ENERGY RESPONSE OF BUILDING STRUCTURES WITH FOUNDATION UPLIFT SUBJECTED TO EARTHQUAKE MOTIONS

T. Asari[1], Y. Fujita[2] and M. Midorikawa[3]

[1] *Assistant Professor, Graduate School of Engineering, Hokkaido University, Sapporo, Japan*
[2] *Graduate Student, Graduate School of Engineering, Hokkaido University, Sapporo, Japan*
[3] *Professor, Graduate School of Engineering, Hokkaido University, Sapporo, Japan*
Email: asari@eng.hokudai.ac.jp, midorim@eng.hokudai.ac.jp

ABSTRACT :

Previous studies by many researchers suggested that rocking vibration accompanied with uplift might reduce the seismic damage of buildings in 1995 Hyogo-ken Nanbu Earthquake. In this paper, reduction effect to the response is discussed by the energy into the foundation-superstructure system using time history analysis. The results from comparing with structures with uplift to that without uplift are follows. Natural period of foundation-superstructure system becomes longer when the uplift occurs, and total input energy into the system increase when the energy spectrum of input ground motion increase and total input energy decrease when the energy spectrum decrease. In many analytical results, the strain energy of the superstructure decreases by uplift even if the total input energy of the system increase by uplift. This result indicates that the seismic damage would be reduced by uplift in many actual cases. When the uplift occurs the strain energy of the superstructure becomes less than 80% of that without uplift in case of the Vs=300 m/s, so that the reduction effect of response caused by uplift on the hard ground is larger than the soft ground. The input energy and strain energy are reduced significantly because of combination with uplift and soil-structure kinetic interaction effect. That is to say, response reduction effect by the foundation uplift can be considerably expected in many actual situations.

KEYWORDS: soil-structure interaction, foundation uplift, reduction of response, input energy, rocking vibration

1. INTRODUCTION

In 1995 Hyogo-ken Nanbu Earthquake, the case of guessing that some buildings were not damaged due to the foundation uplift is reported, and analysis and experimental test of the structure with foundation uplift have been carried out. Though some reasons of reducing the response of the superstructure by foundation uplift are pointed in some researches, the reduction effect by the foundation uplift are sensitive to characteristics of the structure and input motion in many researches. In this paper, the reduction effects due to the foundation uplift are discussed by the energy response with analysis using the input motion that of energy spectrum is constant.

2. ANALYTICAL MODEL AND PROCEDURE

2.1. Analytical Model

2.1.1 Superstructure

The analytical model is a finite rotation model as shown in Figure 1. Multi-story buildings in which yield hinges are formed at the end of beams can be treated as equivalent- single-degree-of-freedom systems. The equation of motion is:

$$\overline{W} = \{1.5(n+1)/(2n+1)\}12nL^2 \quad (\text{kN})$$
$$\overline{H} = 4\{(2n+1)/3\} \quad (\text{m}) \qquad (2.1)$$

where $\overline{W}$ is the equivalent weight, $\overline{H}$ is the equivalent height, n is the number of stories, L is the width of both directions (L^2 means area of each floor). The each story height and the weight per unit area of structure are assumed as 4(m) and 12(kN/m^2) respectively. The natural period of the super structure T_0(s) is taken as T_0 = 0.1n.

2.1.2 Foundation

The dimension of the foundation is same to the super structure. The weight per unit area is assumed 20(kN/m^2). Sway and rocking vibration are considered in the interaction between the foundation and soil. “With-uplift model” considers the foundation uplift, and “without-uplift model” does not consider the uplift. It is assumed that 1)The bottom of the foundation is according to the Navier hypothesis 2)The vertical reaction of the ground is proportional to the subduction of the foundation bottom and do not resist to the tensile stress. Horizontal and vertical reaction R_H, R_V and resisting moment M_R for the rotation are calculated by eccentric distance *e* and distance *Xn* from the extreme compression fiber to the neutral axis and the geometric relation between the foundation and the ground considering a balance of forces at the foundation.

M_R is defined in the following equation because the distribution of reaction at the ground is assumed as a triangle distribution in this analytical model;

$$M_R = R_V \cdot e = \left(\frac{L}{2} - \frac{Xn}{3}\right) R_V \qquad (2.2)$$

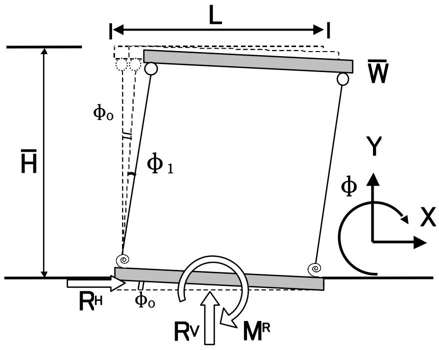

Fig. 1 Analytical model

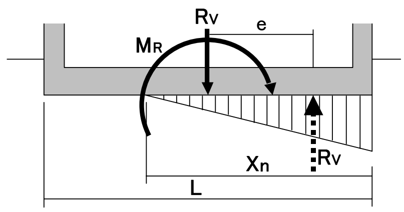

Fig. 2 Balance at the foundation

2.2. Analytical Procedure

Response of the superstructure is assumed in elastic. The analyzed natural period of the superstructure is T_0 = 0.1～2.0(s), and the aspect ratio is $\overline{H}/L$ = 0.5～5.0. The shear wave velocity of the ground is V_S = 150 and 300(m/s). The stiffness and the damping of the ground are calculated by the method by Tajimi. The damping factor of the superstructure is 2% and 5% in the analysis. The superstructure with 2% damping factor simulate a rigid building that resist to earthquake in elastic range, and that with 5% damping factor simulate a building that absorb large hysteresis energy and respond in elast-plastic range assumed.

In this paper, total input energy into the foundation-superstructure system and maximum strain energy of the superstructure are evaluated by an equivalent velocity in following equation.

$$V_E = \sqrt{\frac{2E}{M}} \qquad (2.3)$$

where *E* is energy, *M* is mass of the system or superstructure, V_E is the equivalent velocity.

Potential energy E_p and strain energy E_h of the superstructure are defined by following equations.

$$E_P = \int_0^t (m_0 + m_1)\, g\, \dot{y}_0 dt = (m_0 + m_1)\, g\, \Delta_0$$
$$E_h = \int_0^t m_1(\phi_1)\, \dot{\phi}_1 dt \tag{2.4}$$

where m_0 is mass of the foundation, m_1 is mass of the superstructure, Δy_0 is a increment of the vertical displacement of the foundation, g is the acceleration of gravity, and φ_1 is the relative rotation of the superstructure to the foundation.

2.3. Input Ground Motion

Simulated earthquake ground motion is used in the analysis. The target spectrum is an energy spectrum that have constant V_E=150cm/s when the period T>0.6(s). The phase characteristic is that of El Centro 1940 NS component. The duration and peak ground acceleration of the input ground motion is 60(s) and 462(cm/s^2), respectively. Time history of the acceleration is shown in Figure 3 and spectra are shown in Figure 4 and 5.

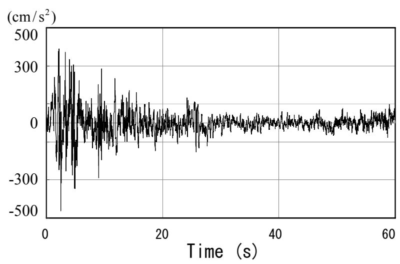

Fig.3 Acceleration of input motion

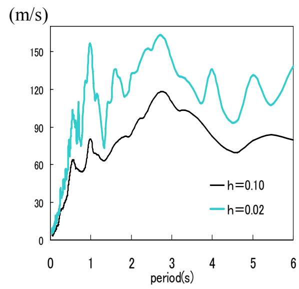

Fig.4 Response velocity spectra

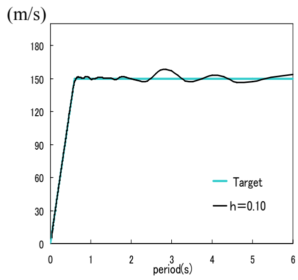

Fig.5 Energy spectra and target

3. ANALYTICAL RESULTS AND DISCUSSION ABOUT RESPONSE ENERGY

On the total input energy to the foundation-superstructure system (abbreviate as 'system" in following) ${}_T E_i$, the maximum strain energy of the superstructure ${}_S E_h$, the total input energy to the superstructure ${}_S E_i$ and the total input energy to the foundation ${}_B E_i$, the ratio of energy of the with-uplift model to that of without-uplift model are shown in following figures which the horizontal axis indicates the period of superstructure T_0 and the vertical axis indicates a aspect ration $\overline{H}/L$.

The minimum contact ratio between the foundation and the ground of the with-uplift model η, equivalent velocity of the maximum potential energy of the system ${}_T E_P$ and the proportion of the potential energy of the system in the total input energy of the system are also shown in the similar figures.

3.1. Ratio of Total Input Energy to the Foundation –Superstructure System

The ratio of total input energy into the system are shown in Figure 6. The ratio of total input energy into the system fluctuates (0.5～1.8), though the energy spectrum of input motion is constant. When the response velocity at the response period which was lengthened by uplift are smaller than that at the period in which uplift is not occurred, the ratio of total input energy becomes less than 1 (example; in Figure 7(c), T_0=1.0(s) and $\overline{H}/L$=4, response period of the without-uplift model is 2.7(s) and response period of the with-uplift model is 3.6(s)). And, When the response velocity at the response period which was lengthened by uplift are larger than that at the period in which uplift is not occurred, the ratio of total input energy becomes more than 1 (example; in Figure 7(c), T_0=0.5(s) and $\overline{H}/L$=2, response period without-uplift model is 1.2(s) and response period with-uplift model is 1.6(s)). Therefore, the ratio of total input energy fluctuates by the fluctuation of response velocity caused by lengthening the response period by the foundation uplift.

3.2. Proportion of the Potential Energy in the Total Input Energy into the Foundation–Superstructure System

The equivalent velocity of the maximum potential energy of the system are shown in Figure 7. Comparison with Figure 6, it seems that the maximum potential energy of the system becomes large when the ratio of total input energy becomes large. Figure 8 shows the proportion of the maximum potential energy in the total input energy of the system. The proportion of the potential energy in the total input energy becomes large when the potential energy becomes large. In cases of which the proportion of the total input energy is large, the ratio of the potential energy in the total energy also large. From the above facts, it can be sais that not only the potential energy increases but also the proportion of the potential energy in the total input energy also increases, when the total input energy of the system increases by the foundation uplift.

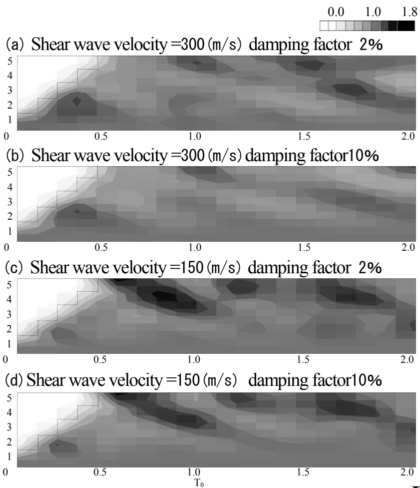

Fig.6 Total input energy of system

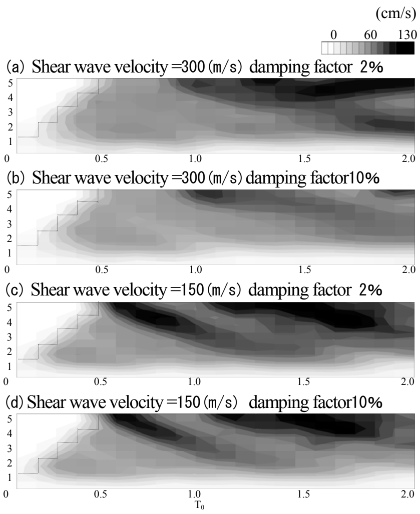

Fig.7 Equivalent velocity of potential energy of system

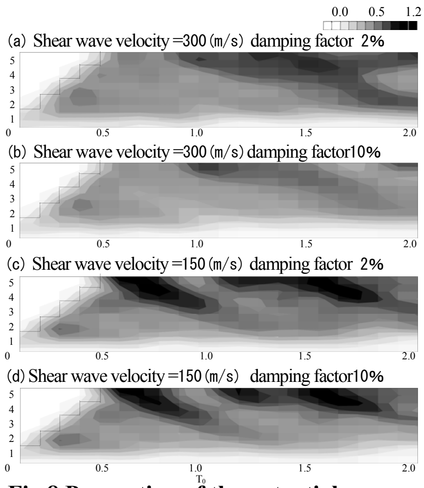

Fig.8 Proportion of the potential energy of system in the total input energy

3.3. Total Input Energy to the Superstructure and the Foundation

The ratio of the total input energy to the superstructure are shown in Figure 9. Though the ratio of total input energy to the superstructure fluctuate (0.4～1.2), the ratio is less than 1 in most cases. In other word, uplifting of the foundation reduce the total input energy into the superstructure. The ratio of the total input energy into the superstructure is less than 1 even if the ratio of the total input energy to the system in most cases (compare Fig.9 with Fig.6). Therefore, the total input energy to the superstructure decreases even if the total input energy to the system increases by the foundation uplift.

Figure 10 shows the ratio of the total input energy to the foundation. The ratio of the total input energy to the foundation fluctuate (0.4～6.5) and becomes more than 1 in many cases. Especially, the ratio is more than 1 in most cases when the shear wave velocity of the ground is 300(m/s) (see Figure 10(a), (b)). The ratio of the total input energy to the foundation becomes very large (>more than 2) when the ratio of the total input energy to the system is more than 1 especially. The reason why the total input energy to the superstructure decreases even if the total input energy to the system increases is the increase of the total input energy to the foundation.

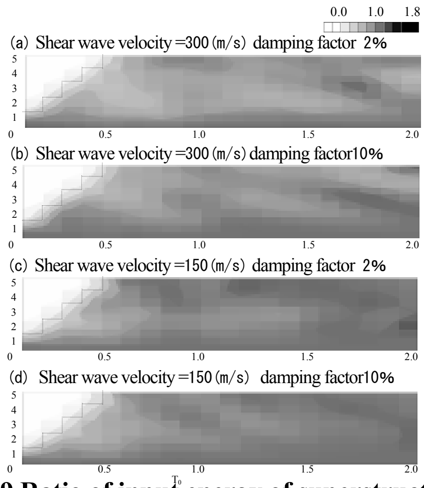

Fig.9 Ratio of input energy of superstructure

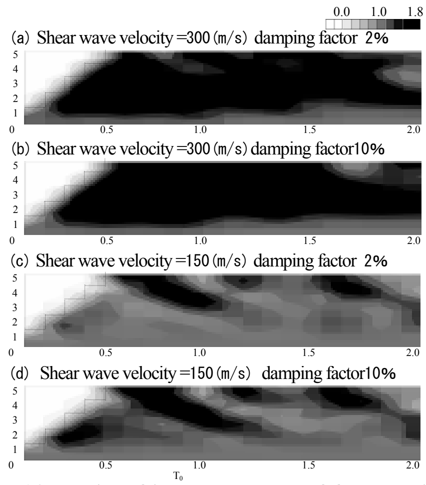

Fig.10 Ratio of input energy of foundation

3.4. Minimum Contact Ratio between the Foundation and the Ground

The minimum contact ratio between the foundation and the ground are shown in Figure 11. The foundation is easily uplifted in case of the ground is harder, because the minimum contact ratio given by the shear wave velocity is 300(m/s) (Fig 11 (a), (b)) are smaller than that given by the shear wave velocity is 150(m/s) (Fig 11 (c), (d)) in many cases. By comparison Figure 11 with Figure 10, the minimum contact ratio are almost small when the ratio of the total input energy into the foundation are less than 1. It is clear that the total input energy to the foundation increases by the foundation uplift.

3.5. Ratio of the Maximum Strain Energy of the Superstructure

Figure 12 shows the ratio of the maximum strain energy of the superstructure. Though the ratio of the maximum strain energy of the superstructure fluctuate (0.4～1.2), the ratio is less than 1 in most cases. In other word, uplifting of the foundation reduce the strain energy of the superstructure. By comparison Figure 12 with Figure 6, the ratio of the maximum strain energy of the superstructure are almost less than 1 even if the ratio of total input energy to the system are more than 1.

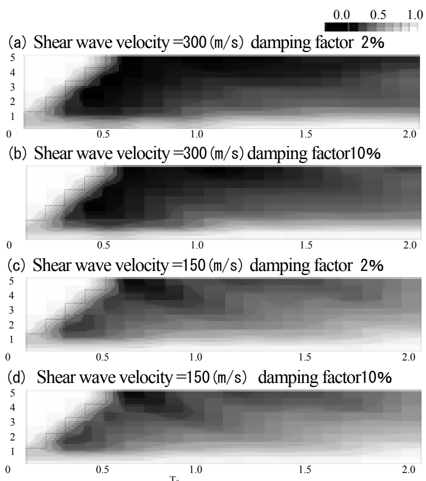

Fig.11 Minimum contact ratio between foundation and ground

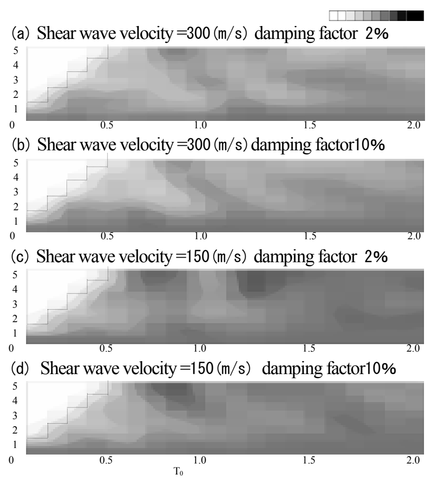

Fig.12 Ratio of the maximum strain energy of superstructure

In addition, by comparison with Figure 9 and Figure 12, it can be said that the ratio of the maximum strain energy of the superstructure becomes less than 1 not only in case that the ratio of the total input energy to the superstructure is less than 1 but also in case that the ratio of the total input energy to the superstructure is more than 1. Therefore, even if the total input energy to the system increases by the foundation uplift, the total input energy to the superstructure does not increase or decrease and the strain energy of the superstructure decreases.

4. DISCUSSION ABOUT A TIME HISTORY OF RESPONSE ENERGY

Symbols used in figures in this section indicate as follows; ${}_TE_i$: total input energy into the system, ${}_TE_k$: kinetic energy of the system, ${}_TE_d$: damping energy of the system, ${}_TE_h$: strain energy of the system, ${}_TE_P$: potential energy of the system when the foundation uplift, ${}_SE_i$: total input energy to the superstructure, ${}_SE_k$: kinetic energy of the superstructure, ${}_SE_d$: damping energy of the superstructure, ${}_SE_h$: strain energy of the superstructure, ${}_BE_i$: total input energy to the foundation. About the input energy, following equation is assumed to be approved; ${}_TE_i={}_SE_i+{}_BE_i+{}_TE_P$ (${}_TE_P = 0$ when the uplift is restricted).

The time history of energies of the system and the superstructure are shown in Figure 13 and 14 as the example in which the total input energy to the system decreases by uplift (T_0 =1.0(s), $\overline{H}/L$ =4, shear wave velocity Vs= 300(m/s), damping factor is 2%, the ratio of the total input energy to the system is 0.7, the ratio of the potential energy of the system is 0.4, the ratio of the total input energy to the superstructure is 0.7, the ratio of the total input energy to the foundation is 1.0, the minimum contact ratio between the foundation and the ground is 0.3, the ratio of the maximum strain energy of the superstructure is 0.7) .

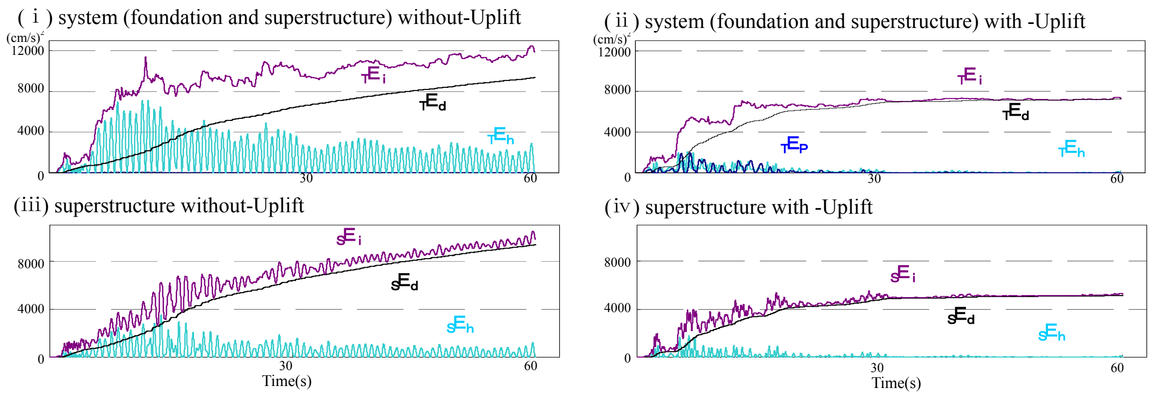

Fig.13 Time history of energy in case of the total input energy is decreased

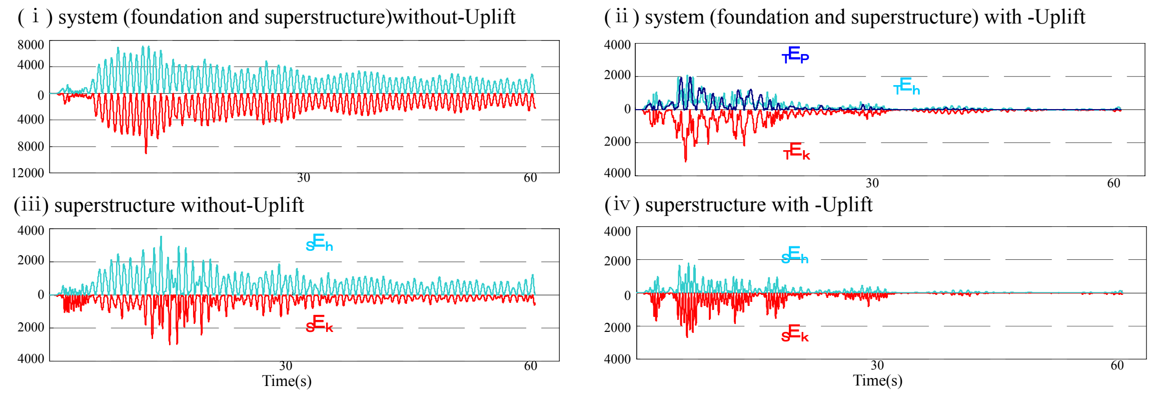

Fig.14 Kinetic energy and strain energy in case of the total input energy is decreased

Figure 13 indicates that not only the input energy but also damping and strain energy are reduced by uplift about the system and superstructure. A reduction of dumping energy of the system is significant.

From Figure 14, because the response period and vibration modes are changed by the foundation uplift, the kinetic energy and the strain energy of the system are reduced (see Fig.14(i), (ii)). On the other hand, the strain energy of the superstructure is reduced but the reduction of the kinetic energy of the superstructure is not so much (see Fig.14(iii), (iv)).

The time history of energies of the system and the superstructure are shown in Figure 15 and 16 as the example in which the total input energy to the system increases by the uplift (T_0 =1.0(s), $\overline{H}/L$ =4.5, shear wave velocity Vs= 300(m/s), damping factor is 2%, the ratio of the total input energy to the system is 1.5, the ratio of the potential energy of the system is 0.9, the ratio of the total input energy to the superstructure is 1.0, the ratio of the total input energy to the foundation is 3.7, the minimum contact ratio between the foundation and the ground is 0.2, the ratio of the maximum strain energy of the superstructure is 0.7) .

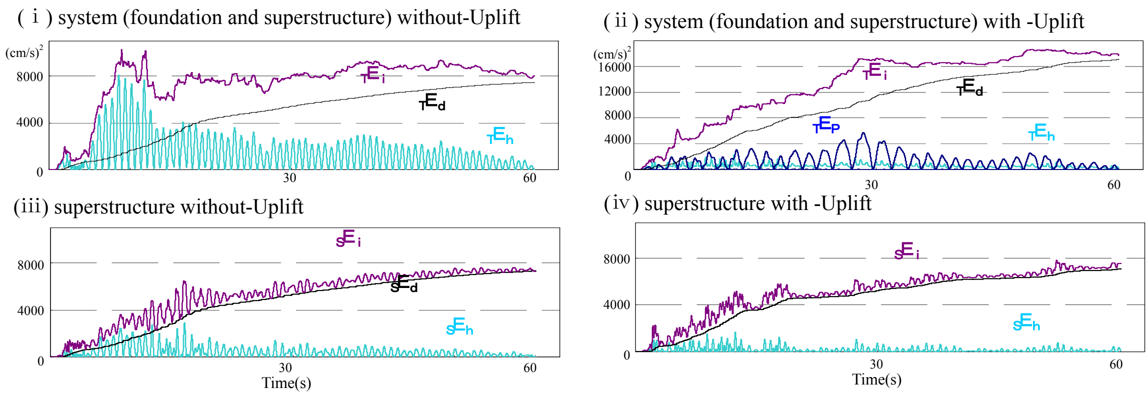

Fig.15 Time history of energy in case of the total input energy is increased

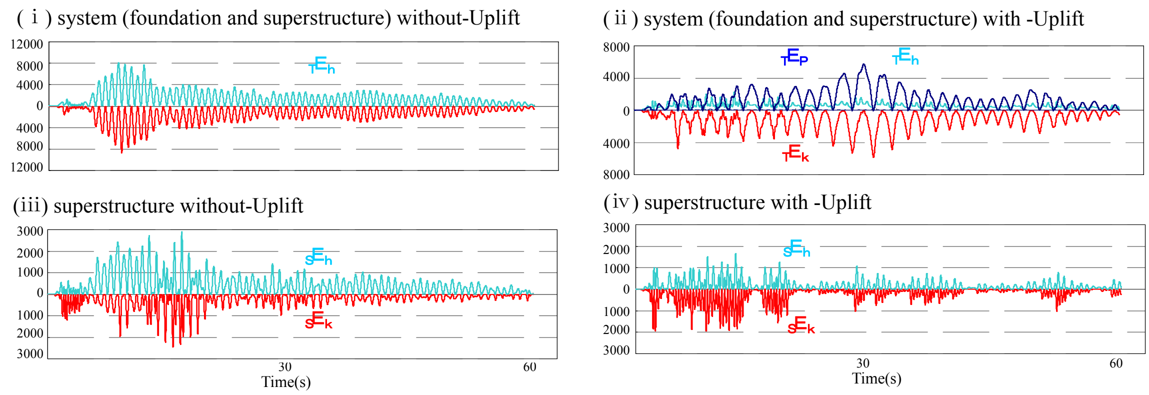

Fig.16 Kinetic energy and strain energy in case of the total input energy is increased

From Figure 15, while the total in put energy to the system increases as doubled, the strain energy of the system decreases greatly because the increase of the damping energy and the potential energy of the system. Moreover, the total input energy to the superstructure does not increase and the strain energy of the superstructure decreases even if the total input energy to the system increases significantly. It seems that the reason why the total input energy to the superstructure does not increase while the total input energy to the system increase greatly is the increase of the total input energy to the foundation by uplift.

The kinetic energy and the strain energy of the system are reduced by changing the response period and vibration modes (see Fig.16(i), (ii)). In the meantime, though the remarkable decrease in the kinetic energy to the superstructure is not observed, the strain energy of the superstructure decreases (see Fig.16(iii), (iv)).

5. CONCLUSIONS

I. The total input energy to the foundation-superstructure system is increased and decreased by the foundation uplift, even if the energy spectrum of the input ground motion is constant. The total input energy is increased when the response velocity increases because the response period is lengthened by the uplift, and the total input energy is decreased when the response velocity decreases because the response period is lengthened by the uplift.

II. When the total input energy to the system is increased by the foundation uplift, not only the potential energy of the system is increased, but also the ratio of the potential energy in the total input energy to the system is increased.

III. The total input energy to the superstructure is not increased because the total input energy to the foundation is increased, even if the total input energy to the system is increased by uplift.

IV. The strain energy of the superstructure is decreased in most cases because the total input energy to the superstructure is not increased, even if the total input energy to the system is increased by uplift.

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