EVALUATION OF EFFECTIVE SEISMIC ENERGY INPUT RATES BASED ON LONG-TERM EARTHQUAKE OBSERVATION RECORDS

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Abstract

The comparison between seismic energy input and a building's energy absorption capacity can be used to evaluate the seismic safety of the building. Soil-structure interaction (SSI) must be considered when calculating the seismic energy input because the seismic response is affected by the interaction. In previous research, an effective seismic energy input rate was proposed to evaluate the extent to which SSIs affect energy input. It was determined that the energy input to a building may increase under certain conditions due to SSIs.

In this study, long-term earthquake observation records were used to estimate the effective energy input rates of buildings located in Tsukuba, Japan. The input rates were calculated from the input energy spectra recorded at three different locations: the bottom of the building, the top of the building, and the ground surface of the building site. First, the natural period and the damping ratio of the buildings were determined using the observation records. The transfer function using an autoregressive with exogenous input (ARX) model for system identification was calculated. Next, the input energy spectra observed at the bottom of the building and on the ground surface were calculated using the determined natural period and damping ratio. The recorded observation at the bottom indicated an input ground motion to the building with SSI. On the other hand, the recorded observation from the ground surface site indicated an input ground motion to an imaginary building without SSI. Finally, the effective energy input rate was calculated as the ratio of the input energy spectrum with soil-structure interaction to the input energy spectrum without the interaction.

The effective energy input rates for the existing buildings were calculated for practical investigation. Various dependencies and the variation coefficients of the input rates were investigated using the long-term observation records. The identified input rates were consistent with prior analytical predictions [1]. The variation coefficients of the input energy rates were smaller than those of input maximum acceleration rates. The energy input rate was shown to be a useful value for evaluating the effect of soil-structure interaction.

Keywords: soil-structure interaction; seismic energy input; earthquake record; ARX model; transfer function

1. Introduction

The quantification of the aseismic performance of buildings is one of the most important aspects of structural design. The comparison between the seismic energy input of a design earthquake and a building's energy absorption capacity can be used to evaluate the seismic safety of the building. Fig. 1 and Eq. (1) outline the calculation for the seismic energy input, W, to a single degree-of-freedom (SDOF) structure

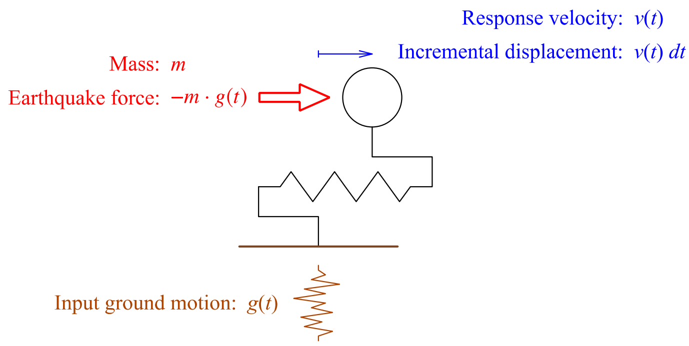


Fig. 1 – Seismic energy input to SDOF structure

$$W = \int_{t=0}^{t_{\mathrm{end}}} -m \cdot g(t) \cdot v(t) dt \tag{1}$$

where m is the mass of the structure, $g(t)$ is the ground acceleration, and $v(t)$ is the earthquake response velocity of the structure. The integration calculates the amount of work by earthquake force. An equivalent velocity, V_E, which satisfies $W = (1/2)mV_E^2$, can be written as follows:

$$V_E = \sqrt{2W/m} \tag{2}$$

The equivalent velocity is a good indicator for structural design because it is determined by the structural period, T, but it is not strongly affected by the damping ratio, h. Soil-structure interaction (SSI) must be considered when calculating the seismic energy input because the seismic response is affected by the interaction. Generally, in a maximum-value based design, the maximum response values tend to be smaller when soil-structure interaction is included. An effective seismic energy input rate for evaluating the extent to which soil-structure interactions affect energy input was previously proposed [1]. The research clarified that the energy input to a building may increase under certain conditions due to soil-structure interactions.

In this research, earthquake observation records were used to estimate the effective energy input rates of existing buildings located in Tsukuba, Japan [2]. Long-term earthquake observations were previously carried out at the buildings. First, the natural period and the damping ratio of the buildings were determined from the observation records. The transfer function with an auto-regressive with an exogenous input (ARX) model for system identification was calculated. Next, the input energy spectra observed at the bottom of the building and on the ground surface of the building site were calculated using the determined natural period and damping ratio. Finally, the effective energy input rate was calculated as the ratio of the input energy spectrum with soil-structure interaction to the input energy spectrum without the interaction. Various dependencies and the variation coefficients of the input rates were investigated using the long-term observation records.

2. Calculation of effective seismic energy input rate

2.1 Definition of effective input rate

The effective seismic input energy rate proposed by Mizutani *et al.* is defined in Fig. 2 [1]. The input rate is calculated as V_{ES}/V_{E0}, where V_{E0} is an equivalent velocity of seismic energy input to a fixed base model and V_{ES} is an equivalent velocity of seismic energy input to the superstructure of an interaction model. Note that SSI is excluded from the fixed-base model and included in the interaction model. The effective input rate indicates the extent to which SSIs change the equivalent velocity of seismic input energy.

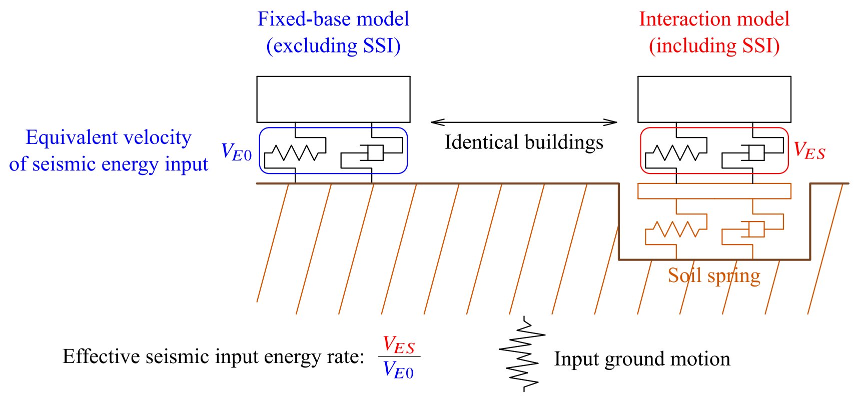


Fig. 2 – Definition of effective seismic energy input rate

Fig. 3 shows a method for evaluating an effective input rate by using earthquake observation records [3]. The fundamental period and the damping ratio of an object building were first identified from the earthquake records taken at the top and bottom of the building. Next, V_{ES} and V_{E0} were calculated using the records from the bottom of the building and ground surface. Then, the effective input rate was represented as a ratio of V_{ES} to V_{E0}.

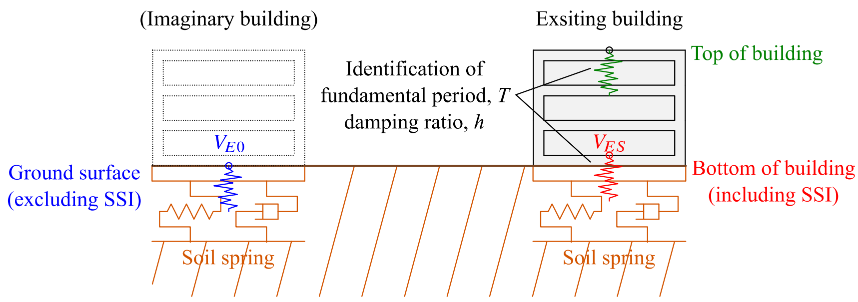


Fig. 3 – Evaluation of effective energy input rate from earthquake observation records

2.2 Object buildings and earthquake records

Fig. 4 shows the object buildings in Tsukuba, Japan [2], where long-term earthquake observations had been previously carried out previously. This research used the earthquake records in the NS and EW directions recorded by seismometers at the top and bottom of the annex building, at the top and bottom of the main building, and at the ground surface of the construction site. Fig. 5 shows the highest recorded accelerograms during the 2011 off the Pacific coast of Tohoku earthquake.

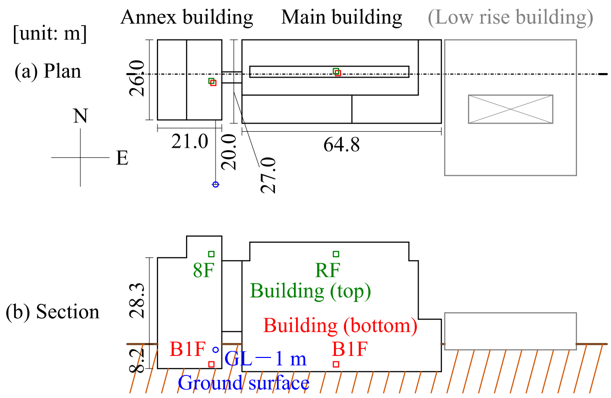


Fig. 4 – Object buildings and layout of seismometers

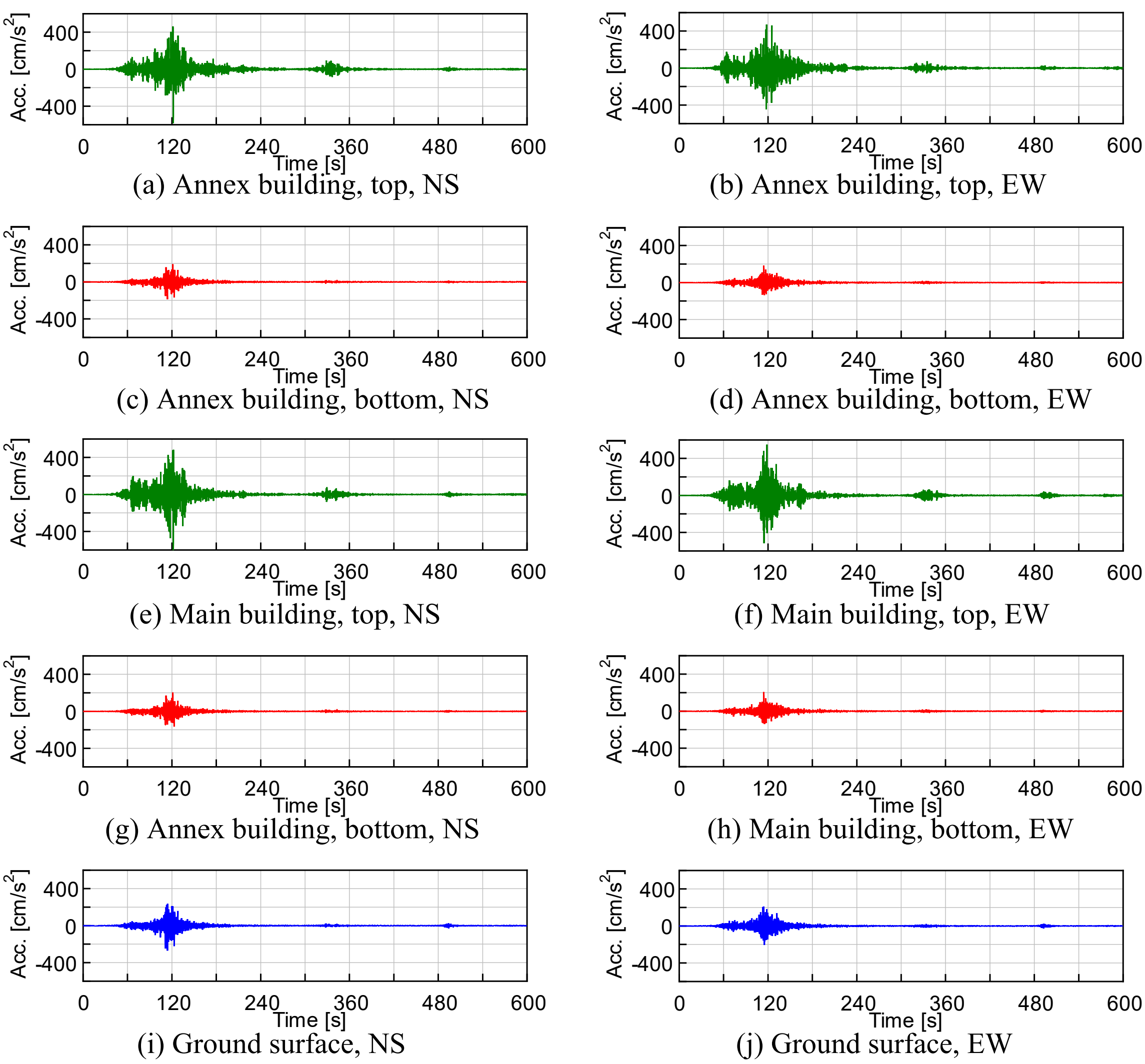
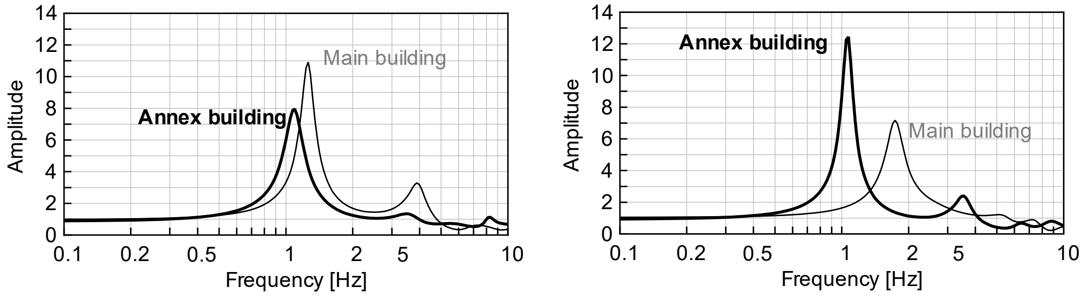


Fig. 5 – Observed records during 2011 off Pacific coast of Tohoku earthquake

2.3 Examples to calculate effective input rates

Using the data shown in Fig. 5, the effective input rates can be calculated as follows. Fig. 6 and Table 1 show transfer functions, fundamental periods, and damping ratios of the buildings in the NS and EW directions. An ARX model with a model order of 40 was used to identify these characteristics.

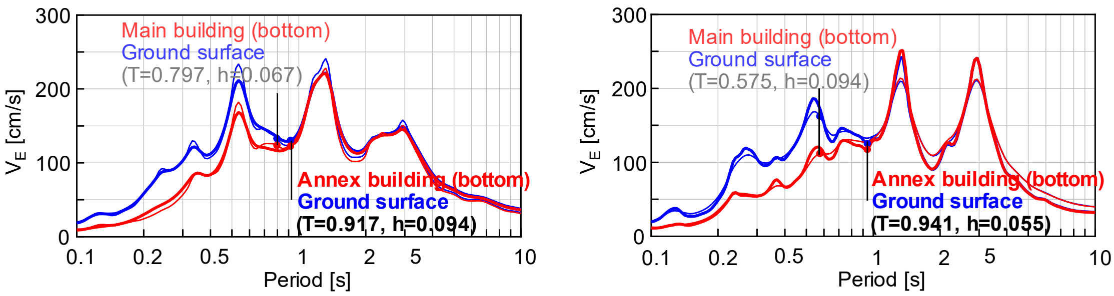


(a) NS (b) EW

Fig. 6 – Transfer functions calculated from ARX model

Table 1 – Identified vibration characteristics

Building	Direction	Period [s]	Damping ratio
Annex building	NS	0.917	0.094
	EW	0.941	0.055
Main building	NS	0.797	0.067
	EW	0.575	0.094



(a) NS (b) EW

Fig. 7 – Comparisons of input energy spectra

Fig. 7 shows a comparison of the input energy spectra calculated from the earthquake records at the bottom of the building and ground surface. Table 2 summarizes the effective input rates obtained from the energy spectra and the identified values in Table 1. The effective input rate of the main building in the EW direction was lower than that of the others.

Table 2 – Comparison of effective input rates

Building	Direction	V_{E0} [m/s]	V_{ES} [m/s]	Input rate
Annex building	NS	130.5	122.8	0.94
	EW	125.6	117.5	0.94
Main building	NS	133.1	123.7	0.93
	EW	162.3	111.9	0.69

2.4 Comparison to alternative estimation method for input rates

A second estimation method for input rates [1] is briefly presented below. The effective input rates calculated using this method were compared with those calculated using the proposed method in the previous section. The effective input rate was estimated from Eqs. (3) to (7) and Table 3 as follows:

$$\frac{K_S}{GB} = \frac{4\pi^2/\alpha^2}{\rho {V_S}^2} \cdot \frac{w/g}{H/B} \tag{3}$$

$$\frac{T_E}{T_S} = \sqrt{1 + \frac{\sqrt{\pi}(2-\nu)}{8}\frac{K_S}{GB} + \frac{\frac{4}{3}\pi\sqrt{\pi}}{8}\frac{K_S}{GB}\left(\frac{H}{B}\right)^2} \tag{4}$$

$$\frac{V_{ES}}{V_{EE}} = 0.2 + 0.8\exp\left[-\left(\sqrt{\sqrt{\boldsymbol{C}}\left\{\left(\frac{T_E}{T_S}\right)^2 - 1\right\} + 1} - \boldsymbol{A}\right)\boldsymbol{B}\right] \tag{5}$$

$$\frac{V_{EE}}{V_{E0}} = \frac{\min\left((T_E/T_S)\cdot T_S, T_c\right)}{\min\left(T_S, T_c\right)} \tag{6}$$

$$\frac{V_{ES}}{V_{E0}} = \frac{V_{EE}}{V_{E0}} \cdot \frac{V_{ES}}{V_{EE}} \tag{7}$$

Table 3 – Parameters for Eq. (5)

H/B	$\boldsymbol{A}$	$\boldsymbol{B}$
0.5	1.00	2.50
1.0	1.05	2.00
1.5	1.10	1.20
2.0	1.15	0.60
3.0	1.30	0.35

h_s	$\boldsymbol{C}$
0.02	11.18
0.05	2.83
0.10	1.00
0.20	0.35

where ρ, ν, and V_s are density, Poisson's ratio, and the S-wave velocity of the soil, respectively; w, α, H/B, T_s, and h_s are unit weight, ratio of the fundamental period to the height, aspect ratio, the fundamental period, and the damping ratio of the building, respectively; T_c is the corner period of an energy spectrum, and g is the gravitational acceleration. By assuming these parameters, the effective input rates were estimated as shown in Table 4. The results from this method were consistent with the results from the proposed method described in Table 2.

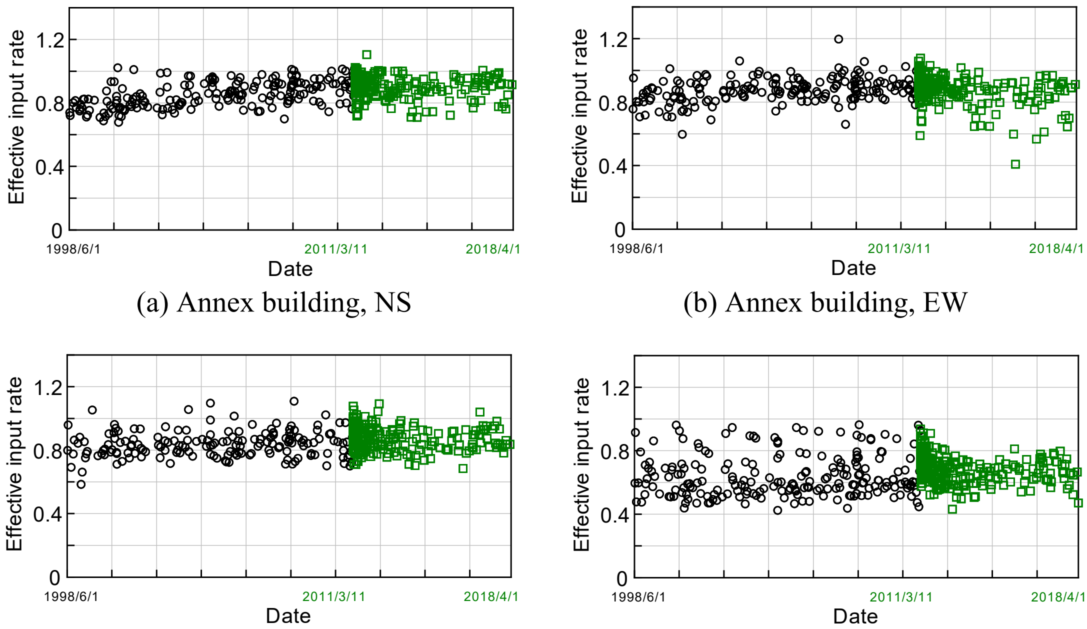
Table 4 – Assumed parameters and effective input rates from Eqs. (3) to (7)

		Annex building, NS Annex building, EW Main building, EW	Main building, EW
Soil parameters	ρ [kg/m^3]	1650	
	ν	0.48	
	V_s [m/s]	210	
Building parameters	w [N/m^3]	3000	
	α [s/m]	0.02	
	H/B	1.0	0.5
	T_s [s]	0.7	0.5
	h_s	0.05	
Earthquake parameter	T_c [s]	0.8	
Constant	g [m/s^2]	9.8	
Input rate	V_{ES}/V_{E0}	0.84	0.70

3. Variation of effective input rates in long-term observation

3.1 Long-term observation results

Long-term observation data of 1730 earthquake records from 1998 to 2018 were analyzed using the proposed method. Figs. 8, 9, and 10 show the variations in effective input rate, fundamental period, and damping ratio, respectively. Minute earthquake records (V_{E0} < 0.2 cm/s) were excluded from these evaluations. The aging effect in the effective input rate was smaller than that observed in the fundamental period and damping ratio.



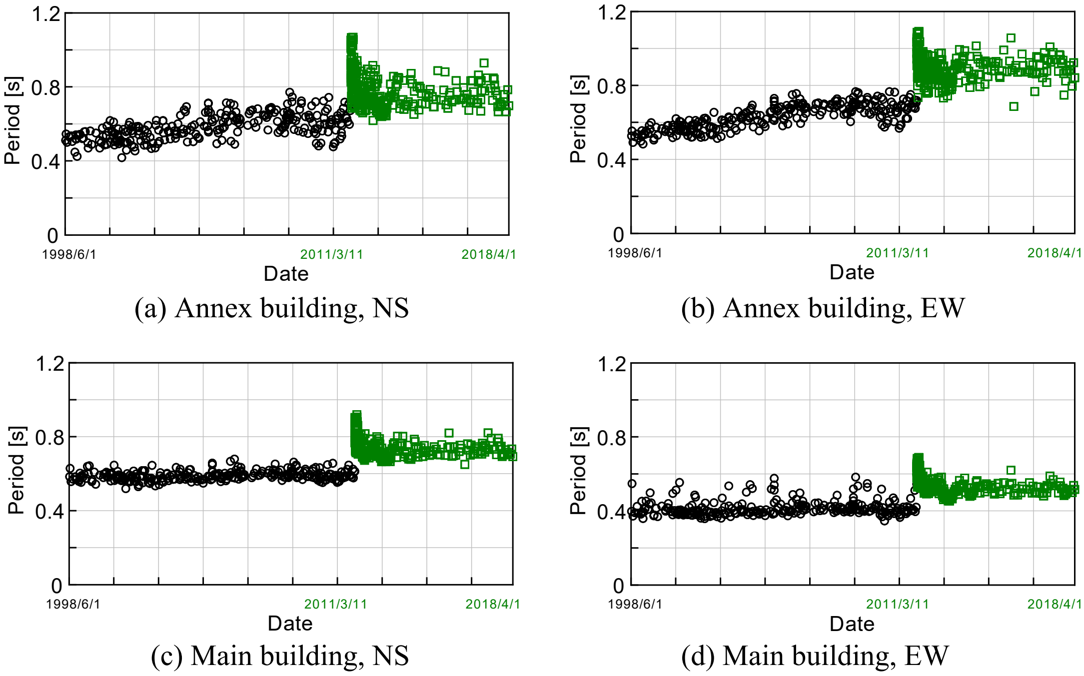
(a) Annex building, NS

(b) Annex building, EW

(c) Main building, NS

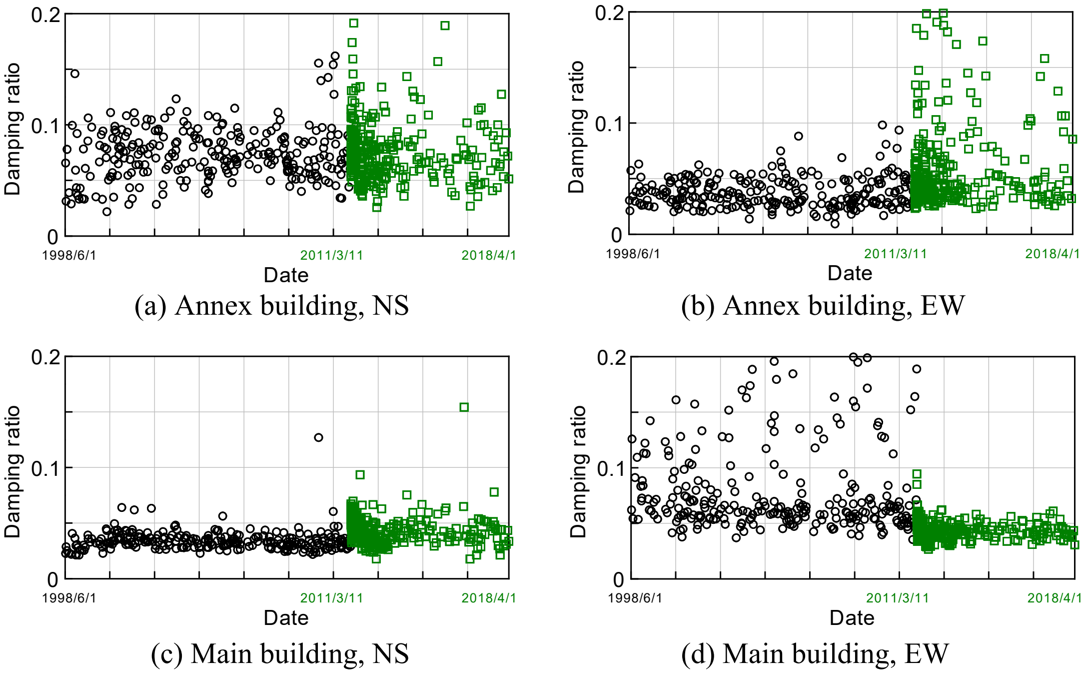
(d) Main building, EW

Fig. 8 – Variation of effective input rate



(a) Annex building, NS
(b) Annex building, EW
(c) Main building, NS
(d) Main building, EW

Fig. 9 – Variation of fundamental period

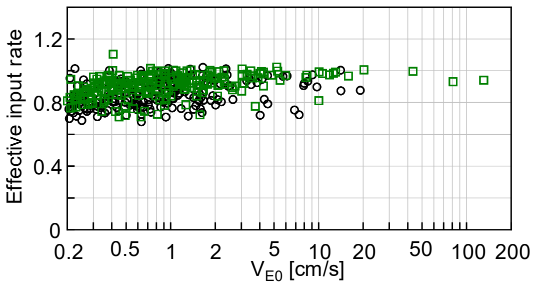


(a) Annex building, NS
(b) Annex building, EW
(c) Main building, NS
(d) Main building, EW

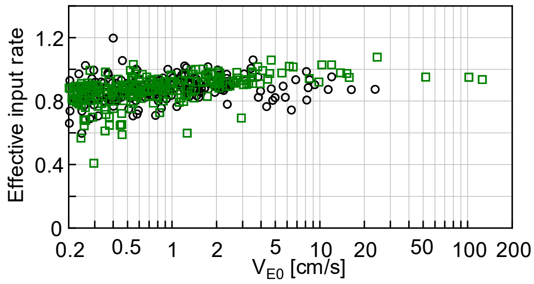
Fig. 10 – Variation of damping ratio

3.2 Dependencies of effective input rate

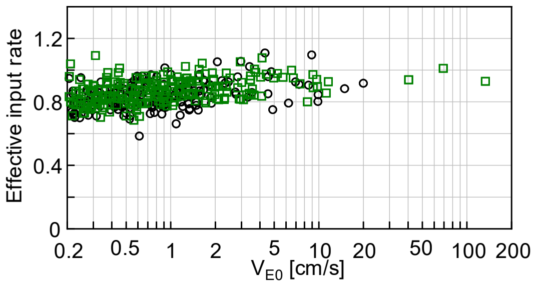
Fig. 11 shows the dependency of the effective input rate on the magnitude of the energy input, V_{E0}. Plots in black and green indicate the data before and after 2011 earthquake, respectively. The input rate, V_{ES}/V_{E0}, can be regarded as almost constant.



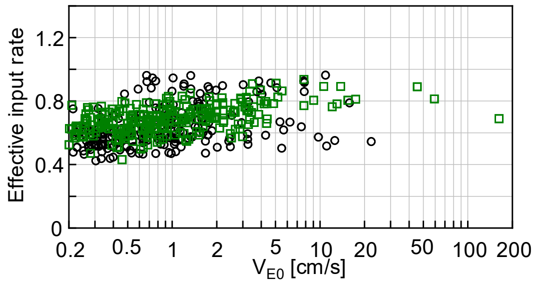
(a) Annex building, NS



(b) Annex building, EW

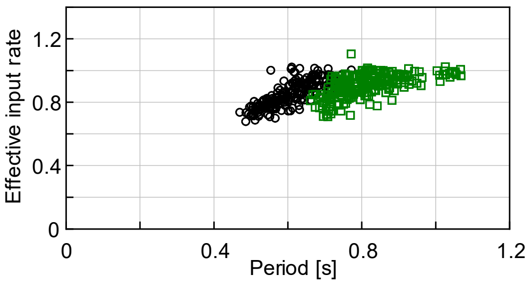


(c) Main building, NS

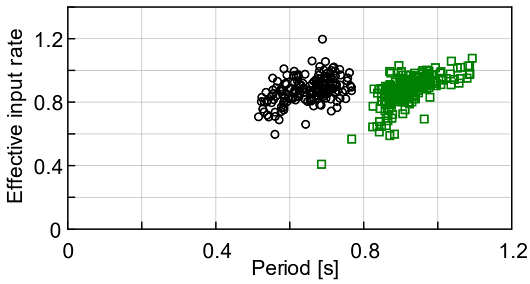


(d) Main building, EW

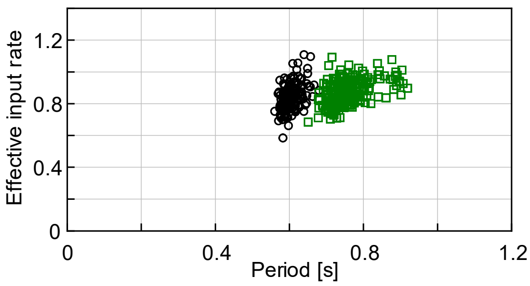
Fig. 11 – Amplitude dependency of effective input rate



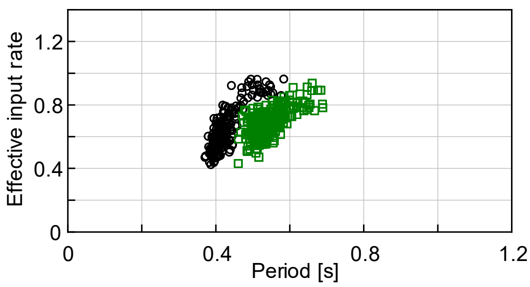
(a) Annex building, NS



(b) Annex building, EW

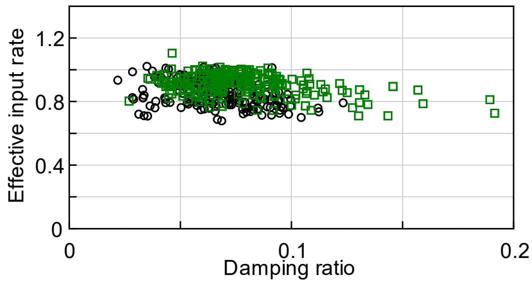


(c) Main building, NS

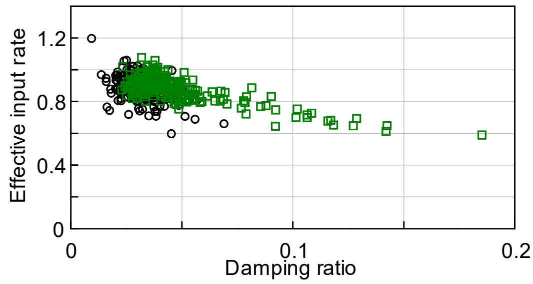


(d) Main building, EW

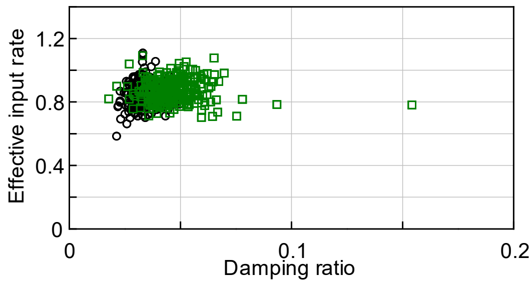
Fig. 12 – Effective input rate vs. fundamental period



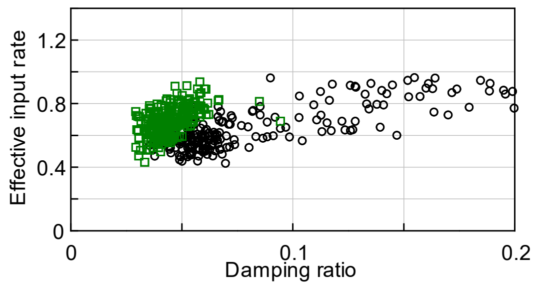
(a) Annex building, NS



(b) Annex building, EW



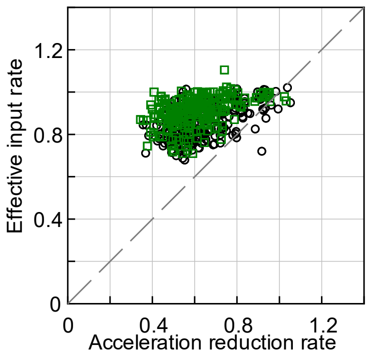
(c) Main building, NS



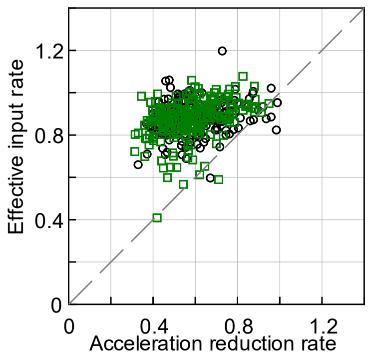
(d) Main building, EW

Fig. 13 – Effective input rate vs. damping ratio

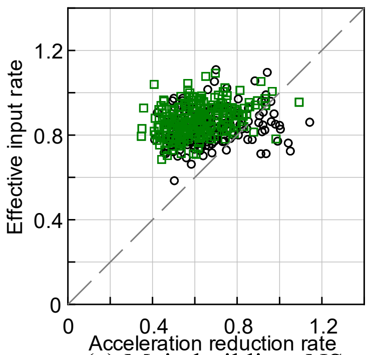
Figs. 12 and 13 show the dependencies on the vibration characteristics. The effective input rate showed a positive/negative correlation to the period/damping except in the case of the main building in the EW direction.



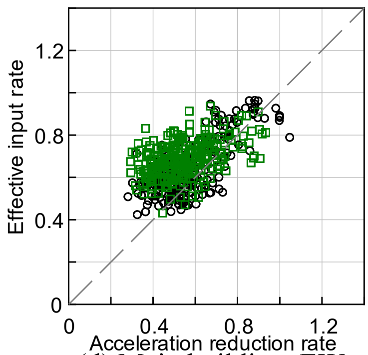
(a) Annex building, NS



(b) Annex building, EW



(c) Main building, NS



(d) Main building, EW

Fig. 14 – Comparison of energy input rate and acceleration reduction rate

Fig. 14 shows the comparison of the energy input rate and acceleration reduction rate. The acceleration reduction rate is defined as a ratio of peak acceleration at the building bottom to that at the ground surface excluding minute earthquake records (PGA < 0.5 cm/s^2). Additionally, the energy input rate and acceleration reduction rate are summarized in Tables 5 and 6. These rates can be regarded as indicators for the effect of soil-structure interaction from the aspects of input energy and input acceleration. The effective energy input rate has smaller coefficient of variation than that of the acceleration reduction rate, therefore, it can be a useful value for evaluating the effect of soil-structure interaction.

Table 5 – Effective energy input rates (V_{E0} > 0.2 cm/s)

Building	Direction	Average	Standard deviation	Coefficient of variation	Number of data
Annex building	NS	0.882	0.083	0.095	1316
	EW	0.876	0.091	0.103	1280
Main building	NS	0.856	0.081	0.094	1244
	EW	0.669	0.109	0.162	1460

Table 6 – Acceleration reduction rates (PGA > 0.5 cm/s^2)

Building	Direction	Average	Standard deviation	Coefficient of variation	Number of data
Annex building	NS	0.593	0.145	0.244	1693
	EW	0.566	0.133	0.236	1722
Main building	NS	0.623	0.140	0.225	1693
	EW	0.536	0.144	0.270	1722

4. Conclusion

The effective energy input rates for existing buildings were estimated by using long-term earthquake observation records. The input rates were calculated from the input energy spectra recorded from three different locations: the bottom of the building, the top of the building, and on the ground surface of the building site. First, the natural period and the damping ratio of the building were determined from observation records. The transfer function with an ARX model for system identification was calculated. Next, the input energy spectra observed at the bottom of the building and on the ground surface of the building site were calculated using the determined natural period and damping ratio. The recorded observation from the bottom of the building indicated an input ground motion to the building with soil-structure interaction. On the other hand, the recorded observation for the ground surface of the building site indicated an input ground motion to an imaginary building without soil-structure interaction. Finally, the effective energy input rate was calculated as the ratio of the input energy spectrum with soil-structure interaction to the input energy spectrum without the interaction.

The effective energy input rates for the existing buildings, located in Tsukuba, Japan, were calculated for practical investigation. Various dependencies and the variation coefficients of the input rates were investigated using the long-term observation records. The identified input rates were consistent with the analytical predictions reported in previous research. The variation coefficients of the input energy rates were smaller than those of input maximum acceleration rates. The energy input rate was shown to be a useful value for evaluating the effect of soil-structure interaction.

5. Acknowledgements

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6. References

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