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SEISMIC SAFETY OF SANDWICH BASE ISOLATED BUILDINGS UNDER SIMULATED NANKAI TROUGH EARTHQUAKE

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Abstract

After 1995 Southern part of Hyogo prefecture earthquake, the far field and near field earthquakes have occurred frequently. The probability of Nankai Trough earthquake which is occurred from 2030 to 2035 is about 70-80 %. In that case base isolated structural buildings are subjected to far-field long period earthquake, it's said that these buildings are likely to be in resonance with the natural period of base isolated buildings and the predominant period of this earthquake. Therefore, the base isolation floor might be deformed excessively and collide with the retaining wall around the foundation.

To avoid a resonance phenomenon of base isolated structure under long period earthquake ground motions, this paper discuss and presents the seismic safety and the seismic response reduction effects of the sandwich based isolated buildings under the long period earthquakes. The sandwich base isolated buildings are the hybrid base isolated buildings which have installed in base isolation and mid-story base isolation layers. The upper structural models assume 38 stories of steel structure. Sandwich base isolated models assume 40 stories. In this paper, it thinks two type far field earthquake as the ground motion models. One is 2003 Tokachi-oki earthquake observed in K-NET Tomakomai. Another is the simulated Nankai trough earthquake. The Nankai trough earthquake models assume the Hoei or Ansei-Tokai earthquake fault models.

According to an analytical result, the maximum displacement of base and mid-story base isolation of the sandwich base isolated model can be reduced by about 50% of the single base isolated model. And the acceleration response of sandwich base isolated models is as same as the base isolated model under mid-story base isolation and can be quite reduced the response on the floor above the mid-story base isolation layer.

Keywords: Sandwich base isolated buildings, Simulated Nakai trough earthquake, Long period ground motion, Seismic safety, Response reduction effects of base isolation floor

1. Introduction

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 earthquakes such as the 2003 Tokachi offshore and the 2011 off Pacific coast of Tohoku earthquakes are happened after the 1995 southern of Hyogo prefecture earthquake. The probability of Nankai Trough earthquake which is occurred from 2030 to 2035 is about 70-80 %. It's said to be in resonance with the natural period of base isolated buildings and the predominant period of this earthquake. As a previous study1),2) , it's examined the response effect of the super-high-rise buildings under Nankai trough coupling earthquakes by Dr. Okawa and Sato etc. And it's examined the response reduction effect of multi-base isolated structure (MBIS) under far-field and near field earthquakes by Dr. Tsuji. According to the analysis results, it's clear the natural frequency characteristics and seismic response of MBIS by choosing the location of mid-story base isolation and the stiffness and damping of base isolation device correctly. It's shown the efficiency of MBIS.

As a way of avoiding the resonance phenomenon, we discuss the seismic response reduction effect of sandwich base isolated building under the simulated Nankai Trough earthquake. The simulated Nankai trough earthquake waves assume the Hoei or Ansei-Tokai earthquake fault models. Two base isolated buildings are sandwich models which have installed in base isolation and mid-story base isolation layers. The upper structural models assume 38 stories of steel structure. Sandwich base isolated models assume 40 stories. The long period earthquake models are 2003 Tokachi-oki earthquake (K-Net Tomakomai) as an observed wave of long period earthquake and the simulated Nankai Trough earthquake models using ARTEQ-LP[3)].

2. Earthquake Response Analysis of the Sandwich base isolated models

2.1 Analytical model and input ground motion models

In this paper, we think the sandwich base isolated models which have located the rubber bearings with lead damper (hereafter, LRB) in base isolation and mid-story base isolation layers of 38 stories steel structural office building. This floor area is 2,268 m^2.

Fig.1 shows the sandwich base isolated structural models. The sandwich base isolated models is composed from base isolation devices (LRB) which have installed in base and mid-story layer, seismic structure of upper structure buildings above foundation and mid-story base isolation layers. The relationship of load and displacement of LRB is bi-liner type hysteretic characteristics.

In which, m_i, r_1k_1, r_ik_i, k_{i-1}, c_{i-1} are mass of i-th floor, the elastic stiffness of the rubber bearing of base isolation and mid-story layers, the stiffness of the upper structural models and viscous damping coefficients respectively.

In this paper, the story number of the single base isolated and sandwich base isolated models are 39 and 40 stories respectively.

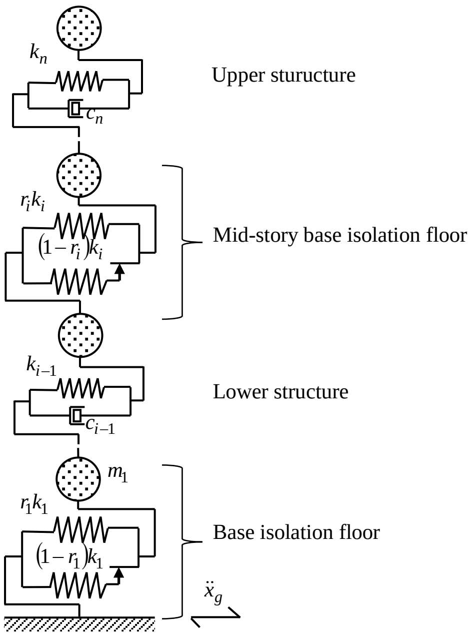

Fig.1 Sandwich base isolated models

On the other hand, the input ground motion models are Tokachi-oki earthquake (K-NET Tomakomai NS component) as the observed wave of long period earthquake models and the simulated Nankai Trough earthquake models created by the reference 1) and 3) as the simulated earthquake models, hereafter referred Hoei Nankai Trough earthquake. Fig.2 shows the source region model of Hoei Nankai trough earthquake. This earthquake is the simulated ground motion models created in Konohna-ku in Osaka. The reason that we selected Konohana-ku is the observation site cited in Reference 1). 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.

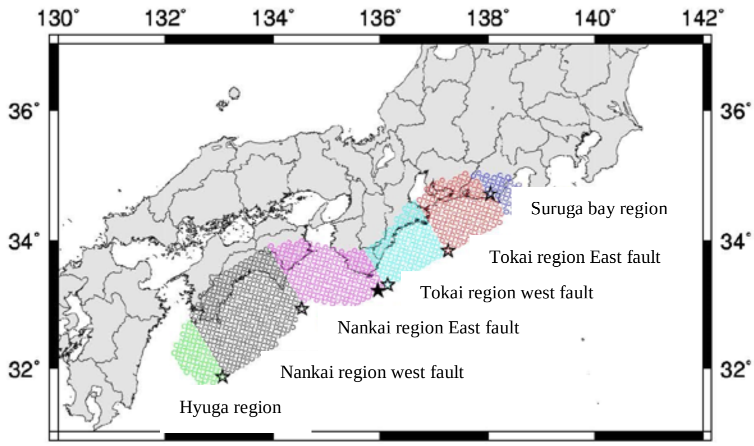

Fig.2 Source region model of Hoei Nankai trough earthquake [1),3)]

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 (Tomakomai NS)	86.74	32.55	266.48
Hoei Nankai (Konohana)	63.75	38.99	163.50

Fig.3 shows the ground motion waves of Tokachi-oki and Hoei-Nankai trough earthquakes. The velocity response spectrum of the Tokachi-oki and Hoei-Nankai trough earthquakes are shown in Fig.4. As shown the Fig.4, the predominate period of the Tokachi-oki earthquake becomes about 3.5, 5.2 and 7.1 sec and the period of the Hoei Nankai trough earthquake becomes from 6.0 to 7.2 sec. Fig.2 also indicates that the Tokachi-oki and Hoei Naknkai trough earthquakes are long period earthquake ground motions.

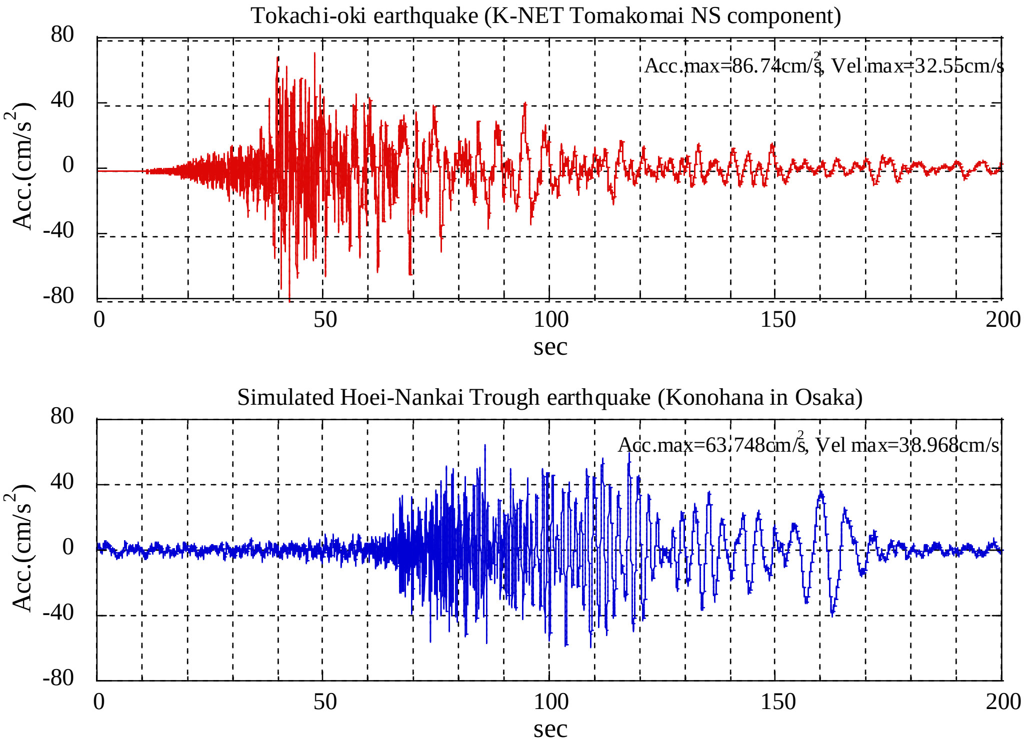

Fig.3 Ground motion waves of Tokachi-oki and Hoei Nankai trough earthquakes

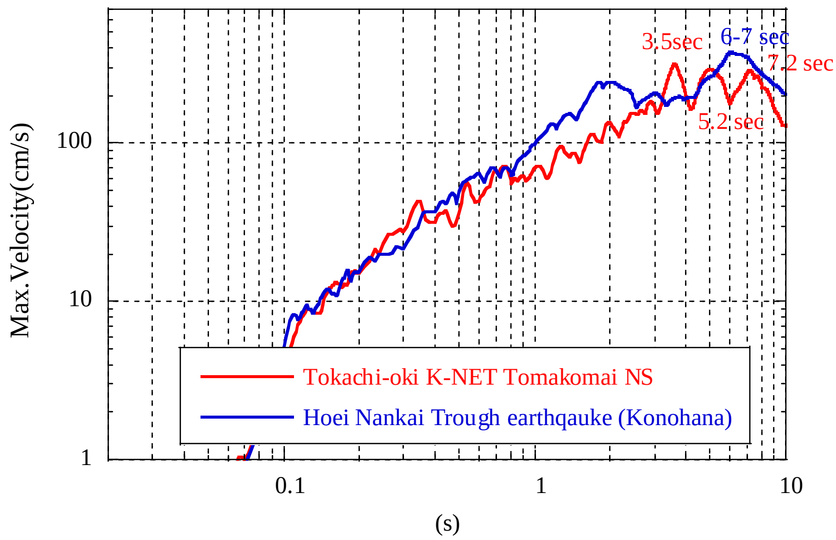

Fig.4 Velocity response spectrum of Tokachi-oki and Hoei Nankai trough earthquakes

2.2 Equation of Motion and State Equation of the two base isolated systems

In the sandwich base isolated models which are shown in Fig.1, the equation of motions of these models can be expressed as the following equations.

Top floor :

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

Mid-story base isolation floor :

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

Second floor :

$$m_2(\ddot{u}_1 + \ddot{u}_2 + \ddot{x}_g) + c_2\dot{u}_2 - c_3\dot{u}_3 + k_2 u_2 - k_3 u_3 = 0 \tag{3}$$

Base isolation floor :

$$m_1(\ddot{u}_1 + \ddot{x}_g) - c_2\dot{u}_2 + r_1 k_1 u_1 - k_2 u_2 + (1 - r_1)k_1 y_1 = 0 \tag{4}$$

In which, $m_i, u_i, y_i, \ddot{x}_g$ are mass of any i-th floor, inter-story displacement response of base isolation and upper structure layer, the displacement one of coulomb slip element composed of the base isolation floor and the earthquake input motions exciting a base layer respectively.
And the inter-story velocity of the coulomb slip element $\dot{y}_i$ can be expressed as the following equations.

$$\dot{y}_i = \frac{\dot{u}_i}{4}\left[2 + \mathrm{sgn}(y_i + \delta_i) - \mathrm{sgn}(y_i - \delta_i) - \mathrm{sgn}(\dot{u}_i)\{\mathrm{sgn}(y_i + \delta_i) + \mathrm{sgn}(y_i - \delta_i)\}\right] \tag{5}$$

In which δ_i is the yield displacement of the lead damper into LRB of equation (5).

Using from equation (1) to (5), the fundamental equations can be expressed as the following equations.

$$\{\ddot{u}\} + [\tilde{c}]\{\dot{u}\} + [\tilde{k}]\{u\} + \{\tilde{k}'\}\{y\} = -\{1'\}\ddot{x}_g \tag{6}$$

In which $\{u\}$ is an inter-story drift response vector, $[\tilde{k}], [\tilde{c}], [\tilde{k}']$ are respectively matrices associated with the stiffness, viscous of upper structure models and the stiffness of base isolated models and $\{1'\}$ is a vector having unit only for the lowest element. $\{y\}$ is a velocity movement vector of the Coulomb slip.

Selecting the response vectors $\{U\} = \{\{u\}, \{\dot{u}\}, \{y\}\}^T$ of the sandwich base isolated models as state variable vectors, Equation (6) can be rewritten in a more simple form as.

$$\frac{d}{dt}\begin{Bmatrix}\{u\}\\ \{\dot{u}\}\end{Bmatrix} = \begin{bmatrix}[0] & [E] & [0]\\ -[\tilde{k}] & -[\tilde{c}] & -[\tilde{k}']\end{bmatrix}\begin{Bmatrix}\{u\}\\ \{\dot{u}\}\\ \{y\}\end{Bmatrix} + \begin{Bmatrix}\{0\}\\ -\{1'\}\end{Bmatrix}\ddot{x}_g \tag{7}$$

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

The responses $\{u\}, \{\dot{u}\}$ are obtained step by step using the fourth-order accuracy Runge-Kutta method [4)].

3. Numerical Example

In this paper, the first natural period of the upper structural buildings assumes 3.8 sec. For example, the stiffness ${}_bk_I$ of the rubber bearing will be determined so that the first natural period of the single base isolated model becomes 6.0 sec by a convergence calculation. The stiffness ${}_bk_I$ of the rubber bearing of base isolation layer of sandwich base isolated model is the same value of single base isolated model. The stiffness ${}_bk_I$ of the rubber bearing of mid-story base isolation layer will be determined so that the first natural period becomes from 4.5 to 6.0 sec by a convergence calculation. But the weight of any i-floor is constant 12,474kN. the yielding strength level α_B of the lead damper into LRB is 5% of all weights and the α_m is 5% of above 10 stories weights.

3.1 The response characteristic of single and sandwich base isolated models under Tokachi-oki earthquake

Fig.5 shows the maximum displacement response of base isolation layer and mid-story base isolation layer when the first natural period T_B of base isolation floor assumes 6.0 sec and the period T_m of mid-story base isolation layer is changed from 4.5 sec to 6.0 sec. Therefore, Fig.5 also shows the first natural period T_L which has obtained by the Eigen value analysis. As shown the Fig.5, as the period of mid-story base isolation floor has increased, it can be seen that the displacement response of base isolation layer is reduced, on the other hand, the displacement response of mid-story base isolation layer is increased from 29.34 cm to 45.60 cm. the first natural period of mid-story base isolation layer that matches the criteria of maximum displacement of rubber bearing 40cm (maximum strain 200%) defined in this paper is 5.4 sec. On the other hand, as the period T_m of mid-story base isolation floor has increased, it can be seen that the period of T_L of the sandwich base isolated models become from 6.85 sec to 7.89 sec. When the period of base isolation and mid-story isolation layers assume 6.0 sec and 5.4 sec respectively, the first natural period T_L of sandwich base isolated models become 7.46 sec from Fig.3.

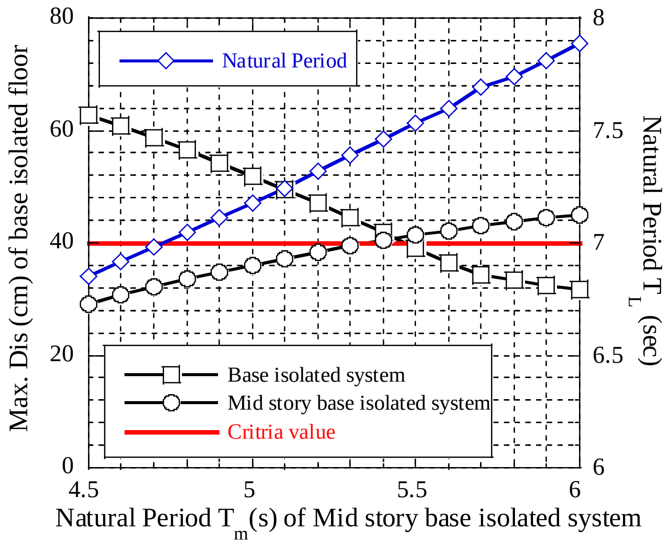

Fig 5 Correlation of maximum displacement response and natural period between base isolation and mid-story base isolation layers

Fig.6 shows the maximum displacement and absolute acceleration response of the single base isolated model and sandwich base isolated model when it selected 6.0 sec and 5.4 sec as the natural period's combination of the base isolation and mid-story base isolation layers respectively. As shown Fig.6, the displacement of the base isolation layer of the single base isolated model is 91.73 cm, while these response of sandwich base isolated model are 41.89 cm and 40,57 cm respectively. It can be reduced up to about 44 % of the maximum displacement response of the single base isolated model.

On the other hand, the acceleration of sandwich base isolated model is almost same value up to 4 stories including the base isolation floor of the single base isolated model but it can be seen that it is greatly reduced in the higher stories.

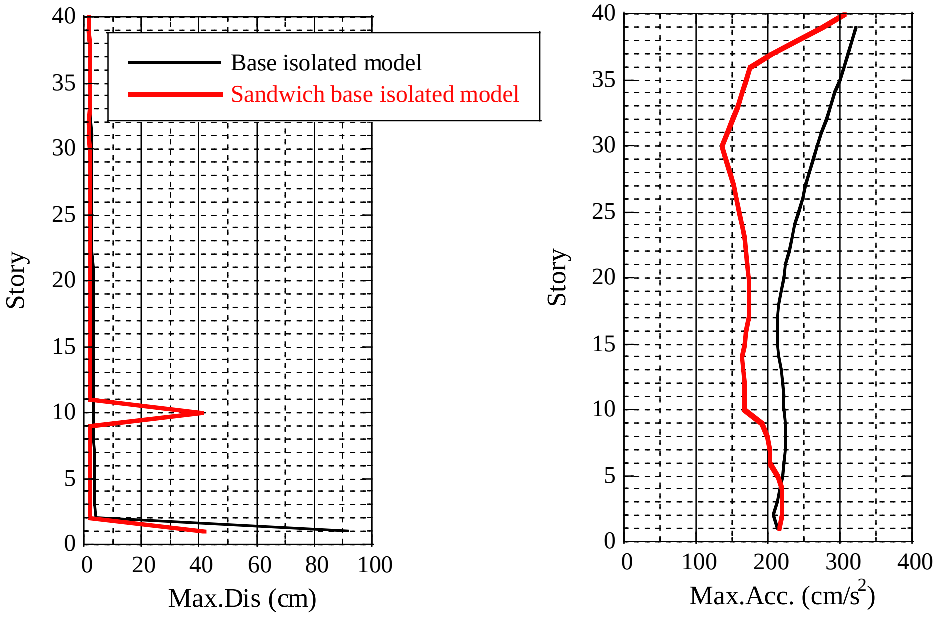

Fig 6 Response characteristics of the single base isolated and sandwich base isolated models under Tokachi-oki earthquake ground motion (K-NET Tomakomai NS)

Hence, considering the relative displacement response base isolation and mid-story base isolation layers, the value becomes 82.46 cm. In this paper, since the earthquake response analysis is conducted using the equivalent shear type model shown in Fig. 1, it is considered that the inter-story displacement response of the base isolation layer distributed in two stories moves in the horizontal direction. It doesn't take into account the bending deformation and P-δ effect of the high-rise buildings. In that case inter-story displacement response of base isolation layer exceeds 50 cm, we have to consider the seismic safety of base isolated building. It's used a mechanism[5), 6)] that provides stoppers inside and outside the laminated rubber bearing in practical structural design field.

3.2 The response characteristic of single and sandwich base isolated models under Hoei-Nankai Trough earthquake

When the Konohana wave (OSKH02) simulating the seismic center model of the Hoei-Nankai earthquake shown in Table 1 and Fig. 3 is analyzed with the same parameters as Fig. 6, the maximum displacement response of the base isolation system model exceeds 1m. In this section, viscous dampers (C '= 400kNs / cm) are added to the base isolation and the mid-story isolation layers.

Fig.7 shows the maximum displacement and absolute acceleration response of the single base isolated model and sandwich base isolated model under the Hoei- Nankai trough earthquake. As shown Fig.7, the displacement of the base isolation floor of the single base isolated model is 93.28 cm, while these response of sandwich base isolated model are 51.02 cm and 47.69 cm respectively. It can be reduced up to about 51 % of the maximum displacement response of the single base isolated model.

On the other hand, the acceleration of sandwich base isolated model is almost same value up to 12 stories including the base isolation floor of the single base isolated model but it can be seen that it is greatly reduced in the higher stories like the analytical results under Tokachi-oki earthquake.

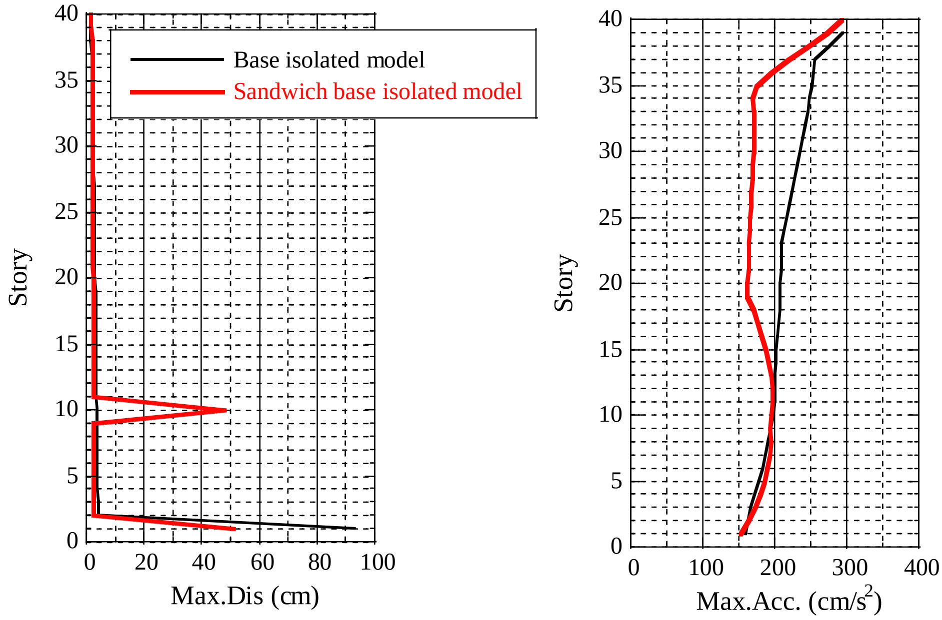

Fig 7 Response characteristics of the single base isolated and sandwich base isolated models under Hoei-Nankai Trough earthquake ground motion (Konohana wave)

4. Concluding

The severe and great earthquake such as the 2003 Tokachi-oki, the 2004 Kii peninsula southeast offshore and the 2011 of Pacific 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. The probability of Nankai Trough earthquake which is occurred from 2030 to 2035 is about 70-80 %.When the long period earthquake acts on the high rise base isolated buildings, it is possible to occur a resonance phenomenon and the base isolation floor might be deformed excessively and collide with the retaining wall around the foundation.

In this paper, we proposed the sandwich base isolated structure which mixed base isolated and mid-story base isolated structures as the long period ground motion measures. We discussed the seismic safety and response reduction effect of the sandwich base isolated buildings under Tokachi-oki (2003) earthquake (K-NET Tomakomai NS wave) and the simulated Nakai Trough earthquake.

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

(1) The first natural period of the sandwich base isolation structural model can be longer than the period of the single basic base isolation structural model.

(2) By arranging the base isolation layer in two layers, the excessive deformation of the base isolation layer can be suppressed, and the maximum inter-story displacement response is about 0.45 to 0.5 times that of the base isolation structural model.

(3) The maximum displacement response of the upper structure in the sandwich isolation system is less than the maximum displacement response of the basic isolation model.

(4) The absolute acceleration response of the sandwich isolation structure is less than the response of the single basic isolation model under the Tokachi-oki earthquake. On the other hand, in the simulated Hoei-Nankai earthquake, the acceleration response lower than mid-story base isolation layer (10th floor) is almost the same as the single basic isolated model, but it is lower than the upper layer.

5. References

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