Analytical Study on Seismic Energy Balance of NPP Buildings
Part 2 Verification, Application and Ultimate State with Energy Index

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1 ABSTRACT

In this paper, Part 2, the energy balance estimation methods proposed in Part 1 are theoretically and experimentally verified for 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 dissipation in the building parts of the lattice model correspond to input energy evaluated from the observed earthquake records.

Using the evaluation method verified above, a quantitative parametric study is carried out on the energy balance of nuclear reactor buildings. As a result, correlation between building damping energy and soil dissipation energy in strong earthquake motions is demonstrated. Also, normalized plastic strain energy is highly correlated to conventional building damage index such as maximum response values.

2 INTRODUCTION

Recently in Japan, there have been many earthquake records with large 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., by 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 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 VERIFICATION ON ENERGY BALANCE ESTIMATION FOR LATTICE MODEL

The energy balance estimation methods proposed in Part 1 are theoretically and experimentally verified for both soil parts and building parts, which are the components of the lattice model. Energy balance in the soil parts is similar to that calculated from wave propagation theory. Energy dissipation in the building parts corresponds to the input energy evaluated from the observed earthquake records.
3.1 Theoretical verification on energy balance estimation methods for soil parts of lattice model

3.1.1 Analytical conditions

It is objective to theoretically verify energy balance estimation methods for the soil parts of the lattice model, which is a kind of discrete model, and to compare the results with those calculated from one-dimensional wave propagation theory, which is a kind of continuum approach. The analytical outline of the actual layered soil property is shown in Fig.1. The shear wave velocity of the soil is 720 to 820 m/s and the damping constant ratio is 5%. The earthquake motion shown in Part 1 is also used in this analysis.

![Analytical outline to verify energy balance estimation methods for soil parts of lattice model](image)

**Figure 1.** Analytical outline to verify energy balance estimation methods for soil parts of lattice model

3.1.2 Analytical results

The velocity-equivalent energy spectra at typical depth, ground surface at GL-21.5m and middle of model at GL-60.0m, are shown in Fig.2 to compare the propagation of input energy of the soil parts of the lattice model with that obtained from one-dimensional wave propagation theory.

The velocity-equivalent energy spectra at typical depth for the soil parts of the lattice model, whose element size is commonly 4 to 8 m deep, is quite similar to that calculated from one-dimensional wave propagation theory. Therefore, the energy balance estimation methods for the soil parts of the discrete lattice model due to damping and vibration are theoretically verified.

In addition, almost the same results are obtained for various types of soil damping such as constant damping to frequency in frequency domain analysis and also strain energy proportional damping in time domain analysis.
3.2 Experimental verification on energy balance estimation methods for building parts of lattice model

3.2.1 Analytical conditions

It is objective to experimentally verify the inventive approach to extract the dissipation energy only by building damping proposed in Part 1, and to compare it with the actual input energy to the building evaluated from the earthquake observation records. The building damping dissipation energy with strain energy proportional damping is analytically obtained by the previous simulation model by Hiraki et al. (2007) and the extraction method mentioned above. The earthquake observation records of the Tsuruga-wan Nanpooki earthquake and the Shizuoka-ken Chubu earthquake are selected in this analysis for the following reasons. The former earthquake occurred on October 11th, 1997. It had a JMA magnitude of Mj5.1 and an epicentral distance from the observation site of 24.5km. It had a relatively large input energy to the building evaluated from the observed acceleration record on top of a mat-slab foundation. The latter earthquake, occurred on October 5th, 1996. It had a JMA magnitude of Mj4.6 and an epicentral distance from the observation site of 42.3km. It had a relatively small input energy to the building. The velocity-equivalent energy spectra of the observed acceleration records on top of a mat-slab foundation are shown in Fig.3. The analytical simulation model is the same lattice model as that by Hiraki et al. (2007). The input motion to the lattice model is evaluated from the free-field observation record. The simulation analysis procedure is shown in Fig.4.

The actual input energy to the building “L” evaluated from the observed records is quantified following the concept of Kurino et al. (2007). That is, the actual input energy to the building “L” is defined in eqn (1) with an observed acceleration record on top of a mat-slab foundation and a relative velocity at an observation point on top of a mat-slab foundation.

\[
L = \int_0^t \dot{y} M J v_i dt
\]

(1)
where

\[ \ddot{y} : \text{Observed acceleration record on the top of a mat-slab foundation} \]

\[ M_i : \text{Dominant weigh at an observe point } i \]

\[ v_i : \text{Relative velocity at an observe point } i \text{ to the top of a mat-slab foundation} \]

\[ t_d : \text{Duration of an earthquake motion} \]

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**Figure 3.** Velocity-equivalent energy spectra of observed acceleration records on top of mat-slab foundation

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**Figure 4.** Simulation analysis procedure with free-field observation record

### 3.2.2 Analytical results

Since the seismic response of the building is elastic under the earthquake in this analysis, input energy to the building “L” derived from eqn (1) seems to be equivalent to the dissipation energy only by building damping derived from eqn (3) proposed in Part 1 if the estimation method is appropriate. The velocity-equivalent energy spectra evaluated from the both procedures are shown in Fig.5 and Fig.6. As the results of this, the actual input energy to the building “L” is almost corresponding to the dissipation energy only by building damping evaluated from simulation analysis. Therefore, the inventive approach to extract the dissipation energy only by building damping proposed in Part 1 is adequate and experimentally verified. In addition, the spike shape of the input energy to the building around 13 second under the Tsuruga-wan Nanpooki earthquake is caused by the noncumulative energy such as the kinematic energy and elastic strain energy.
That is shown in Fig. 7 since the total energy including the kinematic energy and elastic strain energy by simulation is improving corresponding to the result by observed records.

Figure 5. Velocity-equivalent energy spectra evaluated from simulation and observed records (Tsuruga-wan Nanpooki earthquake)

Figure 6. Velocity-equivalent energy spectra evaluated from simulation and observed records (Shizuoka-ken Chubu earthquake)

Figure 7. Velocity-equivalent energy spectra based on total energy including kinematic energy and elastic strain energy (Shizuoka-ken Chubu earthquake)

4 APPLICATION AND FEASIBILITY OF ENERGY BALANCE ESTIMATION

From the viewpoint of application and feasibility of the energy balance estimation methods verified in the previous chapter, 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. This will show the energy relationship between building damping and soil dissipation under strong earthquake motions.

The analytical cases with parameters of building damping constant and amplitude of earthquake motions are shown in Table 1. Case 1 is a basic case with strain energy proportional damping, soil embedment and non-linear building property. The earthquake motions shown in Part 1 are multiplied by amplitudes of 0.75, 1.00, 1.25 and 1.50.

Table 1. Analytical cases for application and feasibility of the energy balance estimation methods

<table>
<thead>
<tr>
<th>Case</th>
<th>Building damping</th>
<th>Amplitude factor</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5%</td>
<td>1.00 x basic EQ wave</td>
<td>For basic case</td>
</tr>
<tr>
<td>2</td>
<td>3%</td>
<td>1.00 x basic EQ wave</td>
<td>For building damping</td>
</tr>
<tr>
<td>3</td>
<td>5%</td>
<td>0.75 x basic EQ wave</td>
<td>For amplitude of input EQ</td>
</tr>
<tr>
<td>4</td>
<td>5%</td>
<td>1.25 x basic EQ wave</td>
<td>For amplitude of input EQ</td>
</tr>
<tr>
<td>5</td>
<td>5%</td>
<td>1.50 x basic EQ wave</td>
<td>For amplitude of input EQ</td>
</tr>
<tr>
<td>6</td>
<td>5%</td>
<td>1.50 x EQ wave 1 w/ another random phase</td>
<td>For various random phases</td>
</tr>
<tr>
<td>7</td>
<td>5%</td>
<td>1.50 x EQ wave 2 w/ another random phase</td>
<td>For various random phases</td>
</tr>
<tr>
<td>8</td>
<td>5%</td>
<td>1.50 x EQ wave 3 w/ another random phase</td>
<td>For various random phases</td>
</tr>
</tbody>
</table>

Note: Both lattice model and SR model shown in Part 1 are used in each case.

4.1 Parametric study on building damping constants

The details of seismic energy dissipation are shown in Fig. 8 for a building damping constant of 5% for case 1 and 3% for case 2. Also, comparisons of each energy dissipation component normalized by the results of the building damping constant 5% for case 1 are shown in Fig. 9.

While there are no big differences between the total energy dissipations for building damping constants of 5% and 3%, the dissipation energy for building damping constant 3% is smaller than that for building damping constant 5% in the ratio of 3% to 5%. However, the soil dissipation energy for building sway mode for building damping constant 3% is larger than that for building damping constant 5% in the inverse ratio of 3% to 5%. Thus, the energies related to building damping and soil sway dissipation have the opposite relationship. Thus, if the building damping energy decreases, the soil sway dissipation energy increases. In addition, the summation of soil dissipation energy for building rocking mode and building plastic strain energy, which influences the maximum response value, is almost the same irrespective of building damping constant 3% or 5%. For simplicity, the “rest” in Fig.8, which means damping energy dissipation by soil spring and viscous boundary, is shown by an equivalent value from soil mass to building mass.

Figure 8. Details of seismic energy dissipation
Figure 9. Comparisons of energy dissipation components normalized by results for building damping constant ratio 5%

4.2 Parametric study on amplitude of earthquake motions

Figure 10 compares the energy dissipation component normalized by the results for the amplitude of 1.00 for case 1 for the analytical cases with parameters of amplitude of earthquake motions multiplied by 0.75 for case 3, 1.00 for case 1, 1.25 for case 4 and 1.50 for case 5. Soil dissipation energy by building sway and rocking mode and dissipation energy by building damping increase in proportion to the amplitude of earthquake motions. However, the building plastic strain energy increases exponentially.

The ratio normalized by the results of case 1 for the energy dissipation of soil and building plastic strain to total energy is shown in Fig. 11. As shown, the soil dissipation energy does not increase but rather slightly decreases, although building plastic strain energy increases if the amplitude of earthquake motions increases.

Figure 10. Comparisons of energy dissipation components normalized by the results for amplitude of 1.00

Figure 11. Normalized ratio by energy dissipation of soil and building plastic strain to total energy

5 ULTIMATE STATE ESTIMATION WITH ENERGY INDEX

From the viewpoint of design-oriented ultimate state with energy index, the energy balance estimation in component levels is investigated under strong artificial earthquake motions with various random phases. This will show that the representative energy index of building damage is highly correlated to conventional indices such as maximum response values.
5.1 Analytical conditions

For assumed strong earthquake motions multiplied by 1.50 for case 5 to 8 with the same spectra response but different random phases, the component damages of the building are investigated from the viewpoint of energy index highly correlated to conventional index such as maximum response values. The response spectra and velocity-equivalent energy spectra of the four earthquake motions with different random phases used in this study are shown in Fig. 12 and Fig. 13. There seems to be velocity-equivalent energy spectra for a longer period different than the natural period of the soil-structure interaction 1st eigen mode.

![Response spectra of four earthquake motions with different random phases](image1)

**Figure 12.** Response spectra of four earthquake motions with different random phases

![Velocity-equivalent energy spectra of four earthquake motions with different random phases](image2)

**Figure 13.** Velocity-equivalent energy spectra of four earthquake motions with different random phases

5.2 Analytical results

Figure 14 compares the plastic strain energy with conventional indices such as maximum shear strain for all components of the building. The plastic strain energy does not correlate well with the maximum shear strain. Nakamura et al. (1995) pointed out that the energy index normalized by the area of the skeleton curve for hysteresis is highly correlated to the deformation angle at maximum strength. Based on that study, Fig. 15 compares the plastic strain energy normalized by the area of the skeleton curve defined in JEAG4601 (1991) used in these seismic response analyses with maximum shear strain. Also, Fig. 16 compares different earthquake motions with various random phases. Normalized plastic strain energy is highly correlated to the maximum shear strain with a correlation coefficient 0.97 and this correlation relationship is not affected by the amplitudes of earthquake motions or differences of random phases. Thus, the regression formula for the normalized plastic strain energy \( \frac{E}{E_n} \) and the maximum shear strain \( \gamma \times 10^{-3} \) in the strong non-linear range with various random phases is:

\[
\frac{E}{E_n} = 0.181\gamma \times 10^{-3} - 0.0348 \geq 0
\]  

(2)
Figure 14. Comparison between plastic strain energy and conventional index such as maximum shear strain

Figure 15. Plastic strain energy normalized by area of skeleton curve defined in JEAG4601 (1991)

Figure 16. Comparison for different earthquake motions with various random phases

6 CONCLUSION

The energy balance estimation methods propose in Part 1 are theoretically and experimentally verified for both soil parts and building parts, which are the components of the lattice model. Energy balance in the soil parts is similar to that calculated from wave propagation theory. Energy consumption in the building parts corresponds to input energy evaluated from the observed earthquake records.

The correlation between building damping energy and soil dissipation energy in strong earthquake motions is shown in this parametric study using the verified evaluation method. Also, normalized plastic strain energy is highly correlated to conventional building damage index such as maximum response values.

Further study regarding the configuration of an acceptable value of normalized plastic strain energy should be performed in the future, considering the real phase by observed earthquake records, experimental data on accumulated energy and also detailed elasto-plastic analyses.

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REFERENCES


