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Analytical Study on Seismic Energy Balance of NPP Buildings Part 1 Formulation and Validity of Lattice Model

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1 ABSTRACT

In this paper, Part 1, seismic energy balances is formulated for a lattice model. In particular, methods for evaluating soil dissipation energy and building damping energy are studied and compared with other soil-structure seismic response models such as the sway and rocking model (SR model). It is thus shown that the seismic energy balances for the lattice model correspond closely to those of the SR model.

Next, the proposed methods are theoretically validated in both soil parts and building parts, which are the components of the lattice model.

In conclusion, a new method for evaluating the seismic energy balance for the lattice model is proposed and theoretically validated by comparison with results obtained from the SR model.

2 INTRODUCTION

Recently in Japan, there have been many earthquake records with large amounts of acceleration data. It is important to evaluate the nonlinear behavior of buildings under these large earthquake ground motions. To understand the non-linearity of the seismic response model, it is necessary to quantitatively evaluate the seismic energy flow by the effect of damping, plasticity and soil-structure interaction in addition to the conventional approach focusing on maximum response values.

However, there have been few studies, e.g., Yang et al. (2000) and Mizutani et al. (2006), on seismic energy balances with soil-structure interaction for massive structures such as nuclear reactor buildings of NPP, compared to those on high-rise buildings with vibration control systems.

Thus, the objective of this study is to develop and verify a method for evaluating the seismic energy balance for nuclear reactor buildings of NPPs using the so-called advanced lattice model with soil-structure interaction proposed by Hiraki et al. (2007). Furthermore, it is aimed to provide clear data for aseismic design.

3 OVERALL FLOWCHART BASED ON PREVIOUS RESEARCH

Results of previous research are used to quantify the seismic energy balance of NPP buildings using the so-called advanced lattice model shown in Fig.1. An overall flowchart of this study including part 1 and part 2 is shown in Fig.3.

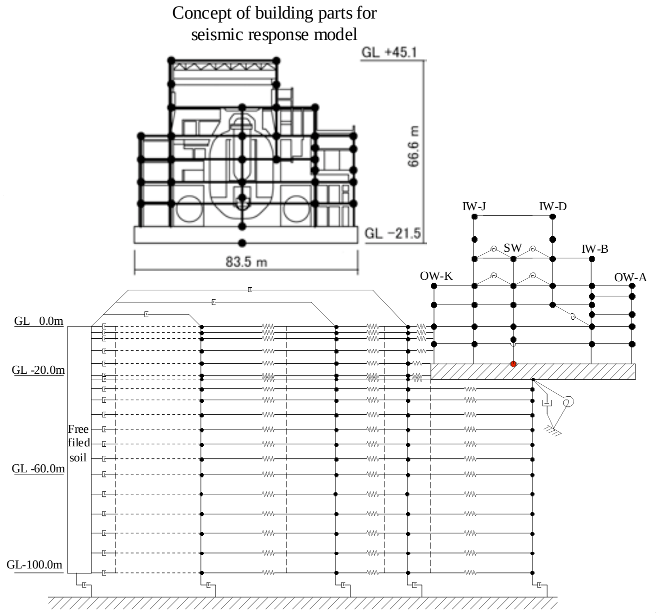

Figure 1. Example of Lattice model

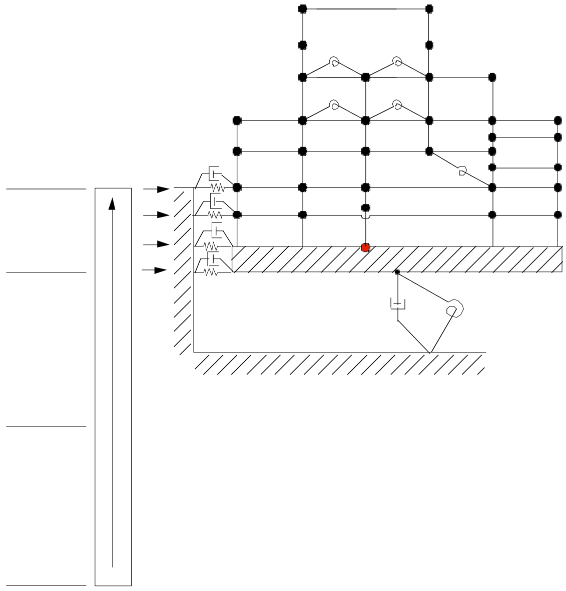

Figure 2. Example of SR model

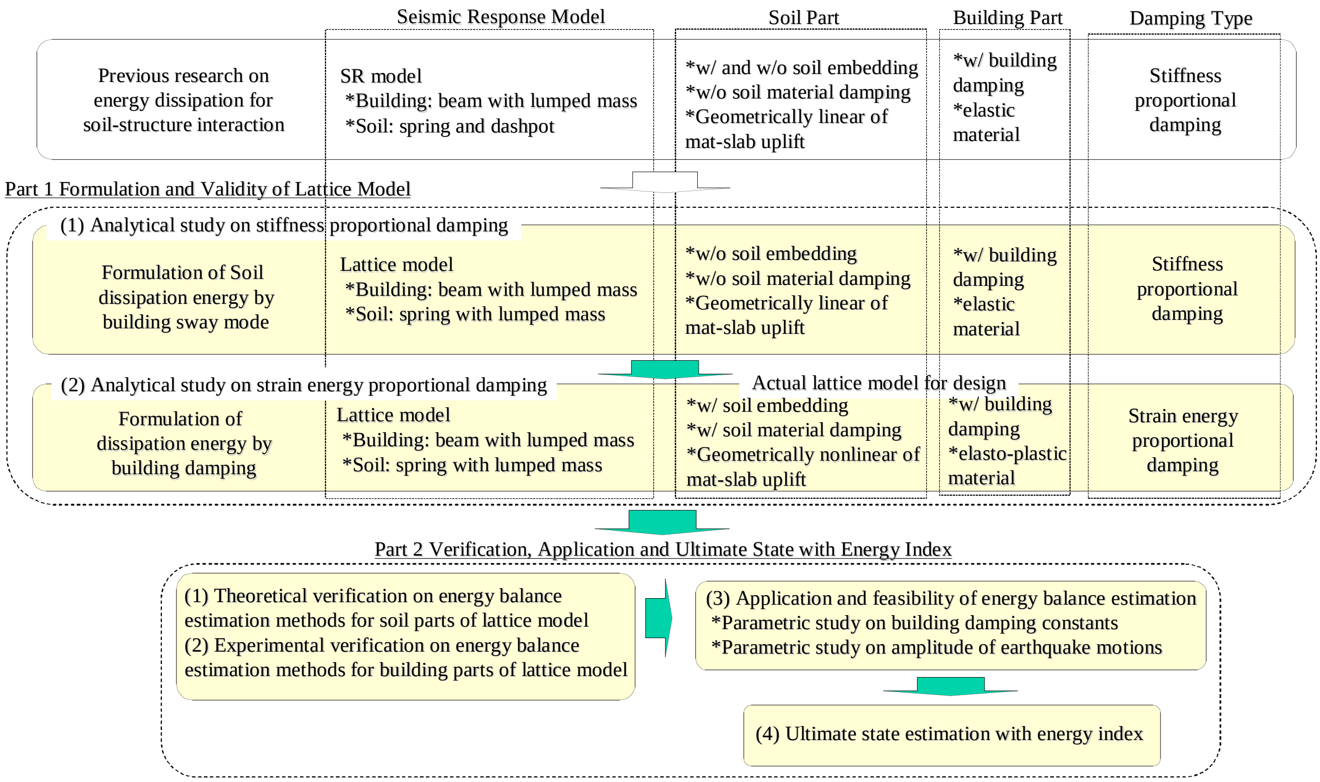

Figure 3. Overall flowchart in this study

3.1 Overview on previous research

It is necessary to consider the soil-structure interaction effect in seismic response analyses of massive structures such as nuclear reactor buildings of NPP. However, many previous researches have focused on seismic energy balance not of soil and the soil-structure interaction system but simply of the structural system.

Kokusho et al. (2000) shows the seismic energy balance formulation for one-dimensional wave propagation theory and also a qualitative comparison between theory and observed records. However, there have been no studies on a lumped mass soil model such as the lattice model.

As a soil-structure interaction system, Yang et al. (2000) and Mizutani et al. (2006) show quantitative results for the sway and rocking (SR) model with and without soil embedment. They show the relationship between dissipation energy by soil and actual input energy to buildings for the linear seismic response model with stiffness proportional damping. An example of an SR model with soil embedment is shown in Fig.2.

3.2 Overall flowchart

Based on the previous research stated in section 3.1, the overall flowchart of this study including part 1 and part 2 is shown in Fig.3.

In part 1 of this paper, based on the previous research, we propose new methods for evaluating the seismic energy balance for a lattice model and also theoretically validate it by comparison with results obtained from the SR model.

In part 2, the proposed methods are experimentally verified in both soil parts and building parts, which are the components of the lattice model. Energy balance in the soil parts of the lattice model is similar to that calculated from wave propagation theory. Energy consumption in building parts of the lattice model corresponds to the input energy evaluated from the observed earthquake records. Using the above verified method, a quantitative parametric study on the energy balance of nuclear reactor buildings is carried out using parameters of building damping constant and amplitude of earthquake motions. Moreover, the energy balance estimation in component levels is investigated under strong artificial earthquake motions with various random phases.

4 FORMULATION OF SEISMIC ENERGY BALANCE FOR LATTICE MODEL

In this chapter, seismic energy balances are formulated for the lattice model. In particular, methods for evaluating soil dissipation energy and building damping energy are studied and compared with other soil-structure seismic response models such as the SR model, which has already been studied by Yang et al. (2000) and Mizutani et al. (2006).

First, the procedure for evaluating soil dissipation energy by building sway mode is shown for the lattice model with stiffness proportional damping and is explicitly computed for the SR model.

Next, the procedure for evaluating dissipation energy by building damping is shown for the lattice model with strain energy proportional damping, which is used in actual aseismic design.

4.1 Seismic energy balance of soil-structure interaction system

Seismic energy balance of a soil-structure interaction system is given by eqn (1), which is derived from the equation of motion multiplied by the response velocity and integrated with respect to duration of earthquake motions.

$$\int_0^{t_d} \dot{X}^T M\ddot{X}dt + \int_0^{t_d} \dot{X}^T C\dot{X}dt + \int_0^{t_d} \dot{X}^T KXdt = -\int_0^{t_d} \dot{X}^T MI\alpha dt \qquad (1)$$

where

I : *Unit Matrix*

$$M = \begin{bmatrix} m_b & 0 \\ 0 & m_s \end{bmatrix},\ C = \begin{bmatrix} c_b & c_{bs} \\ c_{bs} & c_s \end{bmatrix},\ K = \begin{bmatrix} k_b & k_{bs} \\ k_{bs} & k_s \end{bmatrix},\ X = \begin{bmatrix} x_b \\ x_s \end{bmatrix}$$

x_b, x_s : *Building and soil relative displacement*

m_b, m_s : *Building and soil mass matrix*

c_b, c_{bs}, c_s : *Building, soil-structure interaction and soil damping matrix*

k_b, k_{bs}, k_s : *Building, soil-structure interaction and soil stiffness matrix*

α : *Acceleration time history applied to whole model as a body force*

t_d : *Duration of an earthquake motion*

If the soil and soil-structure interaction stiffness are elastic and linear, the seismic energy balance of the soil-structure interaction system is given by eqn (2) after the duration of earthquake motions.

$$E_b^c + E_{bs}^c + E_s^c + E_b^k = E_b^i + E_s^i \quad (2)$$

where

E_b^c, E_{bs}^c, E_s^c : *Dissipation energy by building, soil-structure interaction and soil damping*

E_b^k : *Dissipation energy by plastic strain of building*

$E_b^i,\ E_s^i$: *Input energy to building and soil by earthquake motions*

Dissipation energy by soil-structure interaction damping comprises damping energy due to building sway mode and building rocking mode for both the lattice model and the SR model. The lattice model dissipates energy by soil spring damping and viscous boundary but the SR model does not.

4.2 Formulation of seismic energy balance for lattice model

To formulate the dissipation energy by soil-structure interaction for the lattice model, it is necessary to subtract soil damping energy due to building sway mode from the total. It is also necessary to subtract building damping energy from the total soil-structure damping energy when strain energy proportional damping is applied in the lattice model. These estimation methods are explained in the following.

4.2.1 Analytical conditions

To confirm the basic validity of the above extraction concept, case 1 and case 2 in Table 1 are calculated and compared to the linear lattice model and the SR model without soil embedment. Case 3 in Table 1 is assumed as an actual lattice model for design. The acceleration time history and the velocity-equivalent energy spectrum of earthquake motion used in this study are shown in Fig.4 and Fig.5. The earthquake motion is defined in terms of the bedrock outcrop wave.

Table 1. Analytical cases to formulate and validate the energy balance estimation methods

Case	Soil embedding	Damping type	Nonlinearity	Objective
CASE1	w/o	Stiffness proportional damping	Linear	For soil dissipation energy by building sway mode
CASE2	w/o	Strain energy proportional damping	Linear	For dissipation energy by building damping
CASE3	w/	Strain energy proportional damping	Non-linear	For energy dissipation of actual lattice model for design

Note: Both lattice model and SR model are used in each case.

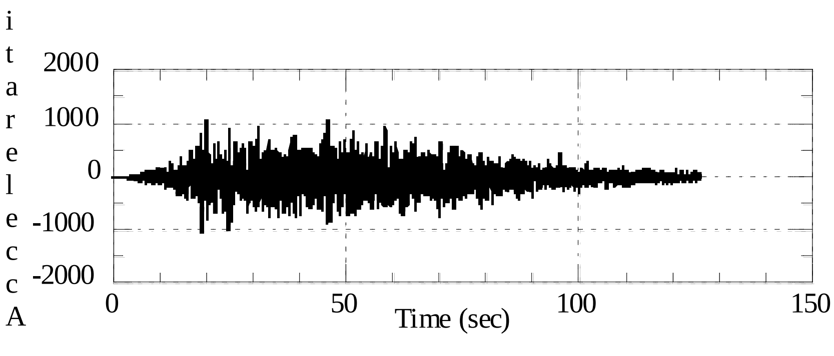

Figure 4. Acceleration time history of earthquake motion in this study

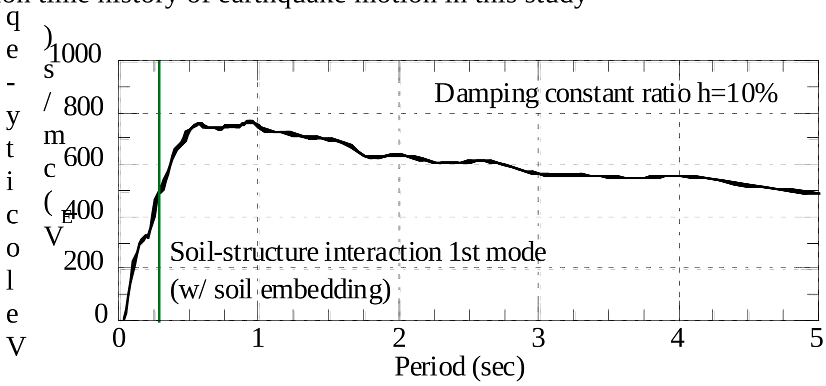

Figure 5. Velocity-equivalent energy spectrum of earthquake motion in this study

4.2.2 Soil dissipation energy by building sway mode

Soil dissipation energy E_s by building sway mode for the lattice model equivalent to that for the SR model is evaluated by the following concept shown in Fig.6. That is, it is evaluated by eqn (3) which is derived from the integration of the soil-structure interaction force Q and soil-structure interaction velocity $\Delta\dot{y}$ at the boundary between building and soil obtained by the additional analysis.

$$E_s = \int_0^{t_d} Q \times \Delta\dot{y} dt \qquad (3)$$

The analytical result for case 1 is shown in Fig.7. Soil dissipation energy by building sway mode for the lattice model closely corresponds to that for the SR model. Although this extraction concept is applicable only to the model with stiffness proportional damping such that $[c_{bs}] = 0$ in a narrow sense, soil dissipation energy by building sway mode is nearly unaffected by the types of damping for not only the SR model but also for the lattice model, as shown in Fig.7.

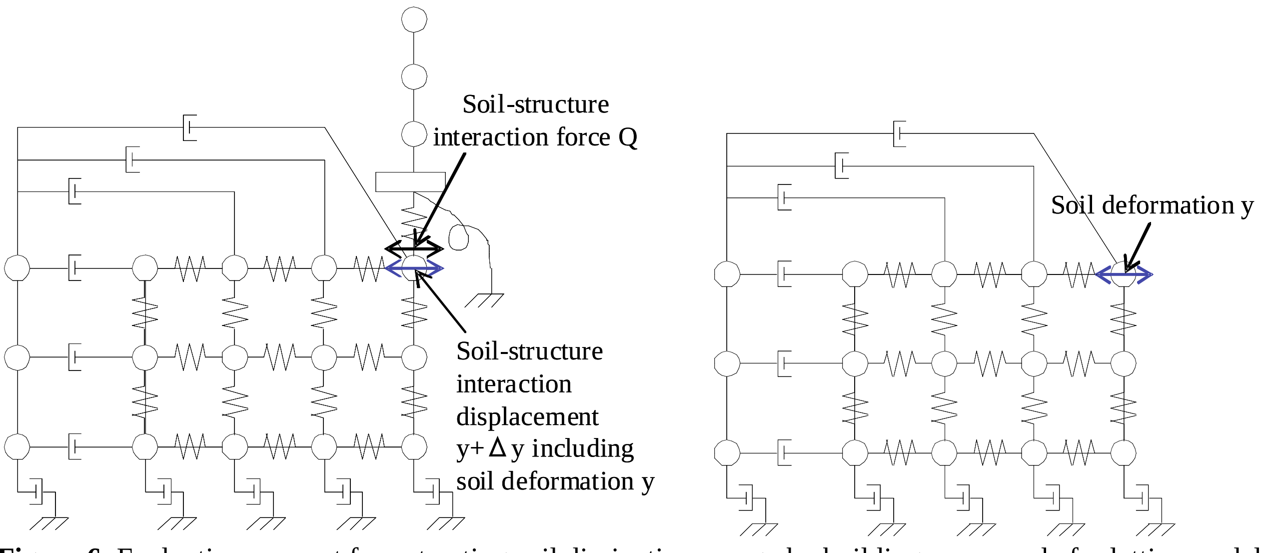

Figure 6. Evaluation concept for extracting soil dissipation energy by building sway mode for lattice model

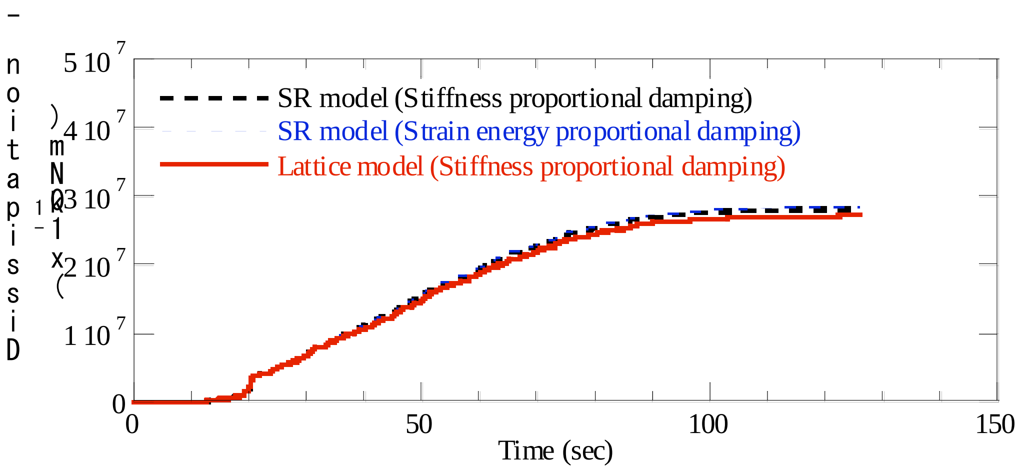

Figure 7. Comparison of soil dissipation energy by building sway mode (Analytical result of CASE1)

4.2.3 Dissipation energy by building damping

Since the lattice model with strain energy proportional damping has coupled damping matrices between soil and building such that $[c_{bs}] \neq 0$ in eqn (1), it is necessary to introduce an inventive approach to extract the dissipation energy by building damping only. Therefore, focusing on linear modal response with strain energy proportional damping, the dissipation energy by building damping is evaluated by eqn (4), which means the contribution ratio, κ_e, of damping energy for member "e" to make up a building.

$$\kappa_e = \frac{\sum_j ({}_j\kappa_e \, {}_jW_d)}{\sum_j {}_jW_d} \quad \text{such that} \quad {}_j\kappa_e = \frac{h_e \, {}_jE_e}{\sum_e (h_e \, {}_jE_e)} \tag{4}$$

where

h_e	*: Damping constant of member e*
${}_jE_e$	*: Strain energy of member e for j-th eigen mode*
${}_jW_d$	*: Damping energy for j-th eigen mode obtained by linear modal response*

The analytical result for case 2 is shown in Fig.8. The dissipation energy by building damping for the lattice model corresponds closely to that for the SR model. Also, from the details of seismic dissipation energy shown in Fig.9 for the lattice model and the SR model, the contributions of energy dissipation for both models closely correspond. In addition, except for the above energy dissipation component, the lattice model dissipates seismic energy in soil spring damping and in-plane side, out-of-plane side and bottom viscous boundary.

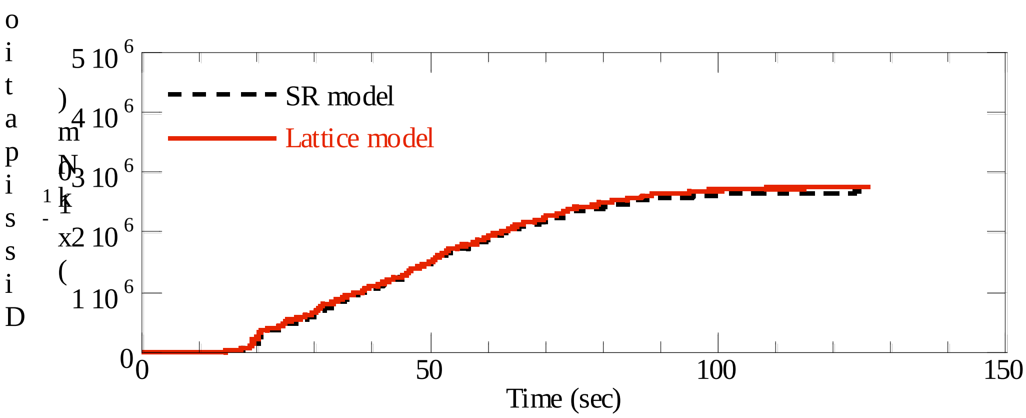

Figure 8. Comparison of soil dissipation energy by building damping (Analytical result of CASE2)

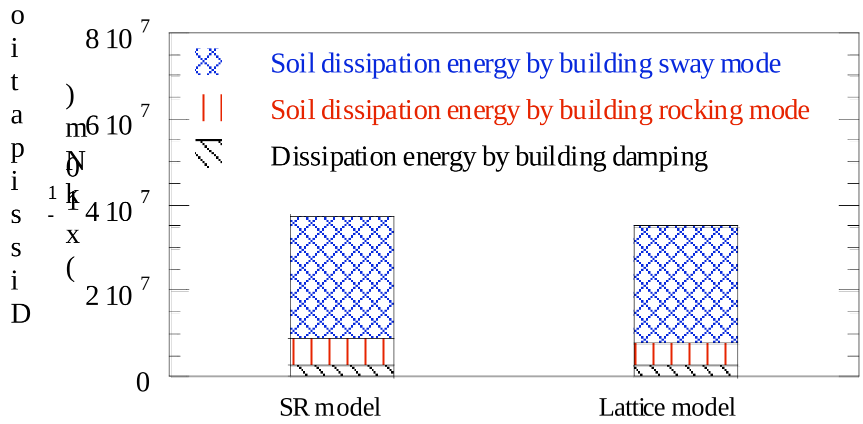

Figure 9. Comparison of components of seismic dissipation energy (Analytical result of CASE2)

4.2.4 Dissipation energy by each component for lattice model

Fig.10 and Fig.11 show the details of seismic energy dissipation for case 3 assumed as an actual lattice model for design. As shown in previous research by Hiraki et al. (2007), soil dissipation energy by building sway mode for the lattice model might be different from that for the SR model because of the difference between the soil embedment model concepts.

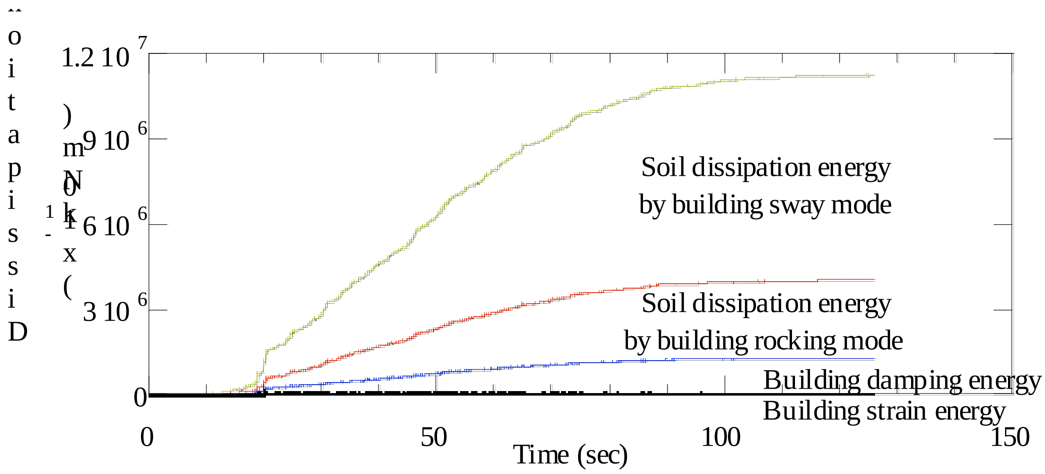

Figure 10. Components of seismic dissipation energy (Analytical result of CASE3)

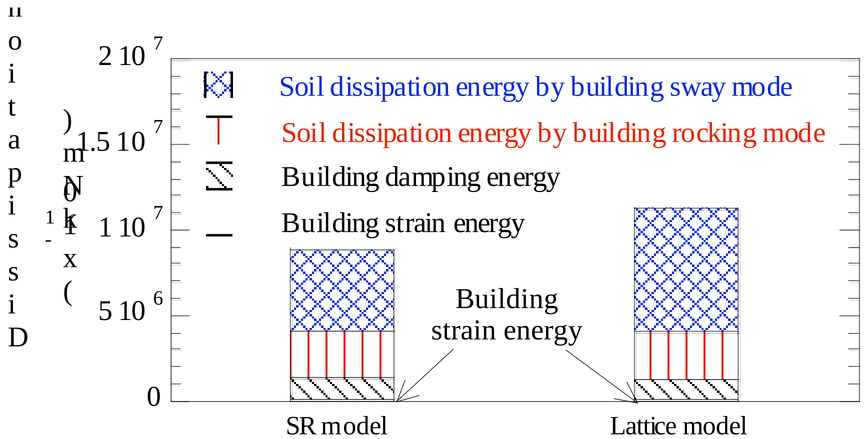

Figure 11. Comparison of components of seismic dissipation energy (Analytical result of CASE3)

5 CONCLUSION

Based on previous research, a new method for evaluating seismic energy balance for a lattice model is proposed and theoretically validated by comparison with the SR model.

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REFERENCES

Yang, Z. and Akiyama, H. 2000. Evaluation of soil-structure interaction in terms of energy input. Journal of structural and construction engineering. Transactions of AIJ. No.536. pp.39-45.

Mizutani, M. and Akiyama, H. et al. 2006. Evaluation of effective energy input to a structure considering soil-structure interaction. Journal of structural and construction engineering. Transactions of AIJ. No.601. pp.43-51.

Hiraki, T. and Onouchi, A. 2007. Study on a Seismic Response Analysis Model of Nuclear Reactor Buildings -Study on an Advanced Lattice Model. 19th International Conference on Structural Mechanics in Reactor Technology (SMiRT19), Toronto, Canada, K03-4.

Kokusho, T., and Motoyama, T. 2000. Energy flow evaluation in surface soil by separating upward and downward seismic waves. Journals of the Japan Society of Civil Engineers. No.652/Ⅲ-51. pp.257-267.