B. Answer Sheet (JAPAN)

B1. Selection and Layout of Devices

Figure 1 shows the layout of isolation devices for the benchmark building. To make the gravity center and stiffness center close, the bearings are located under every column, and the total yield force of the dampers is set to 4 to 5 % of the weight of the superstructure. Dimensions and characteristics of the isolation devices are shown in Table 1 and 2. These devices were selected to support the vertical stress caused by the superstructure almost at the standard face pressure of each device.

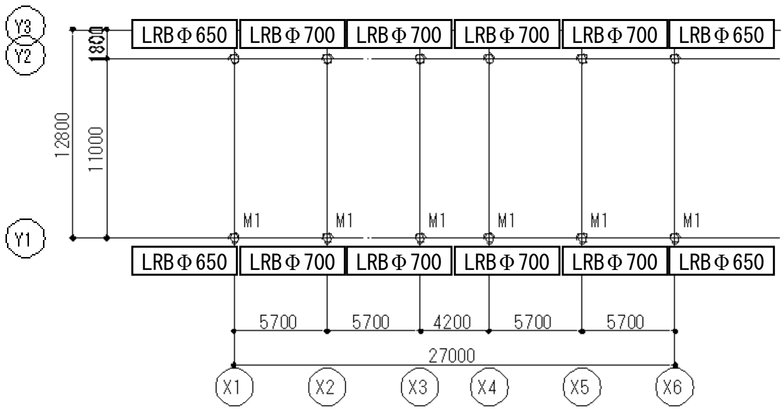

Figure 1 Layout of isolation devices

Table 1 Dimensions of isolation devices

	LRB ϕ650	LRB ϕ700
Material	Natural rubber	Natural rubber
Shear modulus of rubber (N/mm^2)	0.39	0.39
Exterior diameter of rubber (mm)	650	700
Interior diameter of lead plug (mm)	140	150
Thickness of rubber (mm)	159.6	162.0
	4.2 thick ×38	4.5 thick ×36
Primary shape factor S_1	38.7	38.9
Secondary shape factor S_2	4.1	4.3
Number of bearings	4	8

Table 2 Characteristics of isolation devices

		LRB ϕ650	LRB ϕ700
Horizontal stiffness (kN/m)	Initial stiffness K_1	10,695	12,217
	Secondary stiffness K_2	823	940
Yield load (kN)		122.7	140.9
Yield displacement (m)		0.0115	0.0115

B2. Design Performance Criteria

1) Determination of design displacement limit at isolation interface

The design displacement limit, δ_s, at the isolation interface is determined as the minimum value of the design displacement limit ${}_m\delta_d$ for all components of the isolation system. The design displacement limit ${}_m\delta_d$ for each device is obtained by multiplying the safety factor β by the ultimate deformation δ_u for each device. The value of the safety factor β is based on empirical knowledge resulting from experimental data obtained in Japan. A typical example of determining ${}_m\delta_d$ for an elastomeric isolator is shown in Figure 2. This figure shows that the bearing must be designed within the limits of vertical stress, horizontal displacement, and limitation by buckling of bearing. In this figure, ultimate deformation δ_u is derived from 1/3 of ultimate vertical design strength σ_0. For typical devices, safety factors are given as follows:

β =0.8, for elastomeric isolator;

β =0.9, for sliding bearing and rotating ball bearing;

β =1.0, for damper and restorer.

Table 3 shows the ultimate displacement of isolation devices and resulting design displacement limit in this example.

Table 3 Design displacement limit of each isolation device and isolation interface

	LRB ϕ650	
	Rubber bearing	Lead plug
Ultimate deformation δ_u (m)	0.52	0.70
Safety factor β	0.80	1.00
Design displacement limit ${}_m\delta_d$ (m)	0.416	0.70
Design displacement limit of isolation interface δ_s (m)	0.416	

Note: ${}_m\delta_d = \beta \cdot \delta_u$

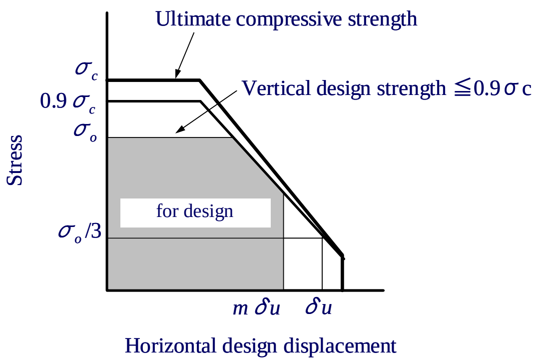

Figure 2 Example of design displacement limit

2) Design performance criteria

Table 4 Design performance criteria

	Criteria	Results
Overall response displacement of isolation interface	0.416 (m)	0.38 (m)
Minimum isolation gap	0.6 (m)	0.58 (m)
Base shear coefficient of superstructure	0.2	0.176

B3. Input Earthquake Ground Motion

1) Determination of input earthquake ground motion

The standard acceleration response spectrum S_0 of 5% damping at so-called engineering bedrock is given as shown in Figure 3, which corresponds to an earthquake with approximately a 500 year return period. The input ground level acceleration spectrum is given as follows:

$$S'_a = ZG_sS_0 \qquad [1]$$

where Z denotes seismic zone category factor(0.7-1.0), G_s is Amplification factor.

Amplification factor G_s is calculated based on the soil properties above engineering bedrock either by the simplified method according to the soil classification of first to third, or by the precise method calculated by using the wave propagation procedure considering the non-linearity of. Figure 4 shows the three types of the amplification factors defined by the simplified method.

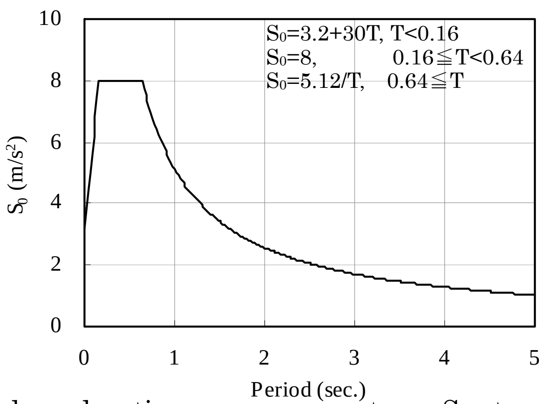

Figure 3 Standard acceleration response spectrum S_0 at engineering bedrock

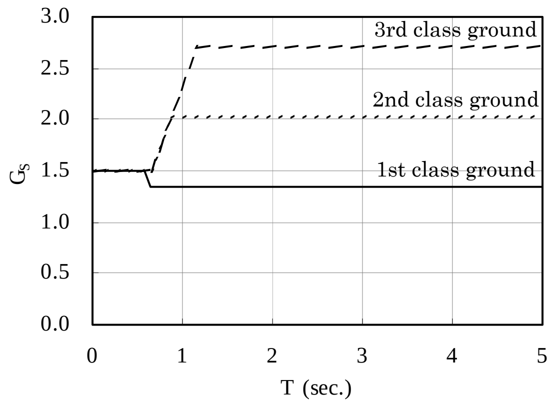

Figure 4 Amplification factors defined by the simplified method

2) Determination of soil amplification factor at the construction site

1st class ground is considered for the construction site of the benchmark building. Thus, the subsurface layers are stiff enough and predominant period of the ground is 0.2 seconds or less.

The soil amplification factor G_s is shown in Figure 4.

B4. Verification of response values

1) Response calculation procedure

a) Structural model

The shear force-displacement relationship of the seismic isolation interface is assumed to be bi-linear based on the properties of isolators and dampers to be utilized at the layer as shown in Figure 5. The maximum design displacement, δ_s , is defined by design engineers by referring to the properties of devices. Then, seismically isolated buildings are considered to be a single degree of freedom system with a mass of superstructure, M and equivalent stiffness, K_{eq} at δ_s as shown in Figure 5. A design equivalent period is defined as follows:

$$T_s = 2\pi\sqrt{M/K_{eq}} \text{ (s)} \quad [2]$$

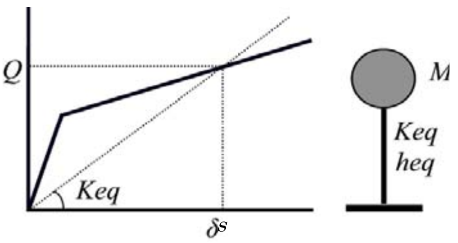

Figure 5 Model of structure with seismic isolation (single-degree of freedom system)

2) Calculation of natural period at design displacement limit

Figure 6 shows the overall shear force-displacement relationship of the isolation interface in this example. The equivalent stiffness and natural period T_s at design displacement limit 0.416 m are calculated as follows:

$$K_{eq} = \frac{6{,}116}{0.416} = 14{,}701(\text{kN/m})$$

$$T_s = 2\pi \cdot \sqrt{M / K_{eq}} = 3.09(\text{s})$$

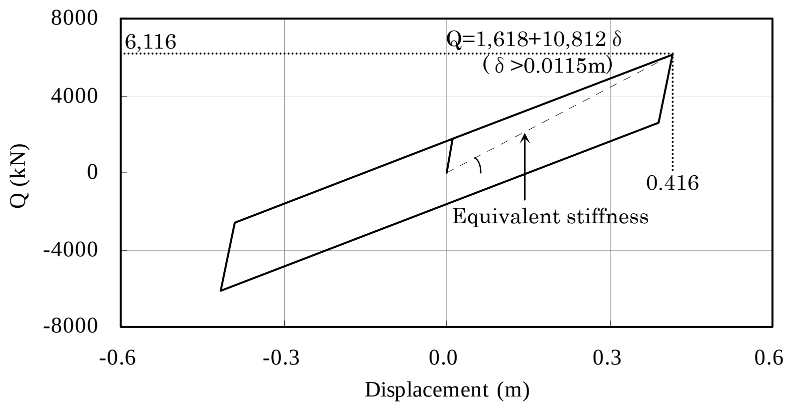

Figure 6 Force-displacement relationship of isolation interface

3) Demand acceleration response spectrum

The demand acceleration response spectrum is determined as follows:

$$S_a = F_h S'_a \quad [3]$$

where F_h denotes reduction factor of response acceleration due to the damping of the seismically isolated layer. The reduction factor for the response acceleration, F_h, is calculated by using the equivalent viscous damping factor of a fluid damper, h_v, and a hysteretic damper, h_d, at δ_s as follows:

$$F_h = \frac{1.5}{1+10(h_v + h_d)} \quad [4]$$

The ratio of the absorbed energy of the damper to the potential energy of the isolator and damper is defined as h_d.

$$h_d = \frac{0.8}{4\pi}\frac{\Sigma \Delta W_i}{\Sigma W_i} \quad [5]$$

where ΔW_i :absorbed energy and W_i the potential energy. Numeral constant (0.8) of Equation [5] is the reduction rate of the non-steady state to steady state vibration.

The ratio of the damping coefficient at the equivalent velocity of fluid damper (V_{eq}) to the critical damping coefficient of the seismic isolation system is defined as h_v. Equivalent velocity is a pseudo velocity obtained by multiplying the circular frequency and design displacement.

$$h_v = \Sigma \frac{C_{vi}}{2\sqrt{M \cdot K_{eq}}} = \frac{1}{4\pi} \cdot T_s \cdot \Sigma \frac{C_{vi}}{M} \quad [6]$$

where, $C_{vi} : (C_{eq})$ equivalent damping coefficient at equivalent velocity of fluid damper,

Equivalent velocity is

$$V_{eq} = 2\pi \cdot \delta_s / T_s \quad \text{(m/s)} \quad [7]$$

where, T_s : design equivalent period (s);

M : mass of superstructure,

δ_s : design displacement limit

In this benchmark building, no fluid damper is utilized. From the hysteresis shown in Figure 6, the equivalent damping factor of base isolation interface is calculated by restoring energy and absorbed energy as follows:

$$h_d = \frac{0.8}{4\pi} \cdot \frac{\sum \Delta W_i}{\sum W_i} = 0.8 \times \frac{2}{\pi} \frac{1{,}618(\delta - 0.0115)}{\delta(1{,}618 + 10{,}812\delta)} = 0.8 \times 0.164 = 0.131$$

Using h_d=0.131, the acceleration reduction rate is calculated as:

$$F_h = \frac{1.5}{1+10h_d}$$

$$= \frac{1.5}{1+10 \times 0.131} = 0.649$$

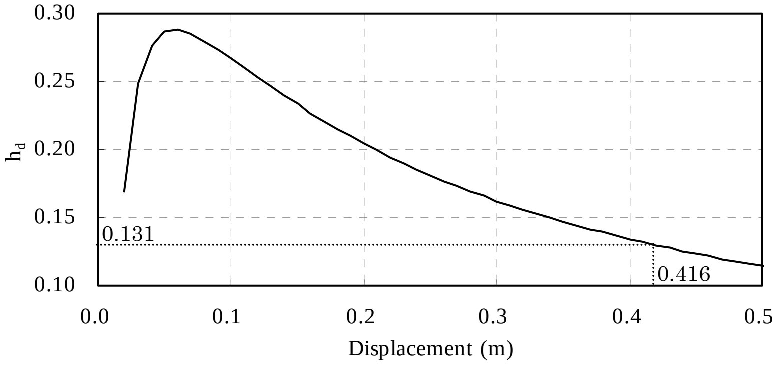

Figure 7 Displacement vs equivalent damping of isolation interface

2) Verification of response values

The response acceleration, ${}_eS_a$, is determined as the value of S_a at the corresponding natural period calculated by Equation [2]. The response displacement, ${}_e\delta$, at gravity center is determined as follows:

$$ {}_e\delta = {}_eQ / K_{eq} = \frac{M_e S_a}{K_{eq}} \quad [8] $$

where eQ is the shear force of the isolation interface, Keq is the equivalent stiffness of the isolation interface. Considering the layout of isolation devices, which cause eccentricities between the gravity center and stiffness center, the overall response displacement of the isolation interface, ${}_e\delta_r$, is obtained as follows:

$$ {}_e\delta_r = 1.1 {}_e\delta'_r < (\delta_s) \quad [9] $$

$$ {}_e\delta'_r = \alpha {}_e\delta \quad [10] $$

where α is safety factor for temperature dependent stiffness changes and property dispersions in manufacturing of devices (the minimum value is equal to 1.2) . The stress in the isolation devices and superstructure must be smaller than their strength and allowable stress, respectively. For the benchmark building, the soil amplification factor G_s at period T_s=3.09s is known to be 1.35 from Figure 4. Considering 0.64<T_s=3.09, shear force in the isolation interface ${}_eQ$ is calculated as:

$$ {}_eQ = \frac{5.12}{T_s} \cdot M \cdot F_h \cdot Z \cdot G_s $$

$$ = \frac{5.12}{3.09} \times 3{,}555 \times 0.649 \times 1.0 \times 1.35 = 5{,}161(\mathrm{kN}) $$

where seismic zone factor Z=1.0.

In Figure 8, the demand acceleration spectrum is converted into the shear force-displacement plane. In this figure, the overall shear force-displacement relationship of the isolation interface is also shown as a capacity spectrum. For the capacity verification of the isolation interface, ${}_eQ_r$ needs to be utilized. If there is a considerable difference between initially assumed K_{eq} at δ_s and at ${}_e\delta$, a few iterations of calculations would be required. The overall response displacement, ${}_e\delta_r$, calculated by Equation [9] in this example is verified as follows:

$$ {}_e\delta = \frac{{}_eQ}{K_{eq}} = \frac{5{,}161}{14{,}701} = 0.351(m) $$

$$ {}_e\delta_r' = \alpha_e\delta = 1.2 \times 0.351 = 0.421(m) $$

$$ {}_e\delta_r = 1.1_e\delta_r' = 1.1 \times 0.421 = 0.463(m) > \delta_S = 0.416 \quad \text{N.G.} $$

Iteration1

Using Figure 6, the equivalent stiffness and natural period at ${}_e\delta$ are calculated as follows:

$$ K_{eq} = \frac{5{,}413}{0.351} = 15{,}422(kN/m) $$

$$ T_s = 2\pi \cdot \sqrt{M / K_{eq}} = 3.02(s) $$

Using Figure 7, the equivalent damping factor for ${}_e\delta$ is as follows:

$$ h_d = \frac{0.8}{4\pi} \cdot \frac{\sum \Delta W_i}{\sum W_i} = 0.8 \times 0.184 = 0.147 $$

Using h_d=0.147, the acceleration reduction rate is calculated as:

$$ F_h = \frac{1.5}{1+10h_d} = \frac{1.5}{1+10\times 0.147} = 0.607 $$

$$ {}_eQ = \frac{5.12}{T_s} \cdot M \cdot F_h \cdot Z \cdot G_s $$

$$ = \frac{5.12}{3.02} \times 3{,}555 \times 0.607 \times 1.0 \times 1.35 = 4{,}942(kN) $$

$$ {}_e\delta = \frac{{}_eQ}{K_{eq}} = \frac{4{,}944}{15{,}422} = 0.320(m) $$

Iteration2

$$ K_{eq} = \frac{5{,}084}{0.320} = 15{,}859(kN/m) $$

$$ T_s = 2\pi \cdot \sqrt{M / K_{eq}} = 2.97(s) $$

$$ h_d = \frac{0.8}{4\pi} \cdot \frac{\sum \Delta W_i}{\sum W_i} = 0.8 \times 0.195 = 0.156 $$

$$ F_h = \frac{1.5}{1+10h_d} = \frac{1.5}{1+10\times 0.156} = 0.585 $$

$$ {}_eQ = \frac{5.12}{2.97} \times 3{,}555 \times 0.586 \times 1.0 \times 1.35 = 4{,}835(kN) $$

$$ {}_e\delta = \frac{{}_eQ}{K_{eq}} = \frac{4{,}835}{15{,}859} = 0.305(m) $$

Iteration3

$$ K_{eq} = \frac{4{,}914}{0.305} = 16{,}119(kN/m) $$

$$ T_s = 2\pi \cdot \sqrt{M / K_{eq}} = 2.95(s) $$

$$ h_d = \frac{0.8}{4\pi} \cdot \frac{\sum \Delta W_i}{\sum W_i} = 0.8 \times 0.202 = 0.161 $$

$$F_h = \frac{1.5}{1+10\times 0.161} = 0.574$$

$${}_eQ = \frac{5.12}{2.95}\times 3{,}555\times 0.575\times 1.0\times 1.35 = 4{,}779(\text{kN})$$

$${}_e\delta = \frac{{}_eQ}{K_{eq}} = \frac{4{,}779}{16{,}119} = 0.297(\text{m})$$

Iteration4

$$K_{eq} = \frac{4{,}824}{0.297} = 16{,}269(\text{kN/m})$$

$$T_s = 2\pi\cdot\sqrt{M/K_{eq}} = 2.94(\text{s})$$

$$h_d = \frac{0.8}{4\pi}\cdot\frac{\sum\Delta W_i}{\sum W_i} = 0.8\times 0.205 = 0.164$$

$$F_h = \frac{1.5}{1+10\times 0.164} = 0.568$$

$${}_eQ = \frac{5.12}{2.94}\times 3{,}555\times 0.568\times 1.0\times 1.35 = 4{,}750(\text{kN})$$

$${}_e\delta = \frac{{}_eQ}{K_{eq}} = \frac{4{,}750}{16{,}269} = 0.292(\text{m})$$

Iteration5

$$K_{eq} = \frac{4{,}775}{0.292} = 16{,}354(\text{kN/m})$$

$$T_s = 2\pi\cdot\sqrt{M/K_{eq}} = 2.93(\text{s})$$

$$h_d = \frac{0.8}{4\pi}\cdot\frac{\sum\Delta W_i}{\sum W_i} = 0.8\times 0.207 = 0.166$$

$$F_h = \frac{1.5}{1+10\times 0.166} = 0.564$$

$${}_eQ = \frac{5.12}{2.93}\times 3{,}555\times 0.564\times 1.0\times 1.35 = 4{,}735(\text{kN})$$

$${}_e\delta = \frac{{}_eQ}{K_{eq}} = \frac{4{,}735}{16{,}354} = 0.290(\text{m})$$

$${}_e\delta_r' = \alpha_e\delta = 1.2\times 0.290 = 0.347(\text{m})$$

$${}_e\delta_r = 1.1{}_e\delta_r' = 1.1\times 0.347 = 0.381(\text{m}) < \delta_S = 0.416 \quad \text{O.K.}$$

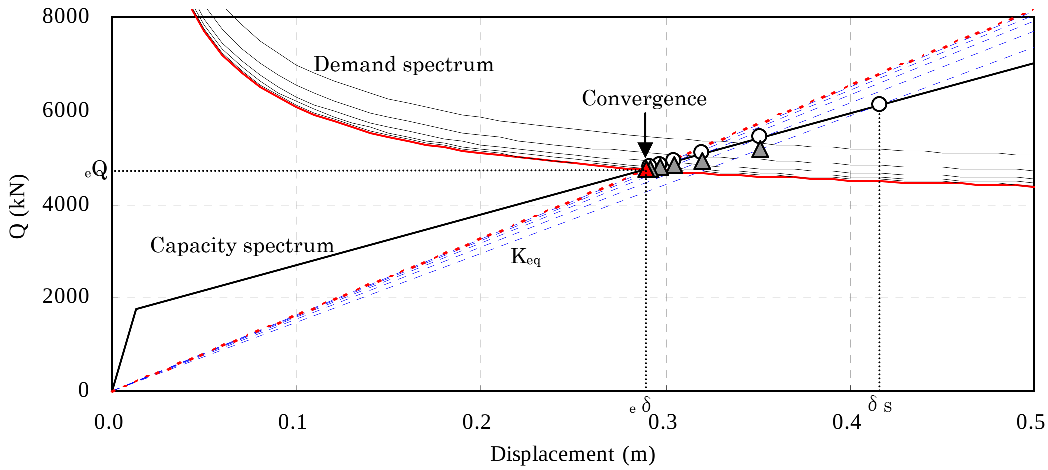

Figure 8 Demand spectrum and capacity spectrum of the seismic isolation interface

The isolation gap also needs to be verified. The isolation gap must be the larger value of 1.25 times the overall displacement or 0.20m plus the response displacement.

$$1.25{}_e\delta_r = 1.25 \times 0.381 = 0.476(\mathrm{m})$$

$$_e\delta_r + 0.20 = 0.381 + 0.20 = 0.581(\mathrm{m})$$

$$\max(1.25{}_e\delta_r, {}_e\delta_r + 0.20) = 0.581(\mathrm{m})$$

Thus, the designed isolation gap should be larger than 0.581m.

B5. Design of superstructure

1) Base shear coefficient of superstructure

Equation [11] provides the story-shear force distribution of the superstructure (C_{ri}: Design coefficient of story-shear force).

$$C_{ri} = \gamma \frac{\sqrt{(Q_h + Q_e)^2 + 2\varepsilon(Q_h + Q_e)Q_v + Q_v{}^2}}{M \cdot g} \times \frac{A_i(Q_h + Q_v) + Q_e}{Q_h + Q_v + Q_e}$$

$$= \gamma \frac{A_i Q_h + Q_e}{M \cdot g} \qquad (Q_v = 0) \tag{11}$$

where γ denotes Multiplier including the effect of aging, temperature, property dispersion by manufacturing of devices; Q_e represents shear force in elastomeric isolators; A_i is prescribed shear force distribution coefficient over the height of the superstructure; and Q_h is shear force in elasto-plastic dampers; and Q_v is shear force in fluid dampers; e:evaluation factor:

$$Q_v = \Sigma C_{vi} \cdot V \tag{12}$$

where the response velocity of the fluid damper $V = \lambda \cdot \omega \cdot \delta = \lambda\sqrt{(K/M)} \cdot \delta$; ω is circular frequency due to equivalent stiffness of seismic isolation system; λ is factor to high frequency component = 2.0.

In the force-displacement relationship between the seismic isolation system with an elastomeric isolator and fluid damper, the phase of shear force between the isolator and fluid damper becomes 90 degrees. The total maximum shear is given as follows by setting the evaluation factor (ε) equal to 0.

$$Q=\sqrt{Q_e^2+Q_v^2} \qquad [13]$$

When the displacement of the isolator and the fluid damper with relief system is 0, the phase of shear force between isolator and fluid damper does not become 90 degrees. The total shear is given as follows by setting evaluation factor (ε) equal to 0.5, which has been chosen from previous time history analyses and empirical knowledge.

$$Q=\sqrt{Q_e^2+Q_e\cdot Q_v+Q_v^2} \qquad [14]$$

In the force-displacement relationship in the seismic isolation system with sliding or rotating ball bearing and fluid damper, when the shared shear force of the isolator is constant, the total shear is simply a summation as follows, as evaluation factor (ε) equals 1.0.

$$Q=Q_e+Q_v \qquad [15]$$

In this example, using equation [11] adopting γ=1.3, the design shear force coefficient at the first floor is calculated as follows:

$$C_0=\gamma\frac{A_iQ_h+Q_e}{M\cdot g}=1.3\times\frac{4{,}735}{3{,}555\times 9.8}=0.176$$

B6. Limitation of design procedure

The above mentioned design procedure is applicable under the following conditions. Otherwise, a time history analysis must be conducted of the design.

a) Liquefaction is not expected at ground layers of the site.

b) Seismic isolation interface must be on or under the ground level.

c) Tangent period calculated from tangential stiffness (K_t) must be larger than 2.5 seconds. This period is set as the lower limit of the effective range for the seismic isolation system based on the data of aforesaid buildings.

$$T_t=2\pi\sqrt{(M/K_t)} \quad \text{(s)}$$

d) Eccentricity of the seismic isolation interface must be less than 0.03.

e) Shear coefficient of dampers must be larger than 0.03.

$$\mu=\frac{\sqrt{(Q_h+Q_e)^2+2\varepsilon(Q_h+Q_e)Q_v+Q_v{}^2}}{M\cdot g}\times\frac{Q_h+Q_v}{Q_h+Q_v+Q_e}\geq 0.03 \qquad [16]$$

f) No tensile stress is allowed in isolator units considering static vertical seismic coefficient ±0.3.

g) The maximum inter-story drift ratio of the superstructure above the isolation system should not exceed 1/300 of the design shear force.

h) Design for peripheral devices is also important, especially on the part of capitals or footings and beams or girders related to devices against shear forces and bending moments transmitted by devices.