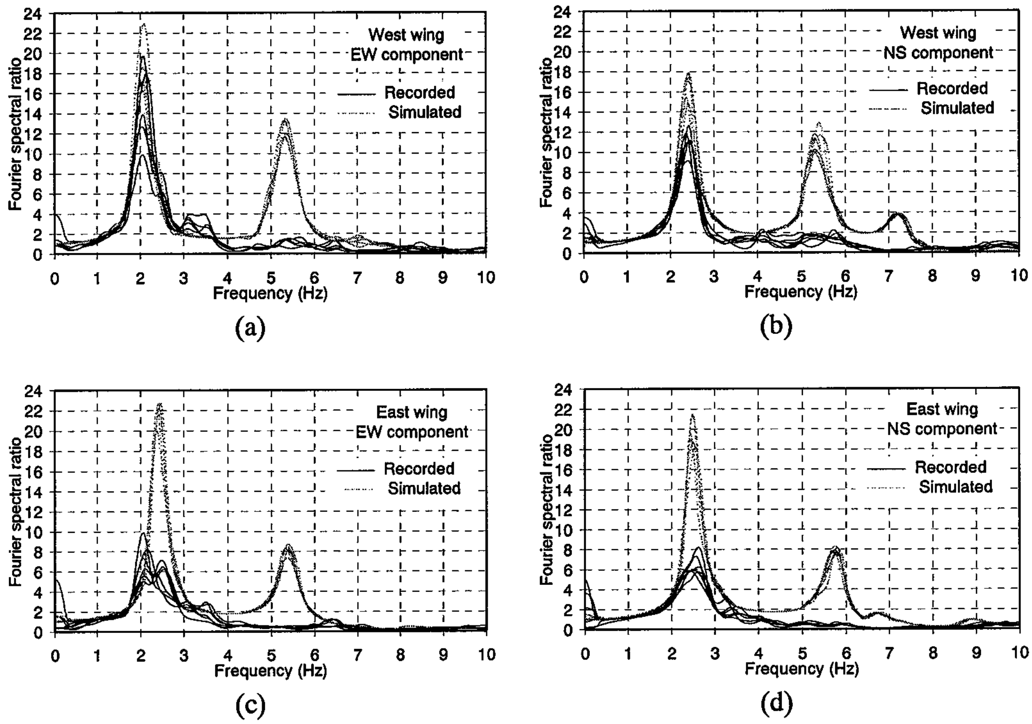


Figure 11. Fourier spectral ratios between the 8th floor of the west wing SW or 6th floor of the east wing SE and ground surface G1 from the 6 seismic events recorded and simulated by the computer model: (a) West wing to the EW direction, (b) West wing to the NS direction, (c) East wing to the EW direction, and (d) East wing to the NS direction.

It should be noticed that any of the analyzed structures are rather irregular. Torsion is one of the most important modes of vibration (second for the west wing and third for the east wing) and its contribution is significant in the model. However, this mode is constrained to a certain extent by the actual boundary condition that were not considered.

As for the seismic records, the same level of matching was achieved when one compares the Fourier spectral ratios of microtremor and those computed from the model. This may be rather obvious if one observes very good agreement between the Fourier spectral ratios of microtremor and seismic records in Figure 8.

In this analysis the variables that were adjusted by trial and error were only the spring constants, and they were basically fitted based on the building model for the west wing. This is the main reason why the east wing model shows a lower level of accuracy compared with the west wing model. However, it should be kept in mind that the foundation conditions of the both wings are rather similar, and it is reflected to the fact that the fundamental frequencies of the both structural models match well for the unique values of spring constants.

CONCLUSIONS

The seismic observation system in Komaba Research Campus of the Institute of Industrial Science, the University of Tokyo was introduced. The amplification of the peak ground acceleration took place mostly within the first 18 m of depth, above the Tokyo Formation layer. The Fourier analysis and H/V spectral ratio method were employed to analyze the records from earthquakes and microtremors. The H/V ratio of microtremor was smaller than that from the seismic records. The anisotropy observed in the seismic records of two horizontal components was not clearly observed in the Fourier spectral ratios of microtremor.

The new building of the Institute of Industrial Science showed rather similar stiffness in the two horizontal directions regardless of the big difference in their lengths. This is due to the bracing system provided in the EW direction. An unusual anisotropy was seen in the Fourier spectral ratios of the ground motions recorded by two accelerometers (G1 and G2) at around 4.2 Hz. Because of the similarity among the records from different events around this particular frequency, source and path effects were excluded from possible causes, and the most probable cause seems to be the soil-structure interaction. However, to explain this anisotropy in a more clear manner two- and/or three-dimensional soil-structure interaction analysis should be carried out.

Finite element models were employed to analyze the structural response of the two wings. It was found that a usual fixed-base model could not represent the actual behavior of the structure properly. Hence the mass-less springs were added to the model to simulate the boundary condition of the embedded parts of the structure. The results in terms of fundamental frequencies match very well with those obtained from the microtremors and seismic records. The discrepancy in the level of amplification may be due to the simplification assumed in the model, especially that introduced in the boundary condition.

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