BULDING DAMAGE EVALUATION BASED ON CHANGES OF STORY SHEAR-WAVE VELOCITIES EXTRACTED FROM A 1D VERTICAL AMBIENT NOISE OBSERVATION SYSTEM

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Abstract

The response of a building structure can be seemed as, in frequency domain, the super summation of shaking modes and alternatively, in time domain, the wave propagation within the structure and multiply reflected by the base and the top of the building. Using the frequency domain method, i.e. the Fourier transform, the frequencies of the building system including soil-structure interaction can be known from the predominant frequencies of the spectrum of the response of the top. Besides, the apparent frequencies of the response including the vibrations due to the base rocking and the upper structure itself can be extracted from the transfer function, which is the ratio of Fourier spectrum of the response of the top and that of the base in frequency domain. It is the so-called impulse response due to the input impulse (visual source) from the base. Because of the effect of the vibration due to the base rocking, the true shear-wave travel time (the phase velocity) within the upper structure is difficult to be extracted from the impulse response. However, for the virtual source on the top of the building, the response of the building, which is also a kind of impulse response (in this study we call it deconvolved waves), only including one acausal up-going wave (one impulse) and one causal down-going (the other impulse) wave, from which the shear-wave travel time from the top to the inter stories can be extracted from the according time of the impulses. And there is little effect of the soil-structure interaction, i.e. the base rocking, to the deconvolved waves if the higher modes are included when the deconvolved waves are calculated. In this study, we first using a multiple-degree-of-freedom model with rocking and horizontal springs at the base to prove the frequency and time domain method can work well to extract the frequency and time domain properties, respectively. Then, we try to apply the frequency and time domain n method to a 1D vertical ambient noise observation system to extract the shear-wave velocities traveling within stories. Based on the deterioration of shear-wave velocity of each story, the story-by-story damage evaluation of a 9-story steel reinforced concrete (SRC) building, which was severely damaged during the Great East Japan Earthquake, is performed. The extracted shear-wave velocities from ambient noise are compared with those calculated ones based on the relationship by inputting the design shear rigidities and masses of a similar building to the damaged one, because the design statements of the damaged building is unavailable. Based on the comparison between extracted shear-wave velocities and those calculated ones, we found that shear-wave velocities in the longitudinal directions reduced more dramatically than in the transverse direction. The shear-wave velocities in the longitudinal direction are almost reduced to less than 300m/s, especially at the first, 4th, 5th, and 8th story, which are reduced to less than 200m/s. In the transverse direction, shear-wave velocities generally become slower with the increase of height. Shear-wave velocities of 5th and 6th story reduced to less than 200m/s in the transverse direction.

Keywords: building damage evaluation, frequency domain, time domain, wave propagation, seismic interferometry, shear-wave velocity, ambient noise measurement

1. Introduction

In frequency domain, the structural response can be represented as a superposition of model responses with corresponding frequency-dependent intrinsic attenuation and radiation from the base due to ground coupling. In time domain, alternatively, the same vibration phenomenon can be regarded as the wave propagation within the building structure and multiple reflected by the base (partially reflect) and the top (totally reflect) of the building, also by internal boundaries if impedance contrast exist between stories[1],[2]. For the same vibration measurement test, if the perspective of structural response is different, data processing approaches, vibration measurement plan, and the identified system dynamic characteristics are variable.

The upper structure together with its foundation and the supporting ground perform as a system, i.e. a building system combining two sub systems, the upper structure system and the soil-structure interaction system. Response of a building system is a summation of the response of the upper structure and that due to soil-structure interaction. Each sub system has its own response properties. Therefore, for the health monitoring of a building system, it is important and necessary to evaluate the changes of response properties of the whole system and those of each sub-system separately. Though the vibration and wave propagation within the structures are intrinsically the same, the former is visible and can be recorded using seismometers, while the latter cannot be recognize directly form recorded waveforms. Therefore, some seismic interferometry methods should be used to reconstruct the wave filed for building a new wave filed from which it is easy to recognize the wave propagation path.

For frequency-domain approach to system identification, the decomposition of different modes and evaluate the changes of frequencies of each mode and mode shapes from vibration measurement are commonly used. The model frequencies of the building system including the responses due to soil-structure interaction can be obtained from the Fourier analysis of the response. However, it is difficult to tell whether the changes of the frequencies are caused by the damage of the upper structure, the foundation or supporting ground soften. On the contrast, the wave propagation velocity within the building only relates to the properties of the upper structure, based on which the characteristics of the building structure itself can be evaluated without the effect of ground coupling. The changes of shear-wave velocity can be used to evaluate the deterioration of the upper structures even each stories if the shear-wave velocity traveling within each story can be extracted. The period of the upper structure can be known from the shear-wave wave travel time from the base to the top, if the upper structure vibrate in pure shear mode. There is a relationship among frequencies of the building system frequency, the upper structure, the soil-structure interaction. Combining the frequency-domain and time-wave method, all of the frequencies can separated.

In previous studies on story damage detection and evaluation, changes of rigidity and damping constants which can be identified directly from the function of motion[3]~[5] and the changes of characteristics of the modes[6],[7]are used. The effectiveness of methods based on microtremor and/or earthquake measurement, and the shaking table has been examined. However, there are various assumptions applied on them. Because the direct identification method is determined from the function of motion, three prerequisites that i: the buildings behave as pure shear beam; ii: no influence of the rigid-body rocking vibration due to the soil-structure interaction; iii: input wave to the building is only vibrations from the ground are necessary. Because there is a need to clarify changes in multiple-mode characteristics, response mode analysis of low-sensitivity modes due to noise contamination and the lack of high-order modes are the limit of this technique.

In this paper, we first present the physical relationship between mode summation and the wave propagation using a multipule-degree-of-freedom (MDOF) model with rockign and horizontal spring. Then, inter-story shear-wave velocities of a 9-story SRC residential building, which was damaged during the Tohoku Earthquake, are extracted from microtremor records. A relationship between shear-wave velocity and story rigidity of buildings is proposed, based on which, the shear-wave velocities of a design example are calculated and compared with those of the damaged building. On the basis of comparison, story-by-story building damage evaluation is performed.

2. Methodology

Building response and frequencies

In this study we use a MDOF model to examine the relationship between the building response and the shear-wave propagation, the image of the model and the parameters of which are shown in Fig. 1 and Table 1, respectively. In order to read the wave propagation easily from the response waveforms, we use a Ricker Wavelet with central frequency of 10 Hz (Fig. 2) and duration of 100 second as the horizontal incident to the model. The wave is reversed to the plus side as shown in the Fig. 2. The acceleration, velocity, and displacement responses to the input Ricker wavelet are shown in Fig. 3. The first peaks of all waveforms are marked with open circle, from the according time of which the impulse travel time in the vertical direction can be extracted, though there is effect of soil-structure inter action. The impulse responses from the acceleration responses, the velocity responses, and the displacement responses are shown in Fig. 4. The spectrum of the transfer function between the displacement response of the top and the base and the spectrum of the displacement response of the top are shown in Fig. 5. The periods and frequencies of each mode which are calculated from the eigenvalue analysis and those from the spectrum (Fig. 5) are shown in the Table 2. The observed values are the same with those from eigenvalue analysis.

Table 1 – Model parameters

Model Parameters	N**	Mi	Ki	hi	di	Kh	Kr	I	M0
	9	2000	1e7	3.0	0.03	1e8	8e8	18	5000

**N: number of freedoms
Mi: mass of each story (kg)
Ki: shear modulus of each story(N/m)
hi: height of each story (m)
di: damping ratio of each mode
Kh: rigidity of sway spring (N/m)
Kr: rigidity of rocking spring (N/m)
I: moment of inertia of area (m^4)
M0: mass of the foundation (kg)

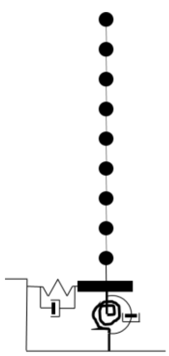


Fig. 1 – MDOF model with rocking and horizontal

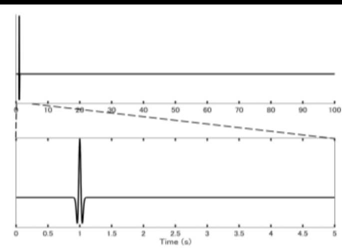


Fig. 2 – incident wave to the MDOF model

Table 2 – Periods and frequencies of the upper structure and the MDOF model system

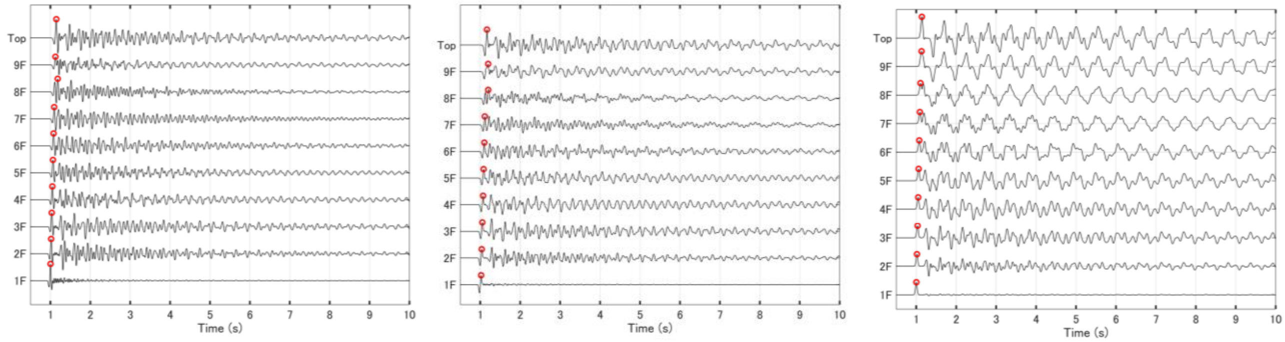
i Mode	1	2	3	4	5	6	7	8	9
$T_{b,i}$	0.538	0.181	0.111	0.081	0.066	0.056	0.051	0.047	0.045
$f_{b,i}$	1.86	5.53	9.04	12.31	15.24	17.76	19.80	21.29	22.20
$T_{app,i}$	0.544	0.183	0.112	0.082	0.066	0.0565	0.051	0.047	0.045
$f_{app,i}$	1.84	5.47	8.96	12.22	15.16	17.92	19.75	21.27	22.20
$f_{app,i}^{obs}$	*1.84*	*5.47*	*8.95*	*12.20*	*15.12*				
$T_{sys,i}$	0.550	0.185	0.1127	0.0826	0.0665	0.0569	0.0509	0.0472	0.0451
$f_{sys,i}$	1.82	5.41	8.87	12.11	15.05	17.58	19.66	21.20	22.17
$f_{sys,i}^{obs}$	*1.82*	*5.42*	*8.87*	*12.10*	*15.01*				

T_b and f_b : periods and frequencies of all modes of the upper structure (fixed-base building)

T_{app}, and f_{app}: periods and frequencies of the combined response of upper structure and base rocking

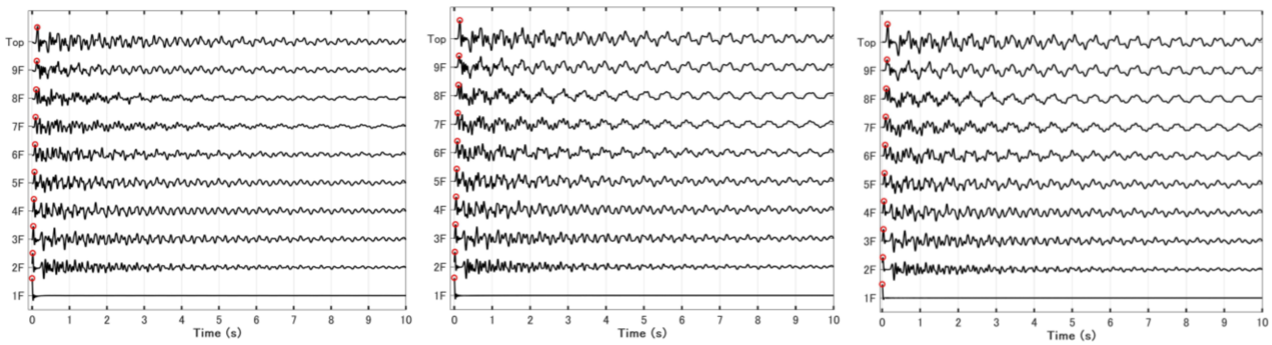
T_{sys} and f_{sys} :periods and frequencies of the building system with soil-structure interaction

$f_{app,obs}$ and $f_{sys,obs}$: observed f_{app} and f_{sys} from the transfer function and spectrum of the response of the top of the building



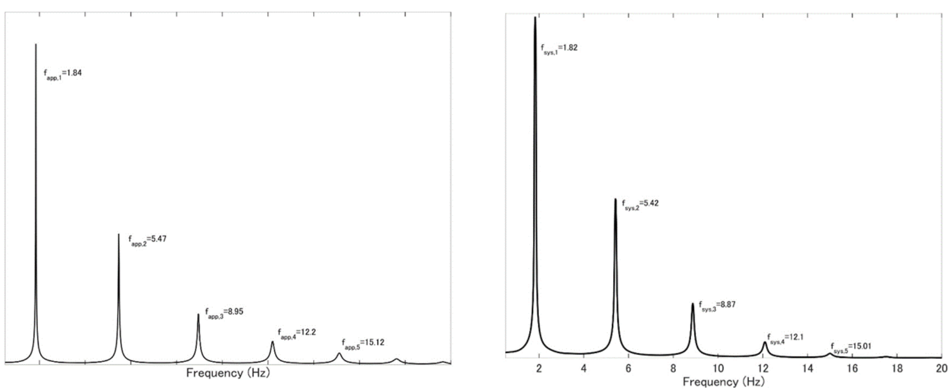
(a) (b) (c)

Fig. 3 – Response of the MDOF model to the input Ricker Wavelet; (a) is acceleration, (b) is the velocity, and (c) is the displacement response waveforms



(a) (b) (c)

Fig. 4 – Impulse response of the MDOF model; (a) is acceleration, (b) is the velocity, and (c) is the displacement response waveforms



(a) (b)

Fig. 5 – (a) transfer function between the displacement response of the top and the base; (b) spectrum of the displacement response of the top

From the waveforms shown in Fig. 3 and Fig. 4 the wave propagation within the upper structure and the reflection by the base and the top can be seen clearly from the former parts of the waveforms. The impulse travel time can be extracted from the first impulse of the response waveforms, which are marked in the figures. And the wave propagation is more easily to be seen form the displacement response. Furthermore, with the increasing of time, i.e. the duration of vibration, the frequency characteristics of the input impulse is weaken by the response characteristics of the building. The latter parts of the waveforms show the frequencies of the building.

Wave propagation

Impulse travel time can be extract directly from the response waveforms (Fig. 3) if the incident wave is an impulse, and also from the impulse responses (Fig. 4). However, the waveforms of the responses and the impulse responses include the vibration due to the soil-structure interaction.

In this study, we use the deconvolved waves, i.e. the impulse response generated by the virtual impulse source at the top of the building[2],[8], to extract the wave travel time within the upper structure itself to eliminate the effect of vibration due to base rocking. In frequency domain, deconvolved wave of i floor $D_i(z,\omega)$ can be presented as the response at the i floor $u_i(z,\omega)$ deconvolved with that of the top of the building $u_T(z=H,\omega)$, as shown in Eg. (1). Eg. (1) is the basic formula of the deconvolution method.

$$D_i(z,\omega)=\frac{u_i(z,\omega)}{u_T(z=H,\omega)} \qquad (1)$$

Where, z is the height of i floor, H is the height of the building. In order to avoid division by very small numbers, in practice, the deconvolution are calculated as the Eg. (2) instead. In time domain, the deconvolved waves can be expressed as the Eq. (2). The details of the transformation from Eq. (1) to Eq. (2) can be find from Snieder and Şafak, 2016[8].

$$D_i(z,t)=\frac{1}{2\pi}\int D_i(z,\omega)e^{i\omega t}d\omega=\frac{1}{4\pi}[\int e^{i\omega(z-H)/c}e^{-\gamma|\omega|(z-H)/c}e^{i\omega t}d\omega+\int e^{i\omega(H-z)/c}e^{-\gamma|\omega|(H-z)/c}e^{i\omega t}d\omega] \quad (2)$$

Based on Eq. (2), deconvolved wave of i floor is the sum of one up-going wave (the first term) and one down-going wave (the second term) with damping ratio of γ. The time of up-going wave and down-going wave of the i floor are presented as $t_{u,i}$ and $t_{d,i}$, respectively. Travel time of the shear wave between i and i+1 floor (i.e. the i story) is calculated from $[(t_{u,i+1}-t_{u,i})+(t_{d,i}-t_{d,i+1})]/2$. The deconvolved waves calculated from the displacement responses are shown in Fig. 6, the picks of up-going and down-going waves are marked with open circles. For the waves of the upper floors, the up-going and down-going waves are overlapped, which lead to the travel time cannot be extracted.

The travel times extracted from response waves, the impulse responses, and the deconvolved waves are shown in the Fig. 7, and are compared with the real values, which are calculated from the 9 aliquots of the 1/4 of the period of the first mode of the upper structure ($T_{b,1}/4=0.135$). The errors of the observed travel times and the real ones of the response wave, impulse response, and the deconvolved waveforms are 0.0014, 0.00156, and 0.00012, respectively. It can be known that the time extracted from deconvolved waves have higher precision.

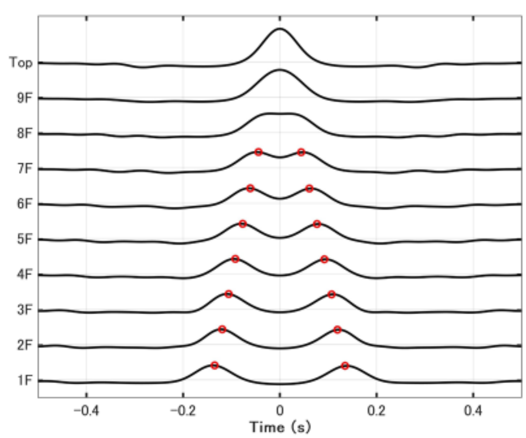


Fig. 6 – Deconvolved waves

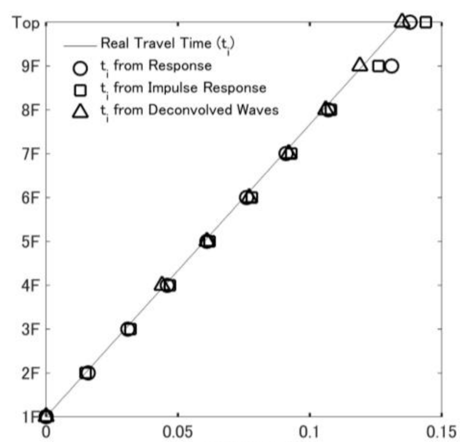


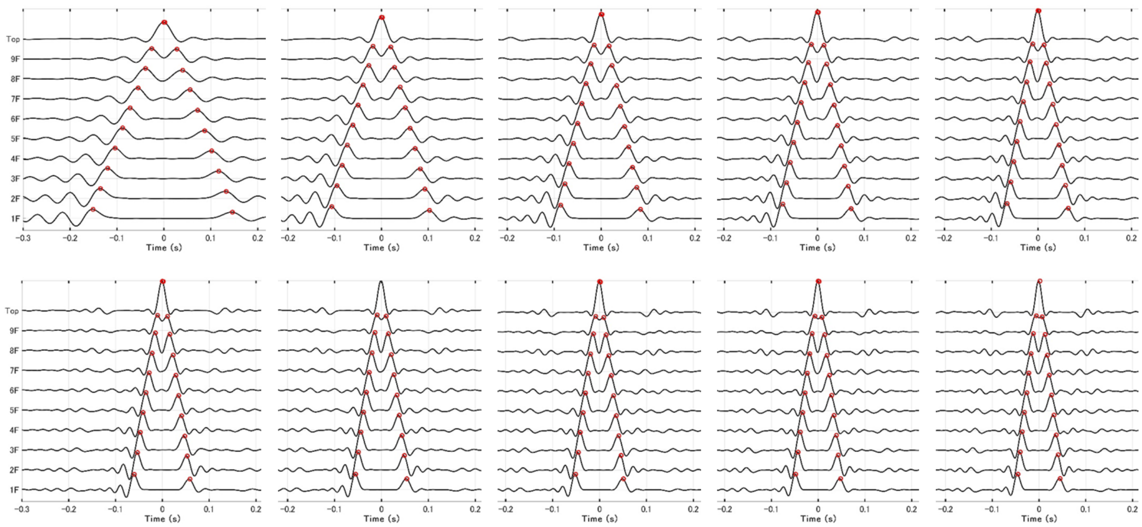
Fig. 7 – Travel time comparison

Wave travel time and the shear rigidity

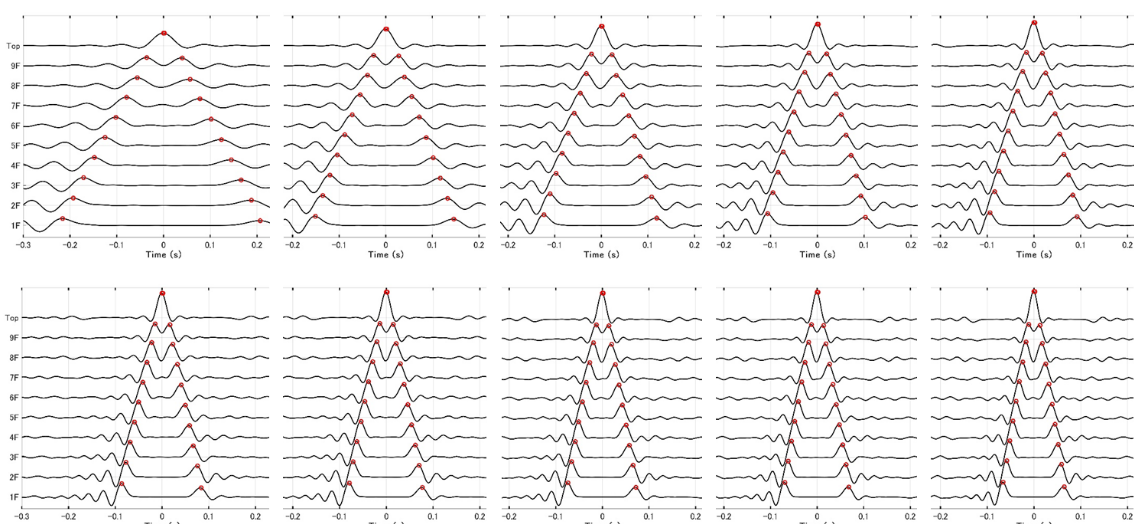
We using three models of different mass of each story to examine the changes of shear-wave travel time with the changing shear rigidity. The parameter setting of the three fixed-base MDOF models are shown in Table 4. The shear rigidities change from 1e7 to 10e7 with the interval of 1e7. The meanings of symbols in the Table 4 are the same with those in Table 1. Deconvolved wave calculated from the responses of the three model are shown in Fig. 8.

Table 4 – Parameters of three models for different mass and shear rigidit

Parameters	N	Mi (kg)	Ki (N/m)	hi (m)	di
Model 1		2000			
Model 2	9	4000	1e7,2e7,3e7,……10e7	3.0	0.03
Model 3		6000			



(a)



(b)

Fig. 8 – Deconvolved waves of (a) model 1, (b) model 2

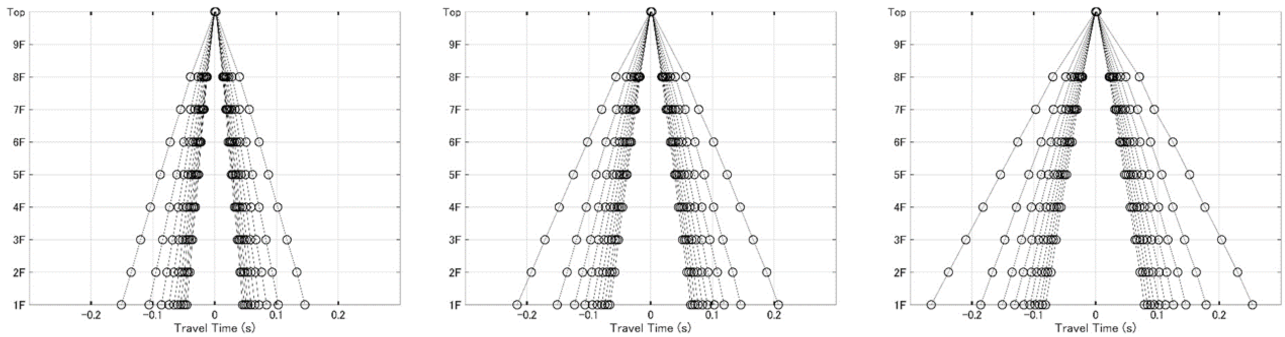


Fig. 9 – The change of travel times of the up-going and down-going waves of deconvolved waves of (a) model 1, (b) model 2, and (c) model 3

It can be seen from Fig. 8 that the travel time becomes shorter with the increasing shear rigidity. The width of impulses of deconvolved waves are different even the input waveforms are the same. That is to say, the natural frequencies of the buildings effect the shape of impulses of deconvolved waves. The changes of wave travel time, picked from the picks of impulses, for each model are shown in Fig. 9. Because the shear rigidities of each story are the same, there are linear distribution of shear wave travel time with the increasing height. The average travel time of all the stories calculated from models with different mass Mi and shear rigidity Ki are plotted in the Fig. 10 with the horizontal axis of Gi. The cures present the function of travel time ti ,Mi, and Gi, which are proposed in the previous study of the authors[9]. It can be seen that the relation of the values from the models are relate to the functions very well. And the travel time changes smaller for higher shear rigidities. Therefore, for buildings with high stiffness, the sampling rate of the records should be small enough to catch the changes of travel time.

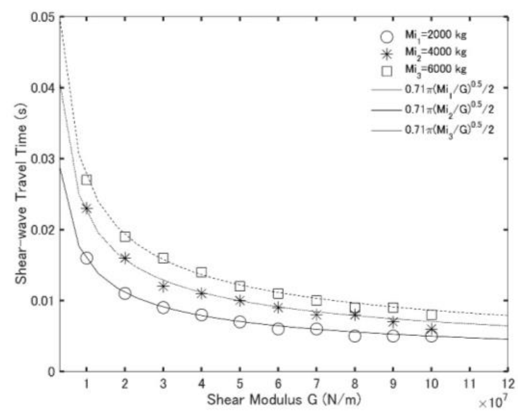


Fig. 10 – change of shear-wave travel time with the increasing shear rigidity

3. Observed Building and Ambient Vibration Measurement

The observed building is a 9-story steel-reinforced-concrete (SRC) residential building (shown in Photo 1), hereafter referred to as the Building QM. It was completed in 1991 designed following the new aseismic design code of Japan. According to the literatures[10]~[12], compressive failure of concrete and buckling of reinforcing steel in the corner columns at the first story and continuous layers can be seen. Besides, obvious shear cracks occurred in the non-structural outer walls in the longitudinal direction. Sever shear failure occurs in the vertical walls from the first floor (ground floor) to the fourth floor in the north elevation in longitudinal direction. Concrete has flaked off and the steels are exposed. Though sever damage in the south elevation cannot be seen, some shear cracks also occurred in the non-structural outer walls up to the fifth floor. In the east elevation (transverse direction) shear cracks can be seen in the concrete of non-structural walls up to third floor. Minor cracks on the walls of the highest story is visible to naked eyes. Relative large cracks are generated in the walls on the 8th story. There are large cracks in the walls on the seventh story, and many spalling of concrete and tiles can be seen. On the sixth story severe cracks, spalling of concrete and exposing of steels can be seen. Shear cracks shaped "X", bended steels and collapsed internal concrete in the walls of the fourth and fifth stories can be seen. In the third and the second story, concretes flaked off from the walls over a wide area, and the inside steel nets are exposed. Steels buckled in the leg of the pillar in the center entrance on the first floor. Microtremor measurement of the Building QM was performed in November 9 to 11, 2011. In order to determine the shear-wave velocity propagating between floors of a building using the deconvolution method, simultaneous records on the roof and inter floors are necessary. In this study, two sets of seismometers with two horizontal components were used. One was fixed on the roof, the other was moved from the first floor (ground floor) to the 9th floor, remaining on each floor 3 hours. Supposing the height of each story is 3 m and the shear-wave velocity is 100 m/s - 500 m/s, the expected travel time within stories is 0.006 s-0.03 s. In order to measure this travel time, the sampling rate fs were set to be 500 Hz in this study, which is the highest sampling rate of the data logger used in this study.

Photo 1 Microtremor measured 9-story SRC residential building QM)

4. Analysis and results

Deconvolved waves calculated from the measured ambient noise are shown in Fig. 11. Because there are no pre-earthquake records and blueprints is unavailable, in this study, shear-wave velocities of the Building QM extracted from microtremor records and those calculated based on the functions using the design values of Building EGB (Fig. 12), are shown in Fig. 13. It can be found that the shear-wave velocities in the longitudinal direction (open circle) are almost less than 300 m/s. The reduce tendency of shear wave velocity with the height increasing can be seen in the transverse direction (open square) not in the longitudinal direction. In the transverse direction shear-wave velocities traveling between the 1F to 2F, 4F to 5F, 5F to 6F, the 6F to 7F slow down significantly. In the longitudinal direction shear-wave velocities traveling between the 1F to 2F, 4F to 5F, 5F to 6F slow down significantly. Shear-wave velocities of Building QM in both of the longitudinal and transverse directions are generally smaller than those of the Building EGB. Shear-wave distribution of Building QM is vary from stories and the change is different from that of the Building EGB which is gradual from the base to the top. Based on the shear-wave distribution of Building QM, it can be found that in the longitudinal direction shear-wave velocities of the second story (2F to 3F) and the 7th story (7F to 8F) are about 300 m/s. Shear-wave velocities of other stories are smaller than 200 m/s, among which those of the 4th story (4F to 5F) and the 5th story (5F to 6F) is smaller than 100 m/s. In transverse direction shear-wave velocity of the QM becomes smaller with the height increasing. However, the shear-wave velocity of first story (1F to 2F) is smaller than that traveling within the second story (2F to 3F). This can be considered as the result of damage of columns in the first story. Moreover, the severely reduced shear-wave velocity in the transverse direction is in the 4th story, 5th story, and the 6th story. Shear-wave velocities become slow in both of the longitudinal and transverse direction of the first, the 4th, the 5th, and the 6th story, which is considered as the result of damage happened in nonstructural walls.

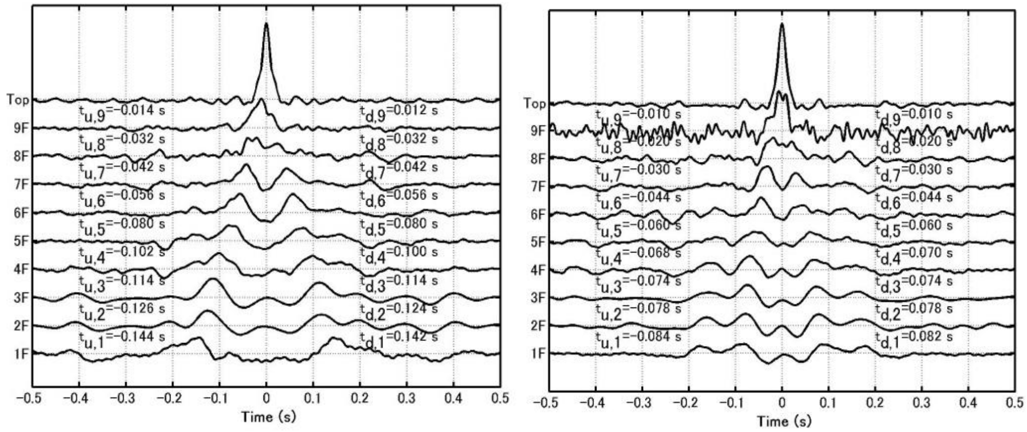


Fig. 11 - Deconvolved waves of Building QM in the longitudinal direction (left figure) and the transverse direction (right figure)

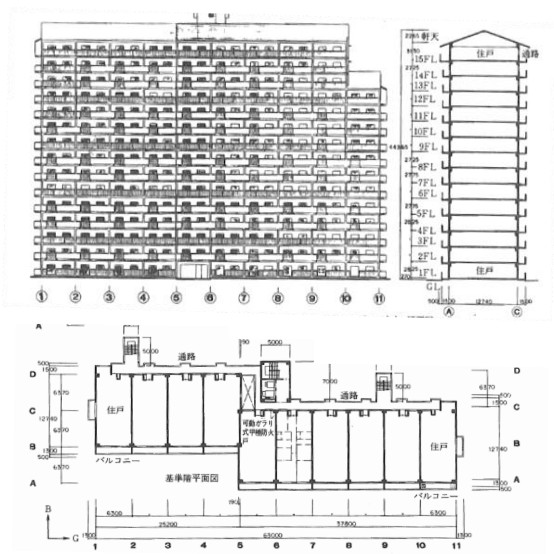


Fig. 12- Facade and plane of the Building EGB

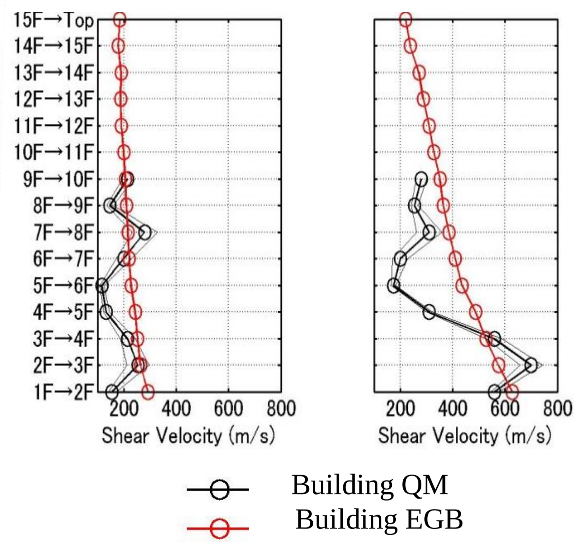


Fig. 13-Shear-wave velocity of the Building QM and the Building EGB

7. Conclusions

In this paper, the feasibility of combine frequency and time domain method to extract the response characteristics of the building system and the upper structures, separately using a multiple-degree-of-freedom model with rocking and horizontal springs. It is feasible to using the deconvolved waves to extract the shear-wave travel time and velocities. Shear-wave velocities of a 9-story SRC residential building (Building QM) damaged during the Tohoku earthquake are extracted from microtremor records based on the deconvolution method. Shear-wave velocities of the Building QM in the longitudinal direction are almost reduced to less than 300 m/s, in which those of the first story (1F to 2F), the 4th story (4F to 5F), the 5th story (5F to 6F), and the 8th story (8F to 9F) are smaller than 200 m/s. In the transverse direction shear-wave velocities generally become slower with the height increasing. Shear-wave velocities of the first story, the 4th story, the 5th story, and the 6th story become slower, especially those of the 5th and the 6th story reduced to less than 200 m/s. Therefore, it can concluded that damage of the first story, the 4th story, the 5th story, and the 6th story is severe in both of the longitudinal and transverse direction.

During the Tohoku Earthquake though the totally damage cases of high-rise buildings are very rare, the cases of severe damage, moderate damage, small damage, and slight damage can be often seen. Though total damage can be easily known from physical inspection, the other damage levels are difficult to be evaluated in this method. Therefore, in this paper, we evaluated the story damage based on the reduction of shear-wave velocities extracted from microtremor records. Because there is no earthquake and microtremor records of the Building QM before the earthquake, it is impossible to compare the reduction of shear-wave velocity between pre- and after-earthquake. If the microtremor records can be obtained, based on the proposed method in this paper story damage evaluation can be performed quantitatively based on the comparison between shear-wave velocity extracted from the microtremor records measured before and after earthquakes. The proposed method cannot only used in the damage evaluation, but also can be used to monitor the health condition and seismic performance of buildings. Moreover, based on the long-term measurement of shear-wave velocity story-by-story health monitoring can be performed.

In the future study, the relationship between damage condition and reduce of shear-wave velocity will be investigated. Moreover, the measurement of sound buildings and damaged buildings with the same structrual types will be increased.

5. References

1. Kanai, K.(1965). "Some new problems of seismic vibrations of a structure." Proceedings of the Third World Conference on Earthquake Engineering, Auckland and Wellington, New Zealand, II-260 – II-275, 22 January – 1 February 1965.
2. Todorovska, M. I. (2009). "Seismic Interferometry of a soil-structure interaction model with coupled horizontal and rocking response."*Bull. Seismol. Soc. Am*. 99, no. 2A, 611-625.
3. Nakamura, M., Yasui, Y. (1999). "Damage evaluation of a steel structure subjected to strong earthquake motion based on ambient vibration measurements. "*Journal of structural and construction engineering (AIJ)*, Vol.517, 61-68. (in Japanese)
4. Nakamura, M., Takewaki, I., Yasui, Y. (2000). "Simultaneous identification of stiffness and damping of building structures using limited earthquake records. " *Journal of structural and construction engineering (AIJ)*, Vol.528, 75-82. (in Japanese)
5. Ikeda, Y. (2009)." Identification of story stiffness for MDOF shear building structures considering consistency with modal information." *Journal of structural and construction engineering (AIJ)*, Vol.646, 2237-2243. (in Japanese)
6. Hassiotis, S., Jeong, G.D. (1995). "Identification of Stiffness Reductions Using Natural Frequencies." *J. Eng. Mech., ASCE*, Vol. 121, No. 10, 1106-1113.
7. Hamamoto, T., Morita, K., Teshigawara, M. (2002). "Story Damage Detection of multistory buildings using natural frequency shifts of multiple modes." *Journal of structural and construction engineering (AIJ)*, Vol.560, 93-100. (in Japanese)
8. Snieder, R., and Şafak, E.(2006). "Extracting the building response using interferometry: theory and applications to the Millikan Library in Pasadena, California." *Bull. Seismol. Soc. Am*. 96, no. 2, 586-598,
9. Wang X., Masaki K., and Irikura K., Inter-story shear-wave velocity measurement of a damaged builidng using microtremor records, Journal of Japan Association for Earthquake Engineering, Vol.14, No.3, 35-47, 2014.
10. Xue, S. T. (2011). "RC building damage situation."*TheKenchikuGijutsu* ,No.740, 109-117.
11. National Institute for Land and Infrastructure Management Ministry of Land, Infrastructure, Transport and Tourism, Building Research Institute Incorporated Administrative Agency, Japan (2011). "Quick report of the field survey and research on the 2011 off the Pacific coast of Tohoku earthquake." Technical note, National institute for land and infrastructure management, No.636.
12. Architectural Institute of Japan (2011). "Preliminary Reconnaissance report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake."