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Response Reduction Effects of Two Base Isolated Buildings Using Linked the Rigid Springs

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ABSTRACT

This paper presents the seismic response reduction effects of two linked type base isolated buildings under far field and near field type earthquake motions. Two linked base isolated buildings are the new structures which were linked each of base isolated building by the rigid springs. The far field earthquake motion, particularly, the long period ground motions based on the K-NET earthquake observation systems are the 2003 Tokachi-oki earthquake in the K-NET Tomakomai, and the 2011 off pacific coast of Tohoku earthquake in K-NET Osaka. The simulated earthquake wave is the building center wave of Japan at level II. And the near filed earthquake motions are 1995 southern Hyogo prefecture earthquake in JMA-Kobe.

As the earthquake response analysis result, the maximum response of two linked base isolated buildings can be reduced to 77~90% of these responses of the single base isolated building.

KEY WORDS: two linked base isolated buildings, far field and near filed earthquakes, long period type earthquake

1. Introduce

When a deadly earthquake shook the southern part of Hyogo prefecture in Japan on 17th of January 1995, people who thought they were living in a safe place such as tall buildings experienced vibrations so severe that all were affected by serious anxiety. Seismic structural response control is therefore needed not only for structural anti-seismic safety but also for improvement of structural amenity under severe earthquake ground motions. For attaining the dual objectives, much been paid to the base isolation system or passive controlled system.

The severe and great earthquake such as the 2003 Tokachi-oki, the 2004 Kii peninsula southeast offshore and the 2011 of Pasific coast of Tohoku earthquakes are happened after the 1995 southern Hyogo prefecture earthquake. It's not too much to say that Japan often has entered a period earthquake activity.

Recently, the long period earthquake has frequently observed. When the long period earthquake acts on the base isolated buildings, it is possible to occur a resonance phenomenon.

In this paper, I would like to proposal two base isolated structural buildings with the linked rigid springs, hereafter referred to TLBIS, to avoid the resonance phenomenon due to the long period earthquake.

The objective of the paper is to show the seismic response reduction effects of the TLBIS under the long period type ground motions and the near field ground motions.

2. Analytical Method

2・1 Analytical model and earthquake ground motion model

The structural model considered here is a lumped mass multi-degree-of-freedom system composed of two base isolated buildings with linked rigid springs.

Fig.1 shows the TLBIS with linked rigid springs. Base isolated building model is installed the rubber bearings with the lead damper, hereafter referred to LRB. TBSI models are the base isolated building model with the linked rigid springs.

In which $m_i, m_i', k_i, k_i', r_1 k_i, r_i' k_i', k_l$ are mass of i-th floor, the elastic stiffness of the rubber bearing of base

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isolation floor and the stiffness of the rigid springs of Building A and B respectively.

In this paper, the story numbers of the base isolated buildings model are 30 stories with both buildings.

The earthquake ground motion models are the Kobe earthquake as the near field type earthquake and the Tokachi-oki[1], the Tohoku[1] earthquakes as the far field earthquake. As the simulated earthquake ground motions, the building center wave of Japan at level II, hereafter referred to BCJWL2, is used.

The maximum velocity of the earthquake ground motions is normalized to 1m/s and used the response analysis, respectively.

The reason why is shown 1m/s as the maximum velocity of earthquake ground motions thinks about the 1.25 times of the simulation waves of Notification 1461 of Ministry of Land, Infrastructure, Transport and Tourism and uses it for the analysis.

Table.1 shows the parameters of the earthquake ground motions used in this analysis.

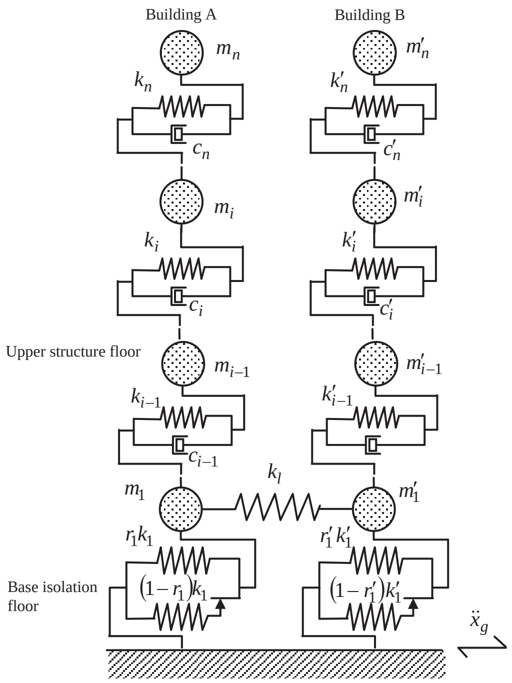

Fig.1 Two base isolated buildings model with the rigid springs

Table.1 Parameters of the earthquake ground motions

Earthquake	Max. acc. (cm/s^2)	Max. vel (cm/s)	1 m/s input (cm/s^2)
Tokachi-oki	86.74	32.55	266.48
Tohoku (K-NET Osaka)	6.89	6.16	111.85
Kobe	818.0	90.4	904.87
BCJWL2	355.66	73.44	484.29

The velocity response spectrum of the Tokachi-oki, Tohoku, Kobe and BCJWL2 earthquake are shown in Fig.2. As shown the Fig.2, the predominate period of the Tokachi-oki earthquake becomes about 3.5, 5.2 and 7.1 sec, the one of the Tohoku becomes 3.2 sec, the one of the Kobe becomes 0.8 and 1.2 sec, and the one of the BCJWL2 increases elastically until 0.5 sec and after that, tends to be constant.

Fig.2 also indicates that the Tokachi-oki and Tohoku (K-NET Osaka) earthquakes are long period earthquake ground motions.

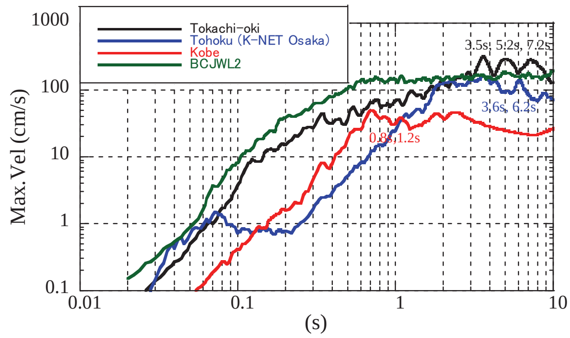

Fig.2 Velocity response spectrum

2・2 Equation of Motion and State Equation of the two base isolated systems

In the TLBIS with linked rigid springs which are shown Fig.1, the equation of motions of Building A and B can be derived as the following equations.

1) Building A

Top floor :

$$m_n(\ddot{u}_1+\cdots+\ddot{u}_n+\ddot{x}_g)+c_n\dot{u}_n+k_nu_n=0 \tag{1}$$

Any i-th floor :

$$m_i(\ddot{u}_1+\cdots+\ddot{u}_i+\ddot{x}_g)+c_i\dot{u}_i-c_{i+1}\dot{u}_{i+1}+k_iu_i-k_{i+1}u_{i+1}=0 \tag{2}$$

Base isolation floor :

$$m_1(\ddot{u}_1+\ddot{x}_g)-c_2\dot{u}_2+r_1k_1u_1-k_2u_2+(1-r_1)k_1y_1+k_l(u_1-u_1')=0 \tag{3}$$

In which $m_i, u_i, y_1, \ddot{x}_g$ are mass of any i-th floor, inter-story drift response of base isolation and upper structure floor, the drift one of coulomb slip element composed of the base isolation floor in the Buildings A and the earthquake input motions exciting a base layer respectively.

2) Building B

Top floor :

$$m_n'\left(\ddot{u}_1' + \cdots + \ddot{u}_n' + \ddot{x}_g\right) + c_n'\dot{u}_n' + k_n'u_n' = 0 \quad (4)$$

Any i-th floor :

$$m_i'\left(\ddot{u}_1' + \cdots + \ddot{u}_i' + \ddot{x}_g'\right) + c_i'\dot{u}_i' - c_{i+1}'\dot{u}_{i+1}' + k_i'u_i' - k_{i+1}'u_{i+1}' - k_l\left(u_1 - u_1'\right) = 0 \quad (5)$$

Base isolation floor :

$$m_1\left(\ddot{u}_1 + \ddot{x}_g\right) - c_2\dot{u}_2 + r_1k_1u_1 - k_2u_2 + \left(1 - r_1\right)k_1y_1 = 0 \quad (6)$$

In which $m_i', u_i', y_1', \ddot{x}_g$ are the same parameters of Building A.

And the inter-story velocity of the coulomb slip element $\dot{y}_i$ and $\dot{y}_i'$ are can be derived as the following equations.

$$\dot{y}_i = \frac{\dot{u}_i}{4}\left[2 + \mathrm{sgn}\left(y_i + \delta_i\right) - \mathrm{sgn}\left(y_i - \delta_i\right) - \mathrm{sgn}\left(\dot{u}_i\right) \cdot \left\{\mathrm{sgn}\left(y_i + \delta_i\right) + \mathrm{sgn}\left(y_i - \delta_i\right)\right\}\right] \quad (7)$$

$$\dot{y}_i' = \frac{\dot{u}_i'}{4}\left[2 + \mathrm{sgn}\left(y_i' + \delta_i'\right) - \mathrm{sgn}\left(y_i' - \delta_i'\right) - \mathrm{sgn}\left(\dot{u}_i'\right) \cdot \left\{\mathrm{sgn}\left(y_i' + \delta_i'\right) + \mathrm{sgn}\left(y_i' - \delta_i'\right)\right\}\right] \quad (8)$$

In which δ_i, δ_i' is the yield displacement of the lead damper.

Using from (1) to (8) equations, the fundamental equation of motion of TLBIS with linked rigid springs can be derived as.

$$\{\ddot{u}\} + \left[\tilde{c}_A\right]\{\dot{u}\} + \left[\tilde{k}_A\right]\{u\} + \left[\tilde{k}_A'\right]\{y\} + \left[\tilde{k}_l\right]\{u - u'\} = -\{1'\}\ddot{x}_g \quad (9)$$

$$\{\ddot{u}'\} + \left[\tilde{c}_B\right]\{\dot{u}'\} + \left[\tilde{k}_B\right]\{u'\} + \left[\tilde{k}_B'\right]\{y'\} - \left[\tilde{k}_l\right]\{u - u'\} = -\{1'\}\ddot{x}_g \quad (10)$$

In which $\{u\}$ is an inter-story drift response vector, $\left[\tilde{k}_A\right], \left[\tilde{k}_A'\right], \left[\tilde{c}_A\right]$ and $\left[\tilde{k}_l\right]$ are respectively matrices associated with the stiffness, viscous of the building A and the stiffness of the rigid springs. $\{1'\}$ is a vector having unit only for the lowest element. $\{y\}$ is a velocity movement vector of the Coulomb slip.

And these character in the Eqs. (10) are the same of the Eqs. (9).

Selecting the response vectors $\{U\}^T = \{\{u\}, \{u'\}, \{\dot{u}\}, \{\dot{u}'\}, \{y\}, \{y'\}\}^T$ of the TLBIS system as state variable vectors, Eqs.(9) and (10) can be rewritten in a more simple form as.

$$\dot{U}_j = \sum_{i=1}^{\tilde{n}} a_{ji}U_i + b_j\ \ddot{x}_g \quad (11)$$

$$\dot{y}_i = \frac{\dot{u}_i}{4}\left[2 + \mathrm{sgn}\left(y_i + \delta_i\right) - \mathrm{sgn}\left(y_i - \delta_i\right) - \mathrm{sgn}\left(\dot{u}_i\right) \cdot \left\{\mathrm{sgn}\left(y_i + \delta_i\right) + \mathrm{sgn}\left(y_i - \delta_i\right)\right\}\right] \quad (12)$$

$$\dot{y}_i' = \frac{\dot{u}_i'}{4}\left[2 + \mathrm{sgn}\left(y_i' + \delta_i'\right) - \mathrm{sgn}\left(y_i' - \delta_i'\right) - \mathrm{sgn}\left(\dot{u}_i'\right) \cdot \left\{\mathrm{sgn}\left(y_i' + \delta_i'\right) + \mathrm{sgn}\left(y_i' - \delta_i'\right)\right\}\right] \quad (13)$$

in which j is the variable of the state variable number with the maximum number $\tilde{n}(=6n)$, a_{ji} are the coefficients associated with the stiffness, viscous damper of the Buildings A,B and the stiffness of rigid springs. $\{b\}^T\left(=\{\{0\}, \{0\}, -\{1'\}, -\{1'\}\}^T\right)$ is the constant vectors associated with an earthquake excitation level. The element of $[a]$ in the Eqs. (11) is the following as.

$$[a] = \begin{bmatrix} [0] & [0] & [E] & [0] & [0] & [0] \\ [0] & [0] & [0] & [E] & [0] & [0] \\ -\left[\tilde{k}_A\right] - \left[\tilde{k}_l\right] & \left[\tilde{k}_l\right] & -\left[\tilde{c}_A\right] & [0] & -\left[\tilde{k}_A'\right] & [0] \\ \left[\tilde{k}_l\right] & -\left[\tilde{k}_B\right] - \left[\tilde{k}_l\right] & [0] & -\left[\tilde{c}_B\right] & [0] & -\left[\tilde{k}_B'\right] \end{bmatrix} \quad (14)$$

3. Numerical Example

3・1 Eigen value analysis of the base isolated system and Two linked base isolated system

In this paper, the first natural period of the upper structural buildings assumes 2.9 sec. For example, the stiffness k_{IA} of the rubber bearing will be determined so that the first natural period of the BIS buildings A becomes 4.0 sec and the stiffness k_{IB} will also be determined so that the one of the BIS buildings B becomes 6.0 sec by a convergence calculation respectively.

Based on the stiffness k_{IA} and k_{IB} provided by the calculation, the Eigen value analysis is carried out for the TLBIS with rigid springs, and the first natural period is determined. Table 2 shows the result of analysis. But, the weight of each floor is constant and assumes 12,500kN.

Table 2 Results of the Eigen value analysis

BIS Building A	BIS Building B	TLBIS
4.0 sec	6.0 sec	4.52 sec
4.5 sec	6.0 sec	5.01 sec
5.0 sec	6.0 sec	5.40 sec
4.0 sec	6.5 sec	4.59 sec
4.5 sec	6.5 sec	5.11 sec
5.0 sec	6.5 sec	5.55 sec

Table 2 indicates that by linking two base isolated models, the period of the TLBIS models is the around median value of both building models.

3・2 Response reduction effects of TLBIS with rigid springs under the Tokachi-oki earthquake

In this section, input earthquake ground motion is the Tokachi-oki earthquake and the yielding strength level α of the lead damper is 5% of all weights

($\alpha = Q_{dy}/\sum W$) and the response analysis results show two case combinations (4.0sec, 6.0sec) and (5.0sec and 6.0sec) Fig.3 shows the maximum relative displacement and absolute acceleration responses of the single base isolated models and TLBIS model. Here, the period of single base isolated models are given 4.0sec and 6.0sec corresponding to the Build A,B. Fig.3 indicates that the maximum displacement of the base isolation floor of Building A and B in BIS model are 62.7cm and 75.2cm and the maximum displacement becomes more than 300% (=60cm) of maximum shear strain of the rubber bearing under the maximum velocity 1m/s earthquake ground motions.

On the other hand, the displacement of the base isolation floor of Building A and B in the TLBIS model are 57.1cm and 57.6cm respectively. By the linked two base isolated buildings with rigid springs, the displacement of base isolation floor can be reduced to 0.77~0.91 times of the base isolated buildings and becomes less than 300% strain. As comparing with the absolute acceleration response, the acceleration response of base isolation floor Building A,B in BIS model are 271.8cm/s^2 and 212.1cm/s^2 respectively. On the other hand, these of TLBIS model are 227.9 cm/s^2 and 236.9 cm/s^2. By the linked two base isolated buildings, as shown the table.2, the period of the TLBIS model becomes 4.52sec and in the Building A, the acceleration response can be reduced 0.83 times of the BIS model,

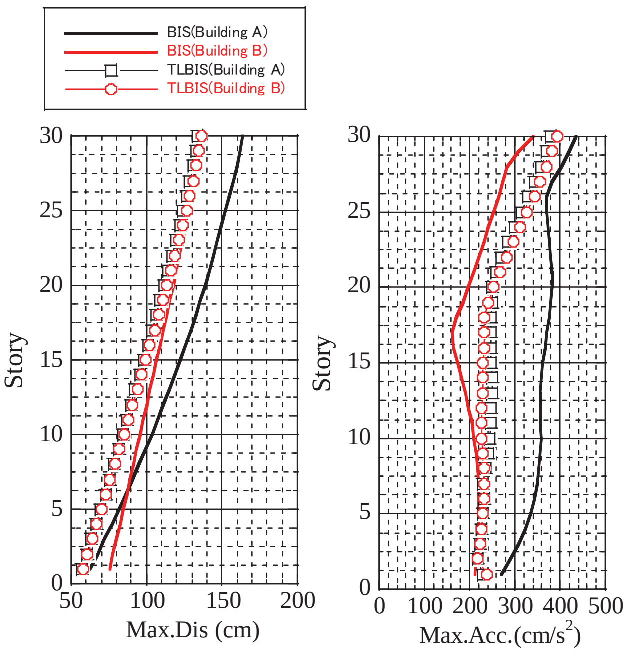

Fig.3 Response characteristics of the BIS and TLBIS with rigid spring models (T_A=4sec, T_B=6sec)

but, in the Building B, it's increasing to 1.12 times of the BIS model.

This is the reason why the period of Buildings B becomes a little shorter than one of the two linked base isolated buildings. Therefore, these responses of TLBIS model can be reduced than these of BIS model

Fig.4 shows these responses of BIS and TLBIS models when the natural period was assumed 5.0sec and 6.0sec. Fig.4 indicates that the maximum displacement of the base isolation floor of Building A and B in BIS model are 73.14cm and 75.2cm respectively. On the other hand, the displacement of the base isolation floor of building A and B in the TLBIS model are 79.56cm and 79.73cm respectively.

By the linked two base isolated buildings with rigid springs, the other way around, the displacement responses are increasing to 1.06~1.09 times of the base isolated buildings.

As shown the table.2, the period of the TLBIS model becomes 5.4 sec and this is because of the closely accordance with the predominate period of Tokachi-oki earthquake.

As comparing with the absolute acceleration response, the acceleration response of base isolation floor Building A,B in BIS model are 210.0cm/s^2 and 212.1 cm/s^2 respectively. On the other hand, these of TLBIS model are 214.5cm/s^2 and 214.5 cm/s^2. Therefore, it is understood that the acceleration response of BIS and TLBIS models aren't so much changed.

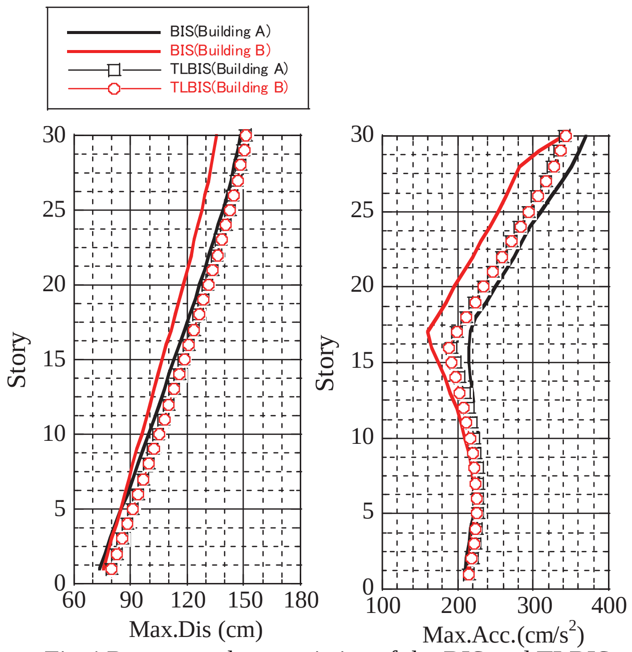

Fig.4 Response characteristics of the BIS and TLBIS with rigid spring models (T_A=5sec, T_B=6sec)

In the combination of the period shown the table.2, the results of the combination (T_A,T_B) equals to (4.5sec, 6sec),(4sec, 6sec) and (4.5sec, 6sec) tend to show the same result similar to Fig.3. On the other hand, (T_A,T_B) equals to (5sec, 6.5sec) tends to show the same result similar to Fig.4.

Therefore, it is concluded that, in the choice of the natural period of the linked base isolated buildings, it has to pay attention to the influence to give to the response reduction effects subjected to the long period earthquake ground motions.

3･3 Response characteristics of TLBIS with rigid springs under the Tohoku, Kobe and BCJWL2 earthquakes

Fig.5 shows that the maximum relative displacement responses of the BIS and TLBIS models under Tohoku (K-NET Osaka), Kobe earthquake and the simulated wave BCJWL2. Here, the period of base isolated models are given 4.0sec and 6.0sec as well as Fig.3 corresponding to the Build A, B. But, in the Fig.5, the left figure shows the Building A of BIS and TLBIS models, and the right figure shows the Building B of these model.

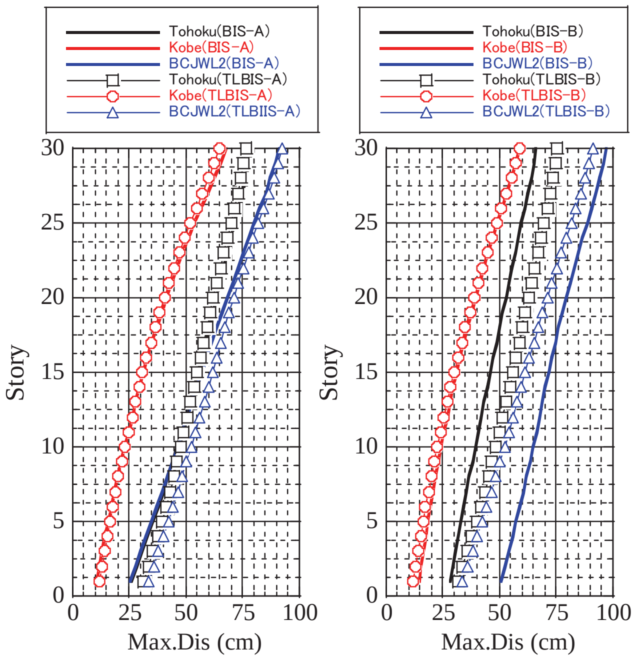

Fig.5 Response characteristics of the BIS and TLBIS with rigid spring models (T_A=4sec, T_B=6sec)

Fig.5 indicates that the displacement of the BIS and TLBIS models under Kobe and Tohoku (K-NET Osaka) earthquake haven't almost changed and the response reduction effects obtained by linked base isolated buildings are a few. But in the displacement of the BIS and TLBIS models under BCJWL2 earthquake, the displacement response of the Building B is 50.5cm and 33.7cm respectively. By the linked two base isolated buildings with rigid springs, the displacement of base isolation floor can be reduced to 0.67 times of the single base isolated buildings

4. Concluding Remarks

The severe and great earthquake such as the 2003 Tokachi-oki, the 2004 Kii peninsula southeast offshore and the 2011 of Pasific coast of Tohoku earthquakes are happened after the 1995 southern Hyogo prefecture earthquake. It's not too much to say that Japan often has entered a period earthquake activity. Recently, the long period earthquake has frequently observed. When the long period earthquake acts on the base isolated buildings, it is possible to occur a resonance phenomenon. This paper proposed two base isolated structural buildings with the linked rigid springs to avoid the resonance phenomenon due to the long period earthquake and discussed the seismic response reduction effects.

The knowledge of engineering obtained from the analytical results is as follows.

(1) Using two linked base isolated structural building with the rigid springs, the seismic response of the base isolation floor under long period earthquake can be reduced more than the response of the single base isolated building.

(2) In the choice of the natural period of the linked base isolated structural buildings, it has to pay attention to the influence to give to the response reduction effects subjected to the long period earthquake ground motions. In particular, when the period of the two linked base isolated buildings have a accordance with the predominate period of Tokachi-oki earthquake, the displacement response of the base isolation floor becomes really bigger than the one of the single base isolated buildings.

(3) The response reduction effects of two linked base isolated building are gotten to Tokachi-oki and BCJWL2 earthquakes, but the reduction effects aren't gotten to Tohoku and Kobe earthquakes.

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