Design Procedures of Response Spectrum Method and Time History Analysis of Seismic Isolation Buildings in Japan

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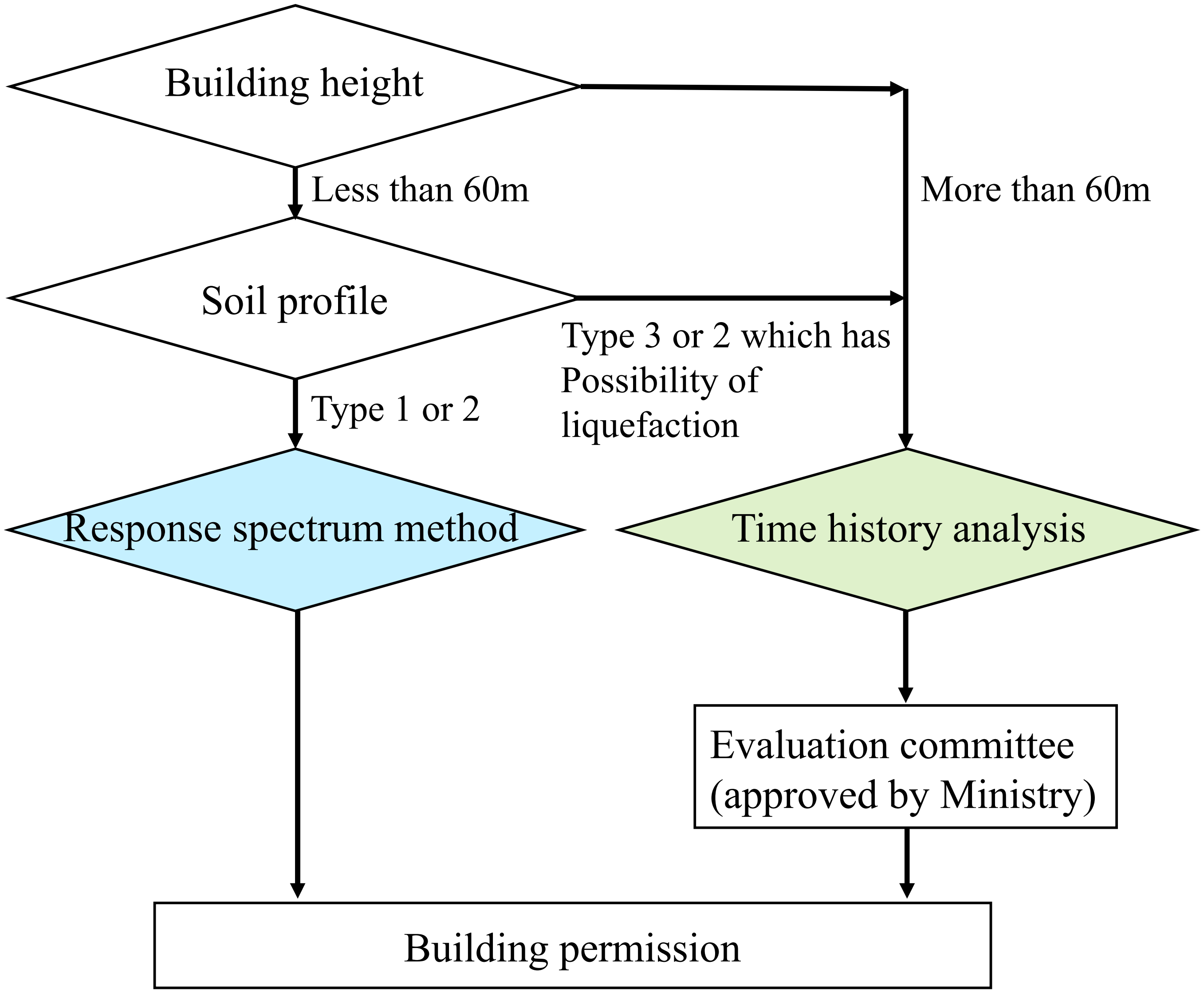
Design procedures of response spectrum method and time history analysis



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1. Introduction for target building
2. Response spectrum method (RSM)
3. Time history analysis (THA)

Building Introduction part 1: Outlook of the building

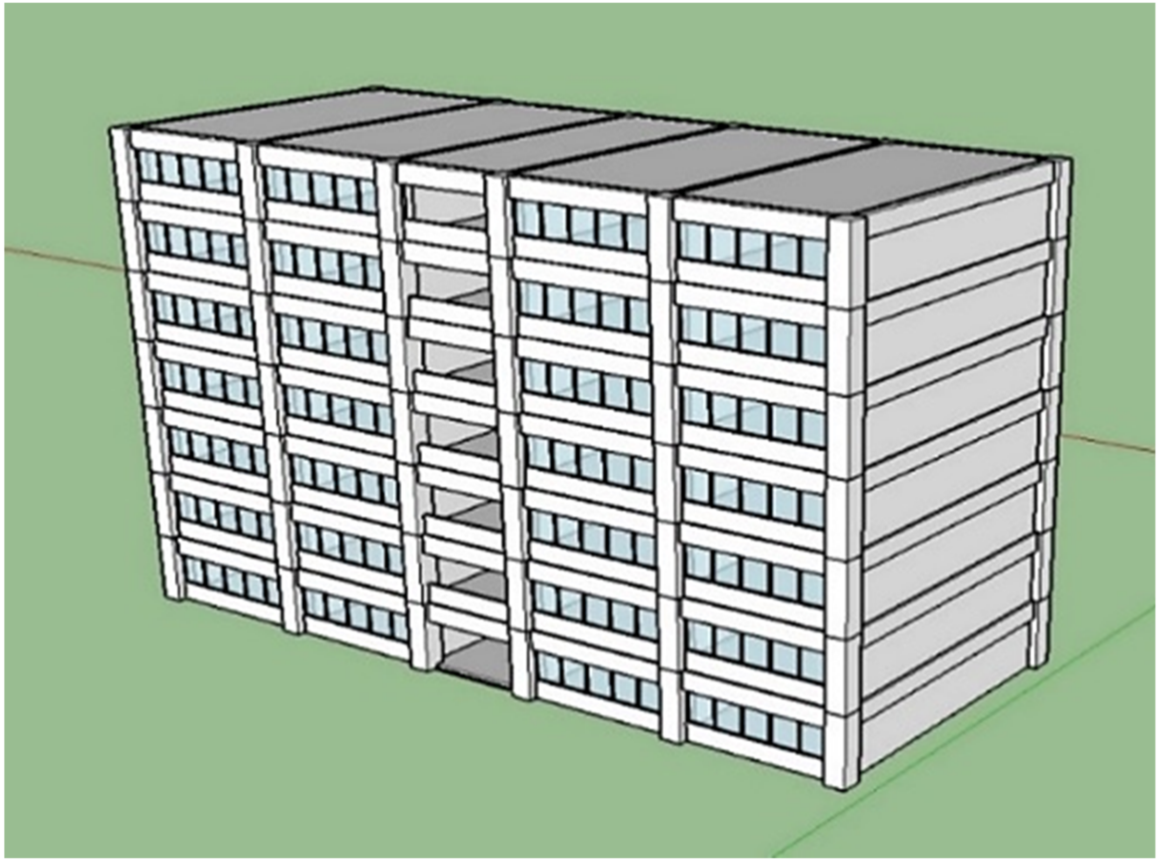


FIGURE.1 Target Building

Building Introduction part 2: Characteristic of the building

Table1: Building detail

Purpose	Condominium	
Total floor areas(m^2)	1950	
Maximum height(m)	23.6	
Sort of building	Reinforced concrete	
Structure type	X axis	RC flame
	Y axis	RC flame +RC wall
Basement	Cast in place concrete	

Table2:Building height and weight

Story	Height(mm)	Weight(kN)
7	3000	4410
6	3000	4165
5	3000	4165
4	3000	4165
3	3000	4214
2	3000	4214
1	3000	4214
i	1700	5292

Table3:Building stiffness

Story	Height (mm)	Horizontal stiffness (kN/mm)	
		X direction	Y direction
7	3000	951	3243
6	3000	2407	3553
5	3000	1242	5957
4	3000	1336	7950
3	3000	1457	10183
2	3000	1544	12966
1	3000	2005	12814

Table4:Materials strength of the building

Material	(N/mm^2)	
Steel bar	Main bar	345
	Stirrup	295
Concrete		24

Building Introduction part 3: Elevation plan

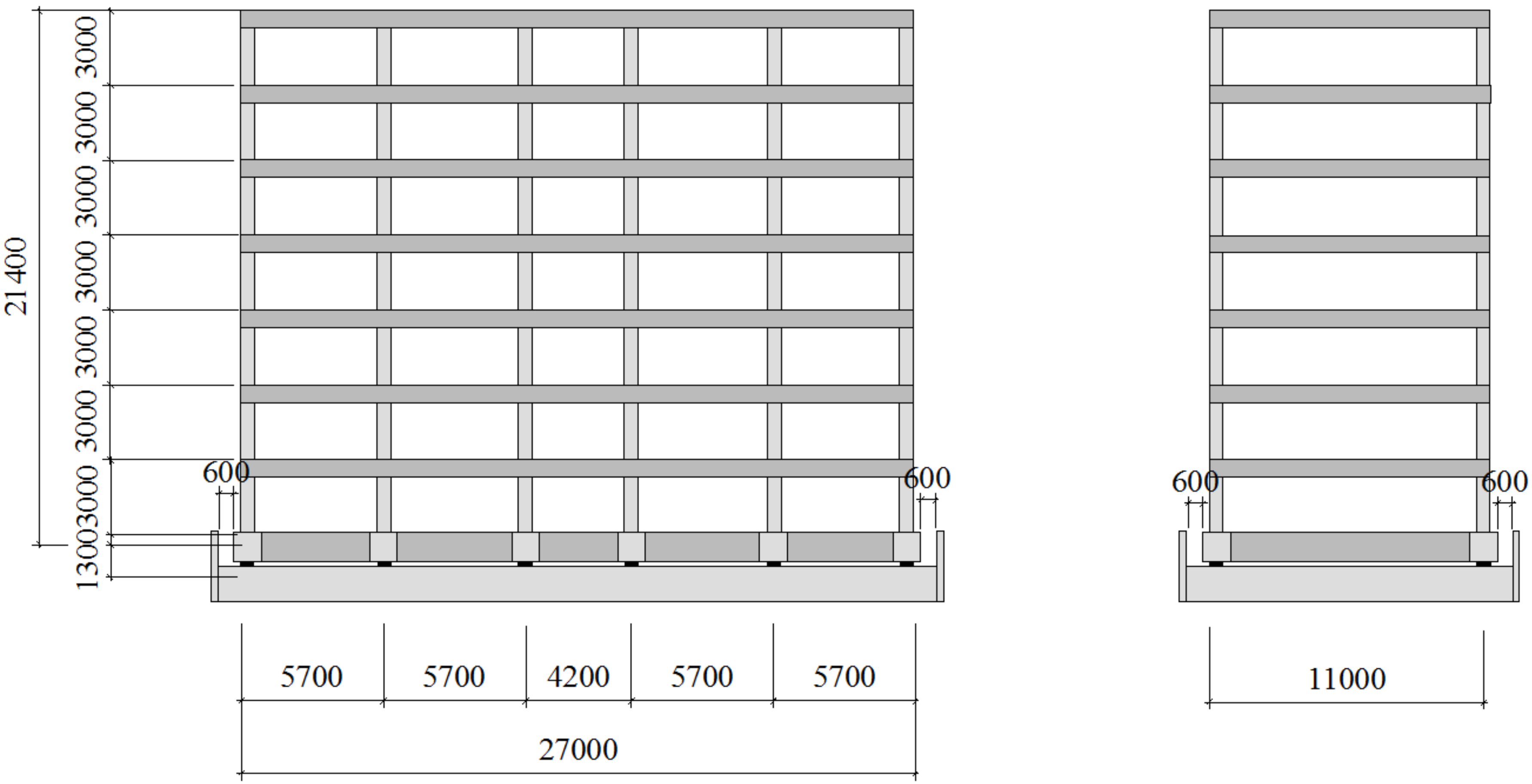
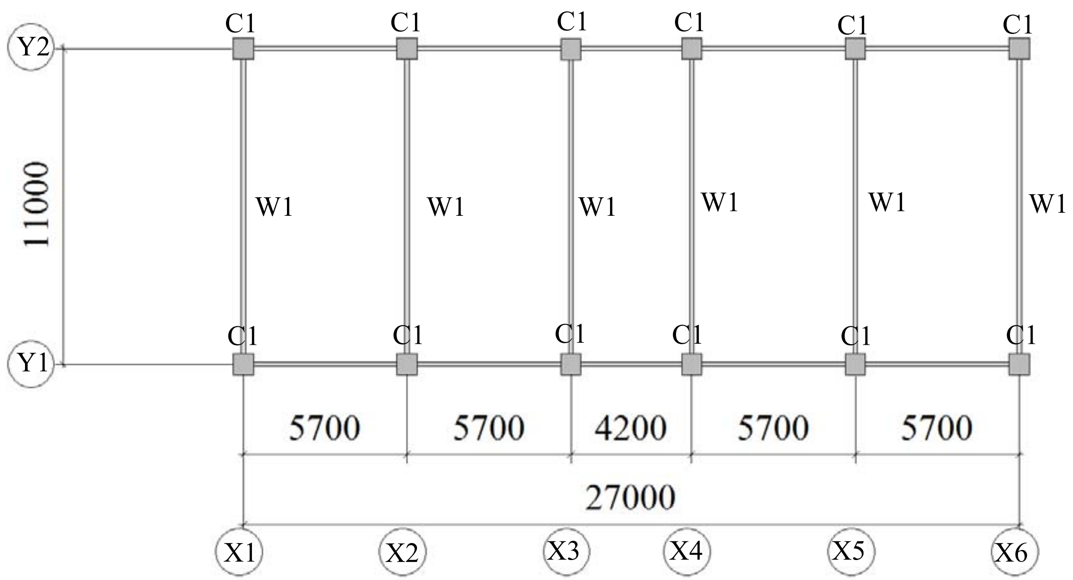
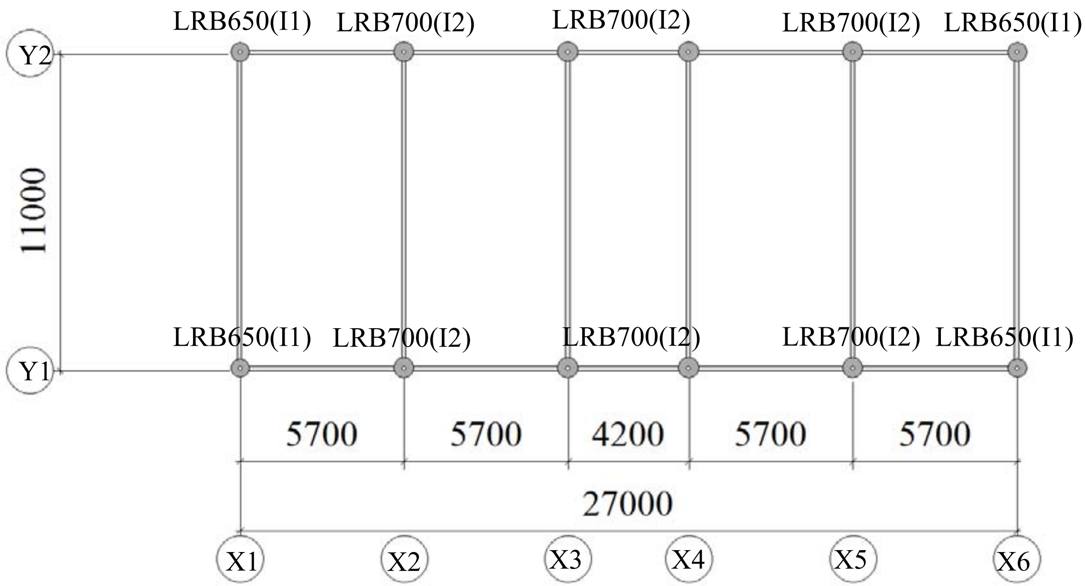


FIGURE.2 Elevation Plan of the building

Building Introduction part 4: Plan of the building



Standard floor plan

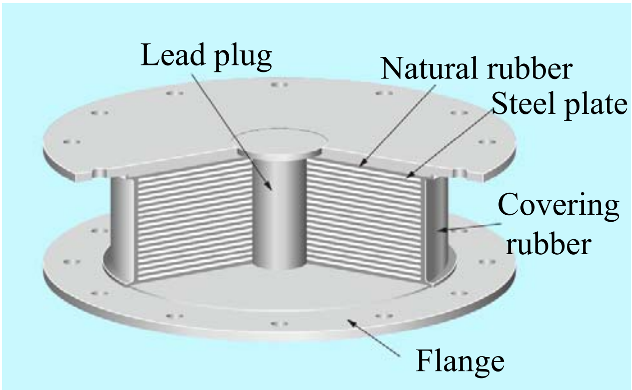


Isolators level

FIGURE.3

LRBφ650 4

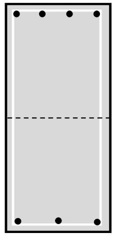
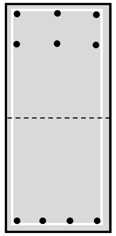
LRBφ700 8

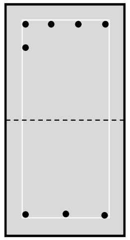
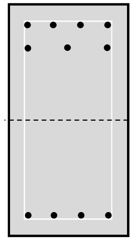


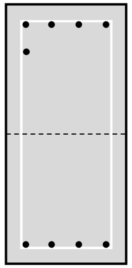
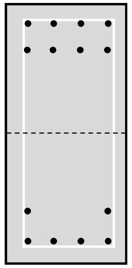
LRB

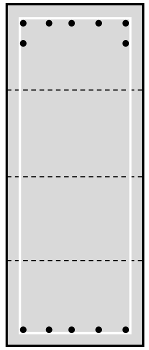
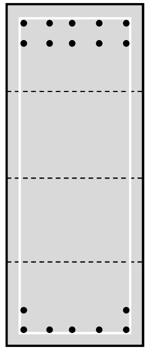
Member information of the building: BEAM

Table5: Detail of the Beam

Story	Beam		
6,7	Symbol	G1	G2
	Main bar (up)	4-D25	6-D25
	Main bar (below)	3-D25	4-D25
	Stirrup	D13-@200	D13-@200
	h*b	700*350	700*350
			

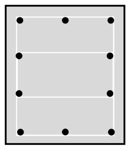
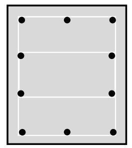
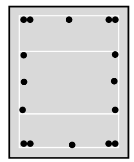
4,5	Symbol	G1	G2
	Main bar (up)	5-D25	7-D25
	Main bar (below)	3-D25	4-D25
	Stirrup	D13-@200	D13-@200
	h*b	750*400	750*400
			

2,3	Symbol	G1	G2
	Main bar (up)	5-D25	8-D25
	Main bar (below)	4-D25	6-D25
	Stirrup	D13-@200	D13-@200
	h*b	800*400	800*400
			

1	Symbol	G1	G2
	Main bar (up)	7-D25	10-D25
	Main bar (below)	5-D25	7-D25
	Stirrup	D13-@200	D13-@200
	h*b	1300*500	1300*500
			

Member information of the building: COLUMN

Table6: Detail of the Columns

Story	Column	
5,6,7	Symbol	C1
	Main bar	10-D25
	Stirrup	D13-@100
	h*b	700*750
		
3,4	Symbol	C1
	Main bar	12-D25
	Stirrup	D13-@100
	h*b	700*750
		
1,2	Symbol	C1
	Main bar	12-D25
	Stirrup	D13-@100
	h*b	750*750
		

Member information of the building: WALL and SLABS

Table7: Detail of the Walls

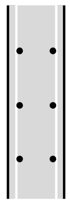
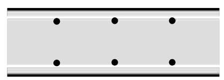
Story	Wall	W1
All	Thickness(mm)	200
	Reinforcement	2-D13@200
		

Table8: Detail of the Slabs

Story	Slab	
All	Thickness(mm)	220
	Reinforcement	D13@100
		

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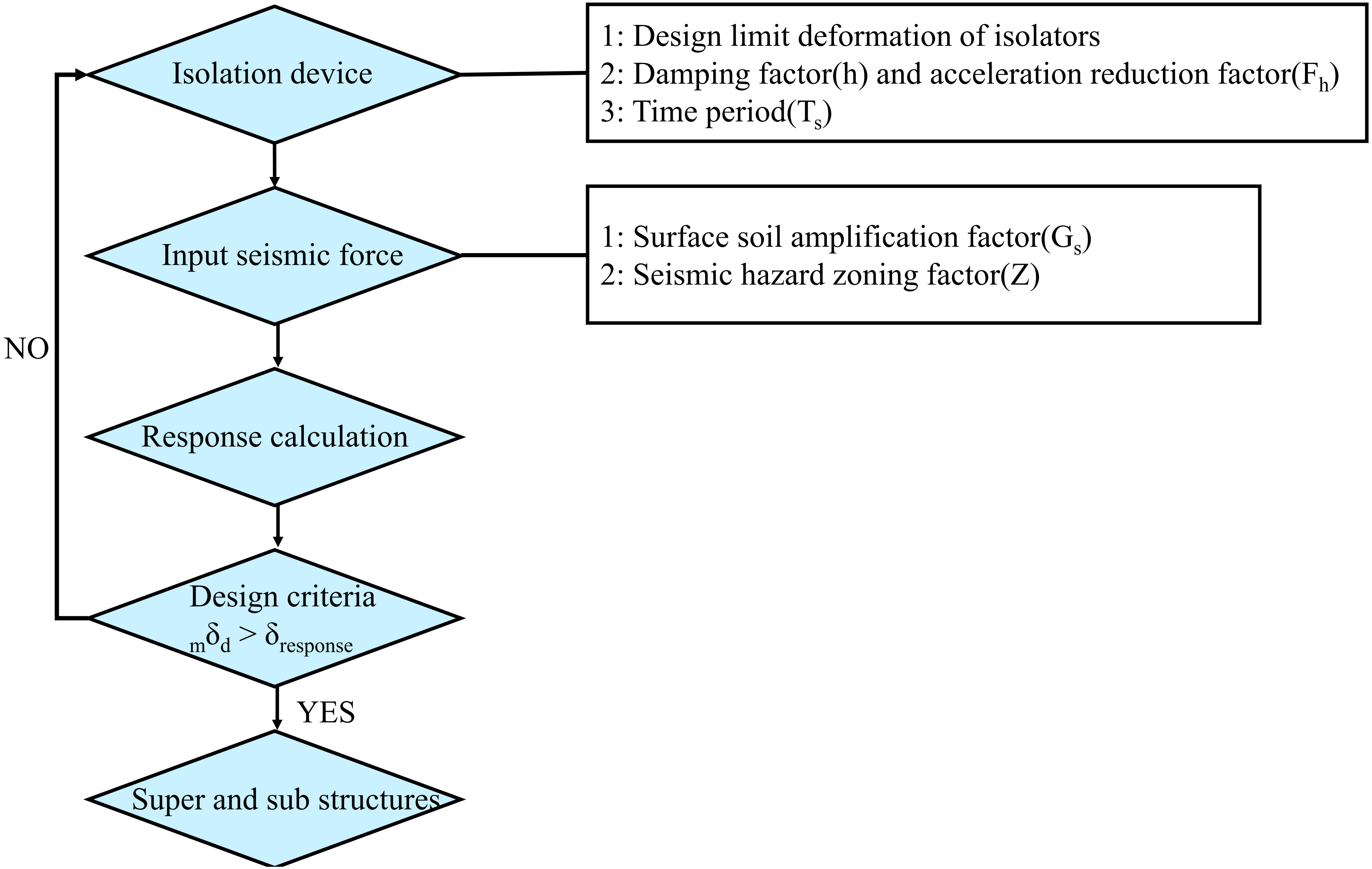
RSM: Design for the seismic isolation level



RSM: How to design seismic force on the building

Seismic force on the building can calculate by formula (1) and (2)

$$Q = S_a \cdot M$$

$$\delta_{response} = 1.1 \cdot \alpha \cdot \left(\frac{Q}{M} \right)$$

$$S_a = S_0 \cdot F_h \cdot G_h \cdot Z$$

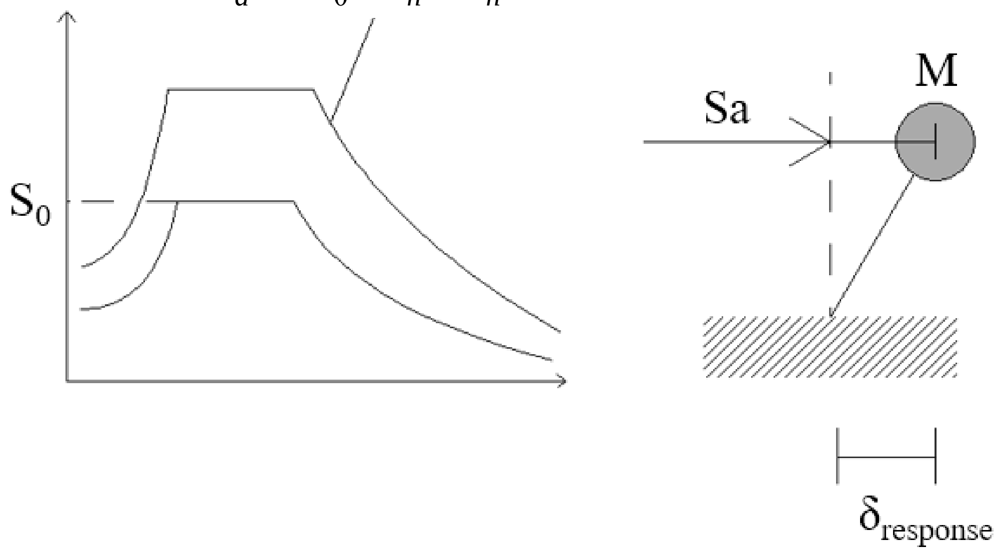


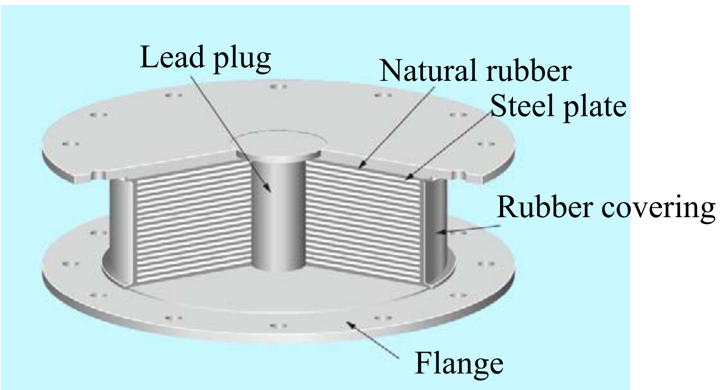
FIGURE.4 Design method of calculation for seismic force

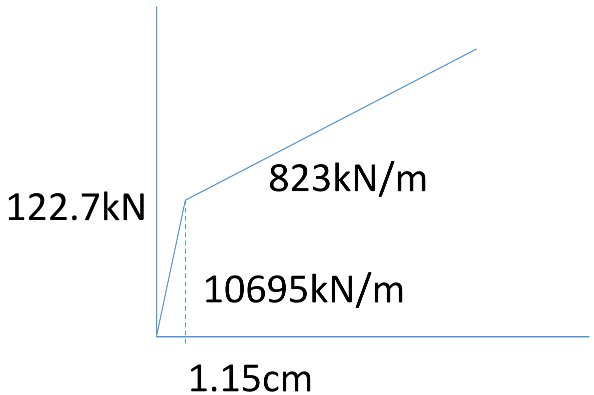
S_0: Acceleration response spectrum at the engineering bedrock (h=0.05)
F_h: Reduction factor due to damping
G_s: Surface soil amplification factor
Z: Seismic zoning factor
α: factor considering variation of material (>= 1.2)

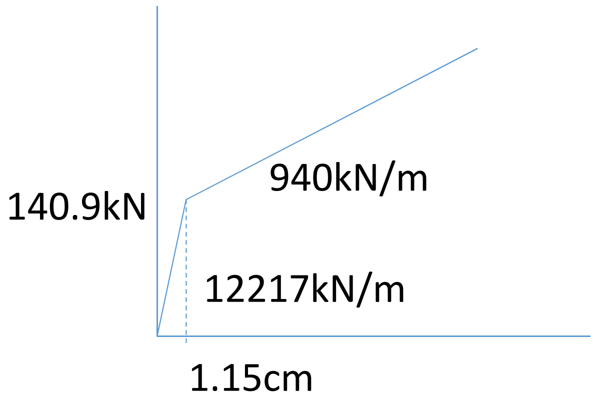
RSM: Seismic isolation device (1)

Table9: Detail of the Seismic Isolation Device

Seismic isolation system	LRBφ650(I1)	LRBφ700(I2)
Diameter (mm)	650	700
Thickness of rubber layer (mm)	10	12
Hr(mm): Effective height of rubber	159.6 (4.2×38 layers)	162 (4.5×36 layers)
S1: Primary shape factor	38.7	38.9
S2: Secondary shape factor	4.1	4.3
K1(kN/m): Initial stiffness	10,695	12,217
K2(kN/m): Secondary stiffness	823	940
Qy(kN): Yielding strength	122.7	140.9
δy(m): Yielding deformation	0.0115	0.0115







RSM: Seismic isolation device (2)

Table9: Detail of the Seismic Isolation Device

Seismic isolation system	LRBφ650(I1)	LRBφ700(I2)
σ_0(N/mm^2):Basic vertical strength	30	36
1/3(σ_0) (N/mm^2)	10	12
γ (%) : Horizontal limit strain	342.27	353.62
δ_u(mm):Horizontal limit deformation	546	573
β:Coefficient due to device	0.8	
$_m\delta_d$(mm):Limit design deformation	437	459

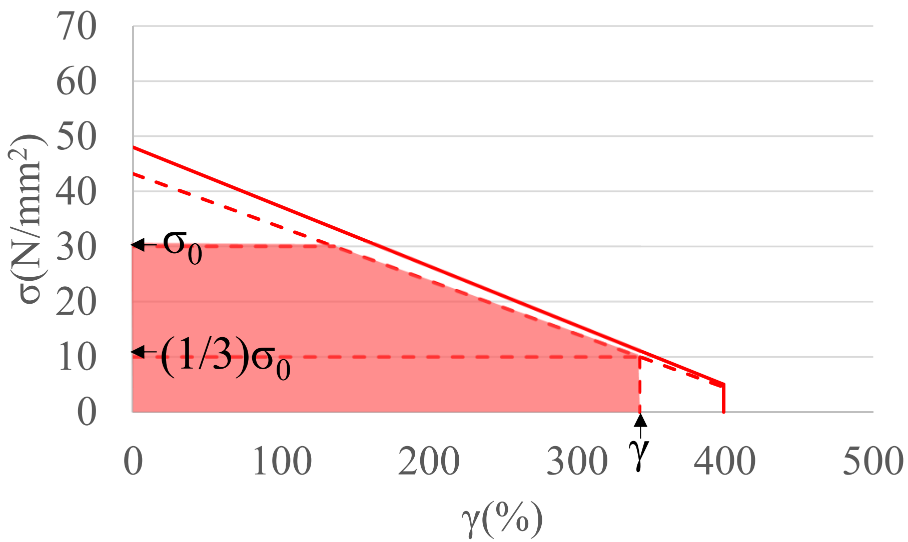


FIGURE.4 LRBΦ650

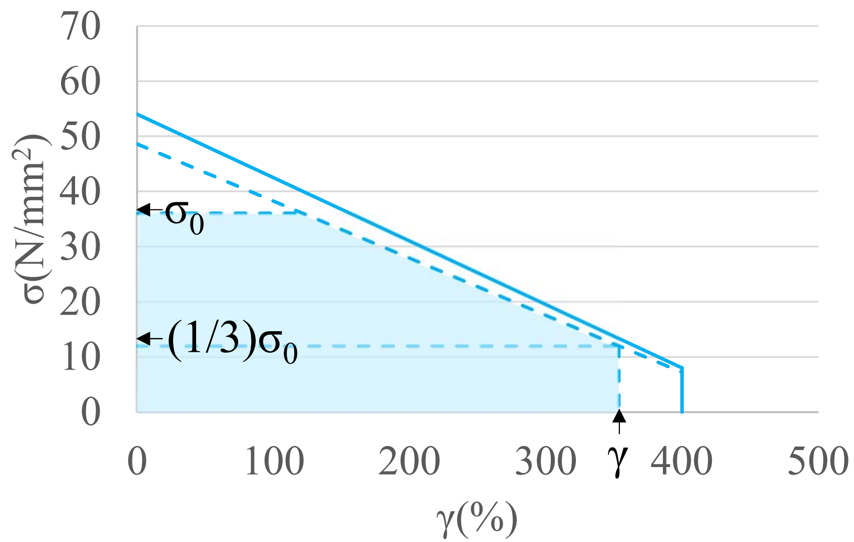


FIGURE.5 LRBΦ700

RSM: Factors calculation part ①: Equivalent damping factor

Damping factor of the building can be calculated by formula (3) to (7)

Equivalent damping factor

$$h = \frac{0.8}{4\pi} \cdot \frac{\Delta W}{W}$$

Reduction factor of response spectrum

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

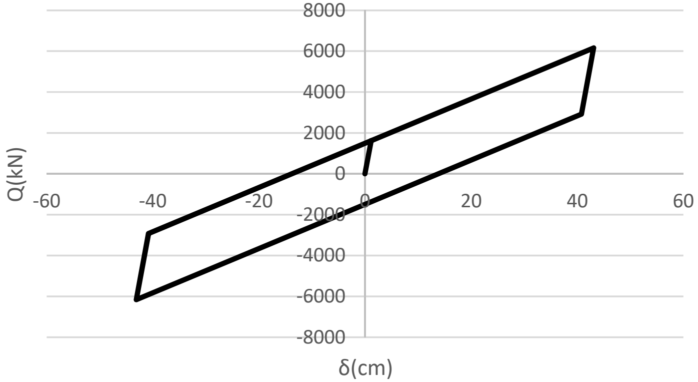
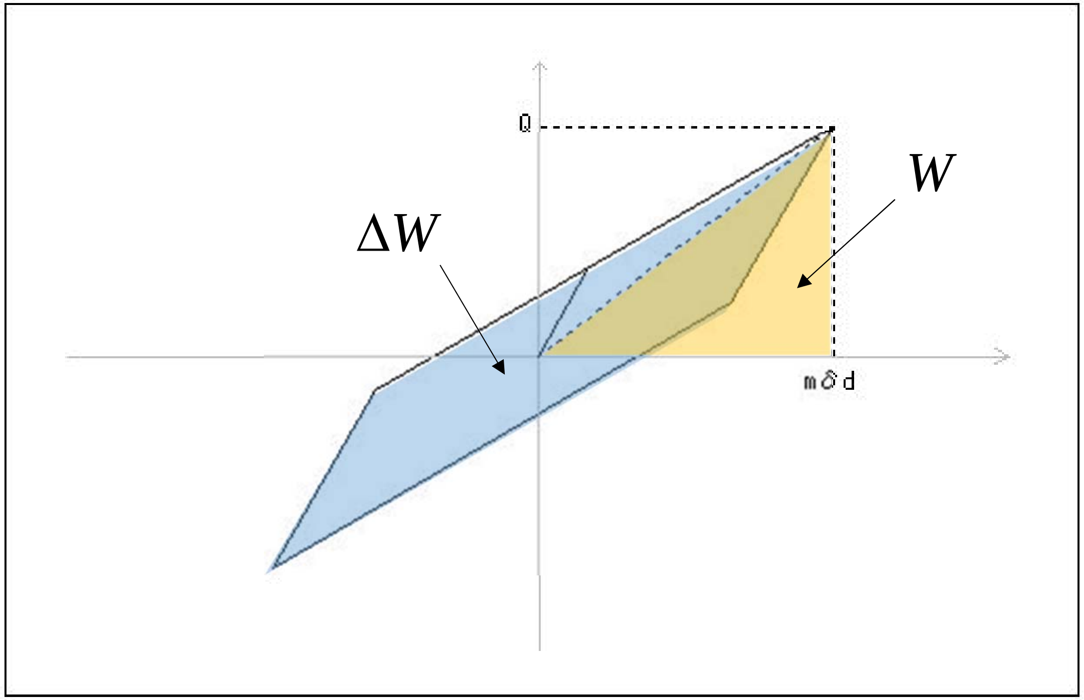
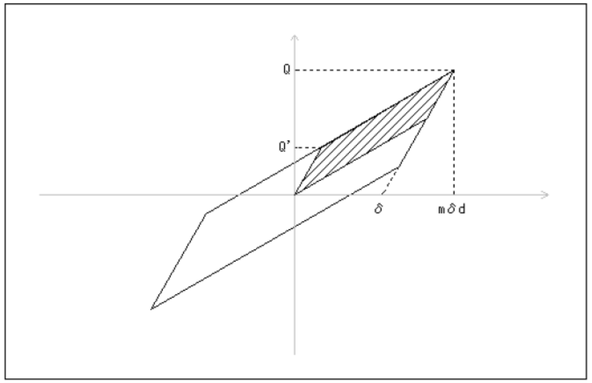
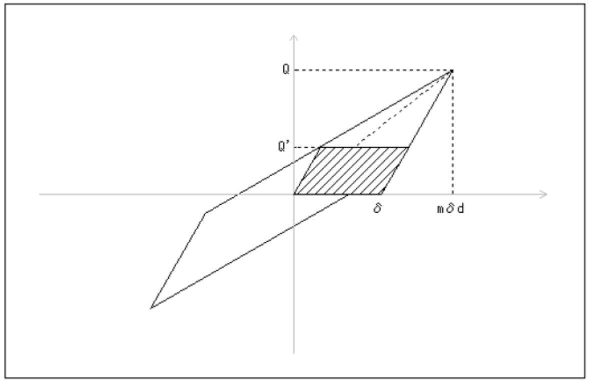
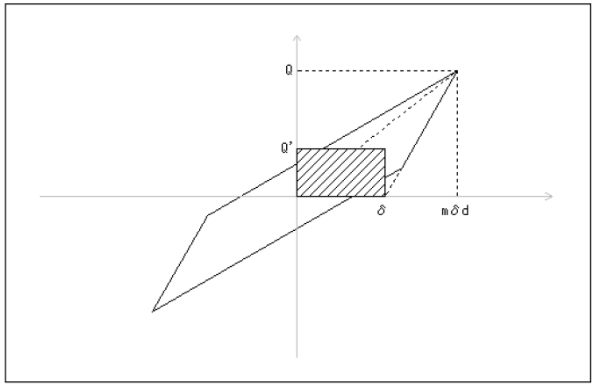


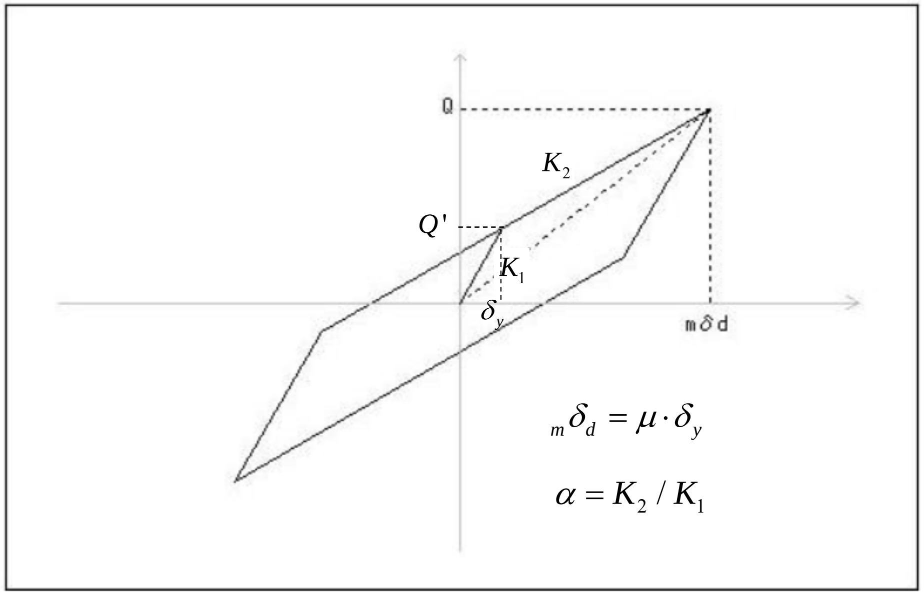
FIGURE.6 Hysteresis loop











$$h = \frac{0.8}{4\pi} \cdot \frac{\Delta W}{W} \qquad W = \frac{1}{2} \cdot {}_m\delta_d \cdot Q \qquad \Delta W = 4 \cdot \delta \cdot Q'$$

$$Q = Q'\{1 + \alpha(\mu - 1)\}$$

$$\delta = {}_m\delta_d - Q / K_1 = \mu\delta_y - Q / K_1$$

$$= \mu\delta_y - \delta_y\{1 + \alpha(\mu - 1)\} = \delta_y(\mu - 1)(1 - \alpha)$$

$$h = \frac{0.8}{4\pi} \cdot \frac{\Delta W}{W} = 0.8\frac{2}{\pi} \cdot \left(1 - \frac{1}{\mu}\right)\frac{1 - \alpha}{1 + \alpha(\mu - 1)}$$

RSM: Factors calculation part ②: Acceleration response spectrum

Acceleration response spectrum can be calculated by equation below

$$S_0 = \begin{cases} 320 + 30 \cdot T_s & T_s < 0.16 \\ 800 & 0.16 \le T_s < 0.64 \\ 512 / T_s & 0.64 \le T_s \end{cases}$$

(cm/s^2)

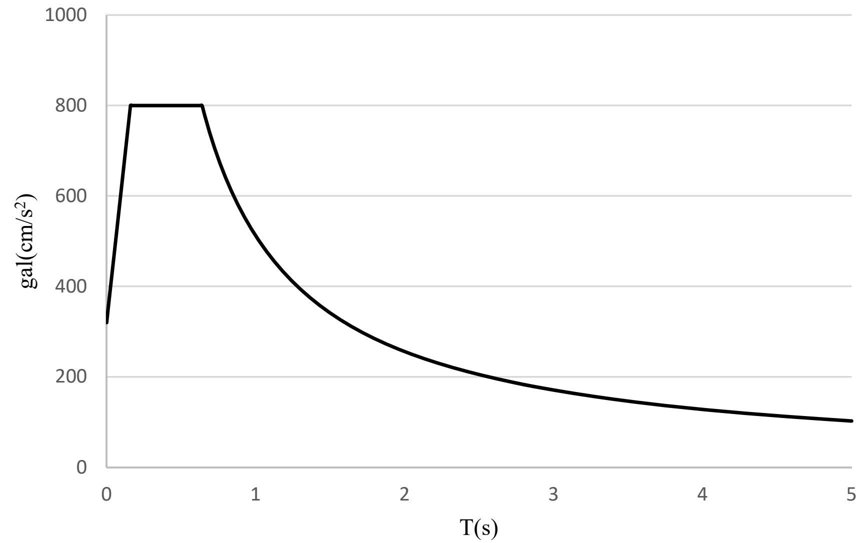


FIGURE.7 Acceleration response spectrum

RSM：Factors calculation part ③: Time period of the building

Acceleration response spectrum can be calculated by equation below

$$T_s = 2\pi\sqrt{\frac{M}{K}}$$

$$M = \sum \text{ Super mass}$$

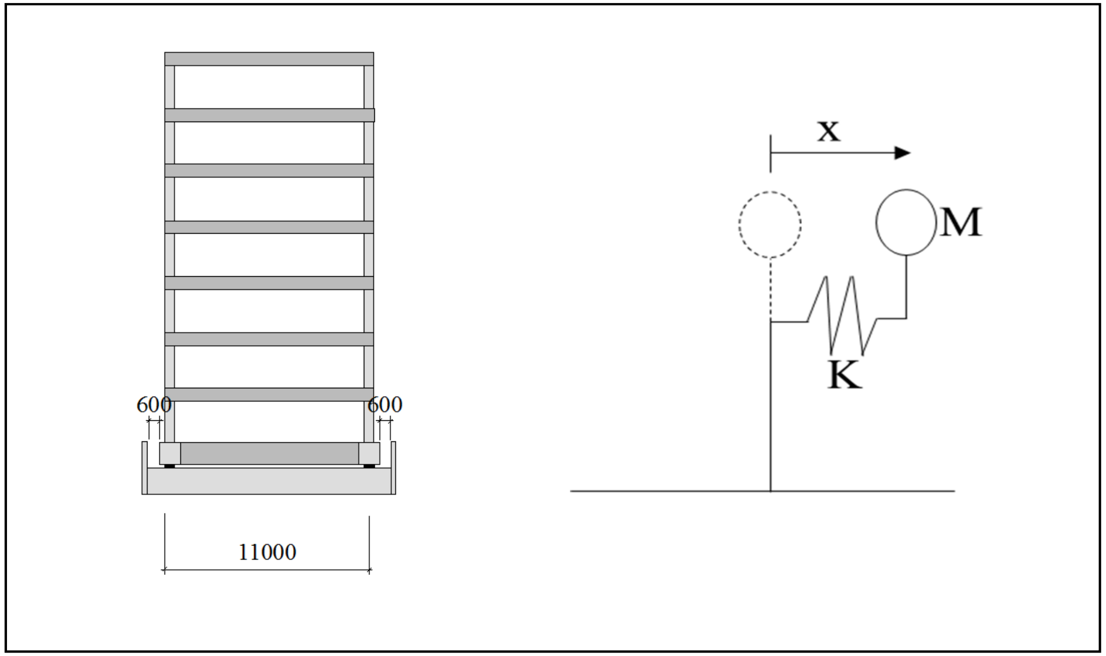
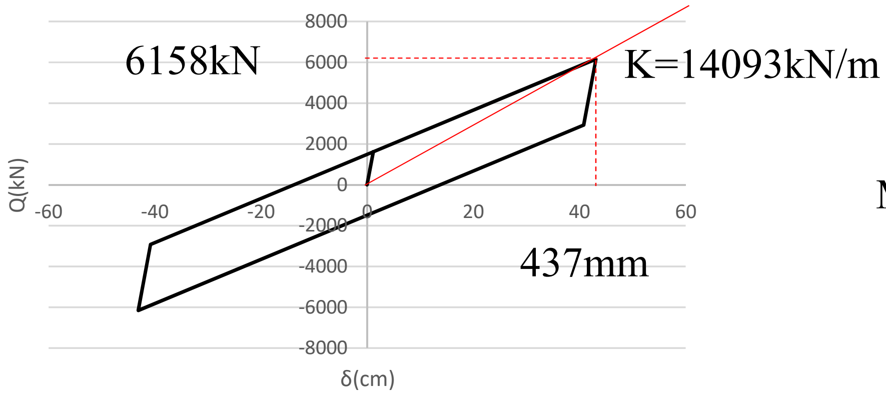


FIGURE.8 Building mass



$M = 3555 kNs^2/m$ → $Ts = 3.16$ s

RSM: Factors calculation part ④: Surface soil amplification factor

Table10: Soil profile type definition

Soil profile type (G_s)	Definition	Describe
1	T=0.4	Solid soil
2	T=0.6	Moderate
3	T=0.8	Soft soil

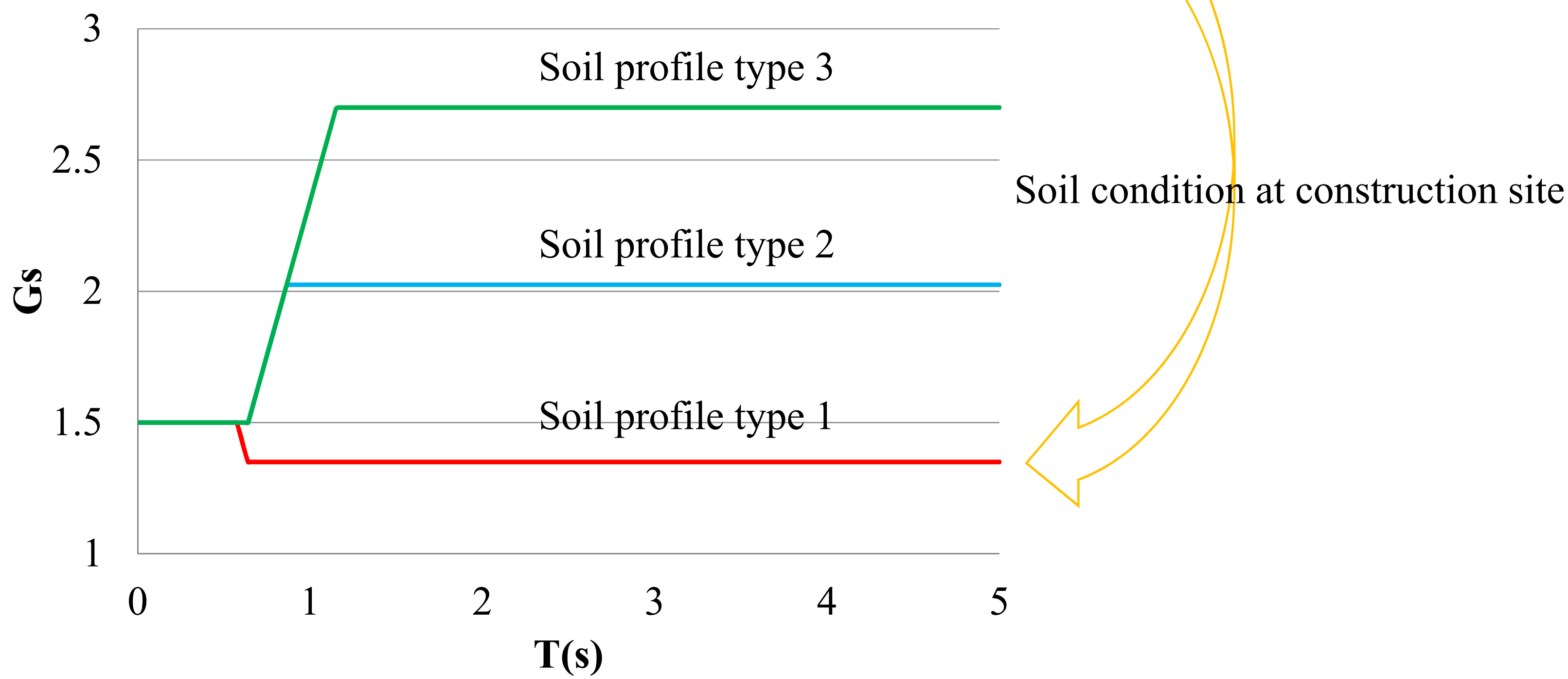
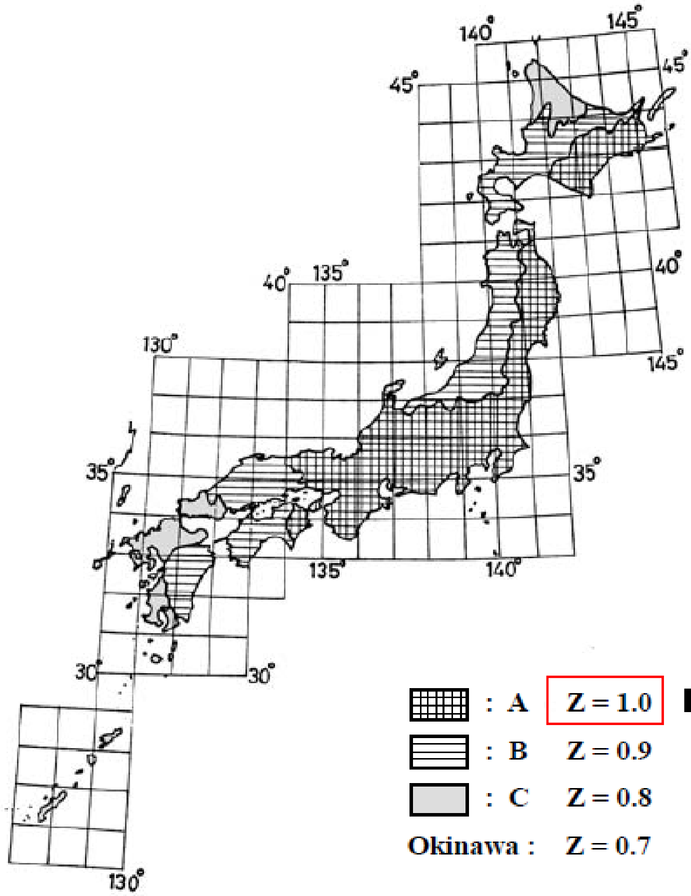


FIGURE.9 Soil profile type

RSM: Factors calculation part ⑤: Seismic hazard zoning factor



This value is taken for design

FIGURE.9 Soil profile type

RSM: Summary of design factors

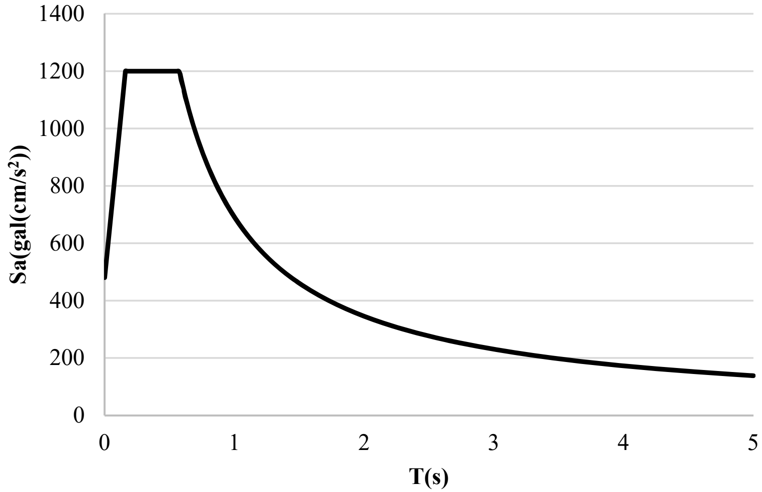
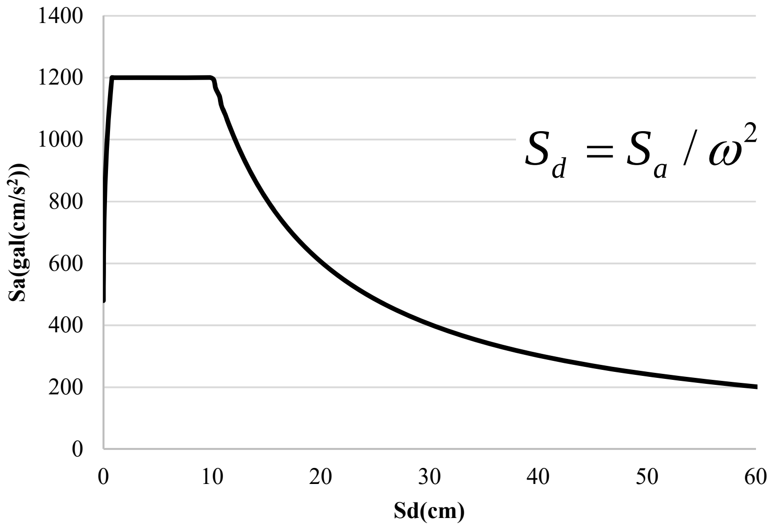


FIGURE.10 S_a-T curve



$$S_d = S_a / \omega^2 = S_a \cdot T^2 / (2\pi)^2$$

FIGURE.11 S_a-S_d curve

RSM: Capacity spectrum method part ①: Introduction

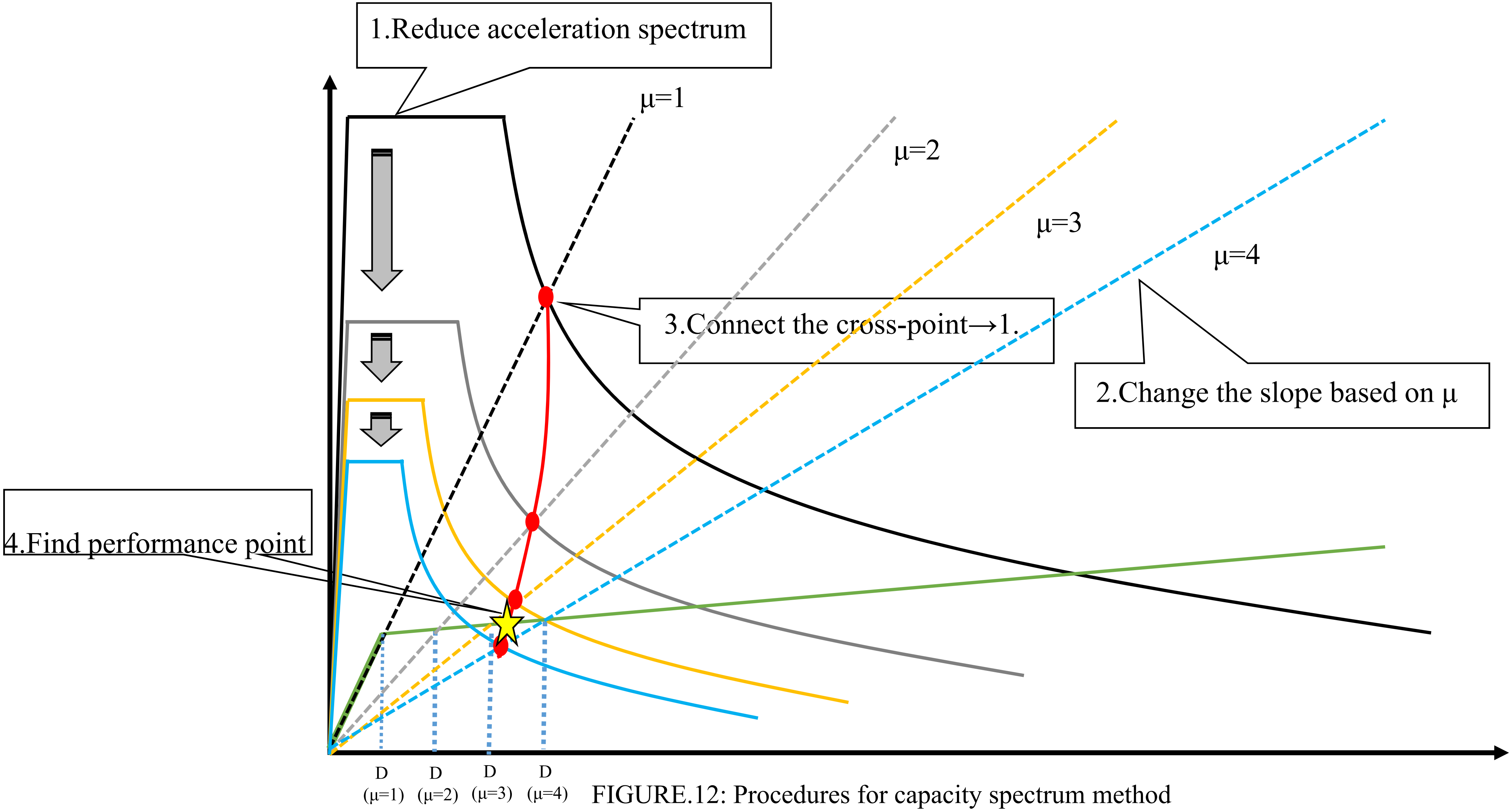


FIGURE.12: Procedures for capacity spectrum method

RSM: Capacity spectrum method part ②: Result

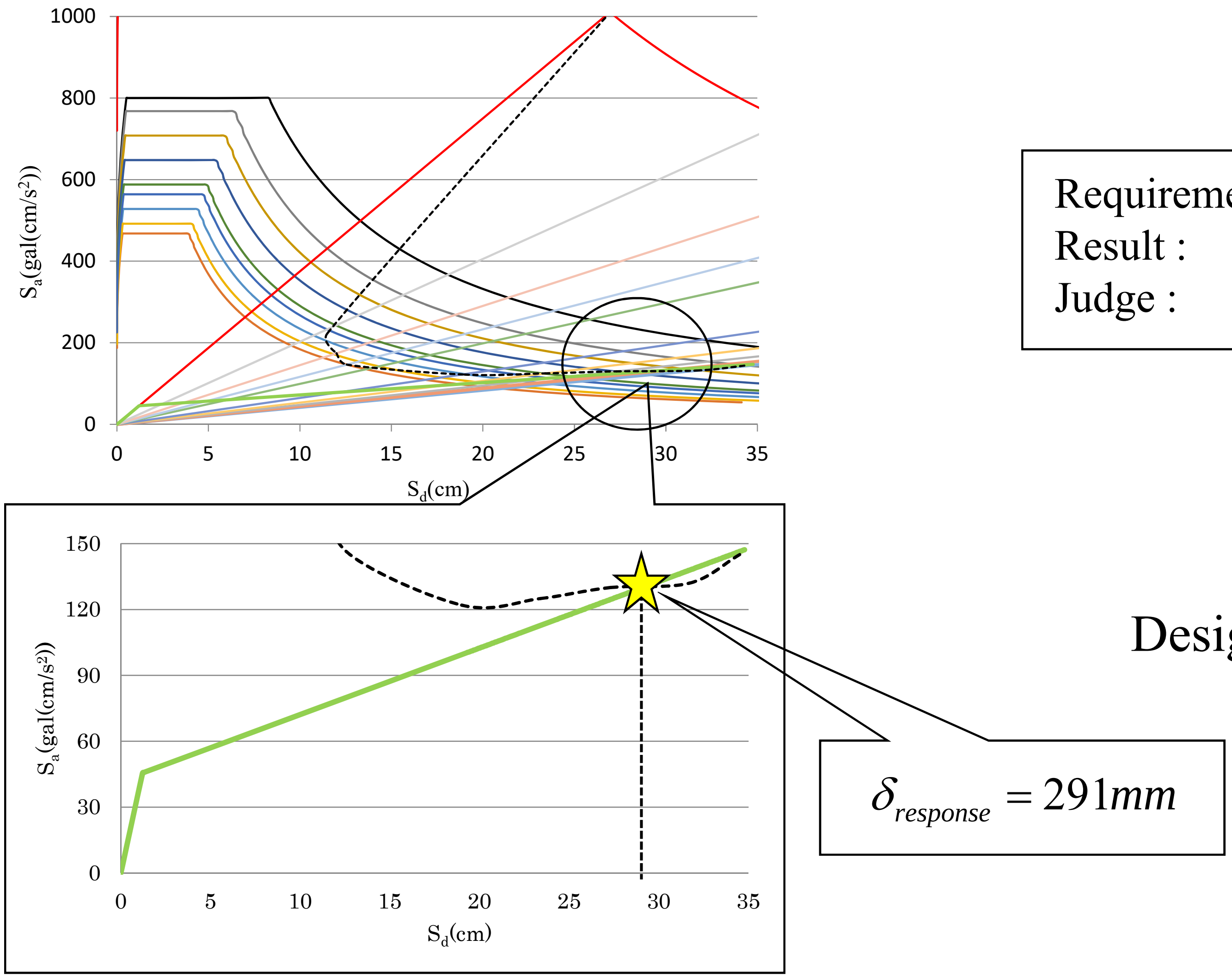
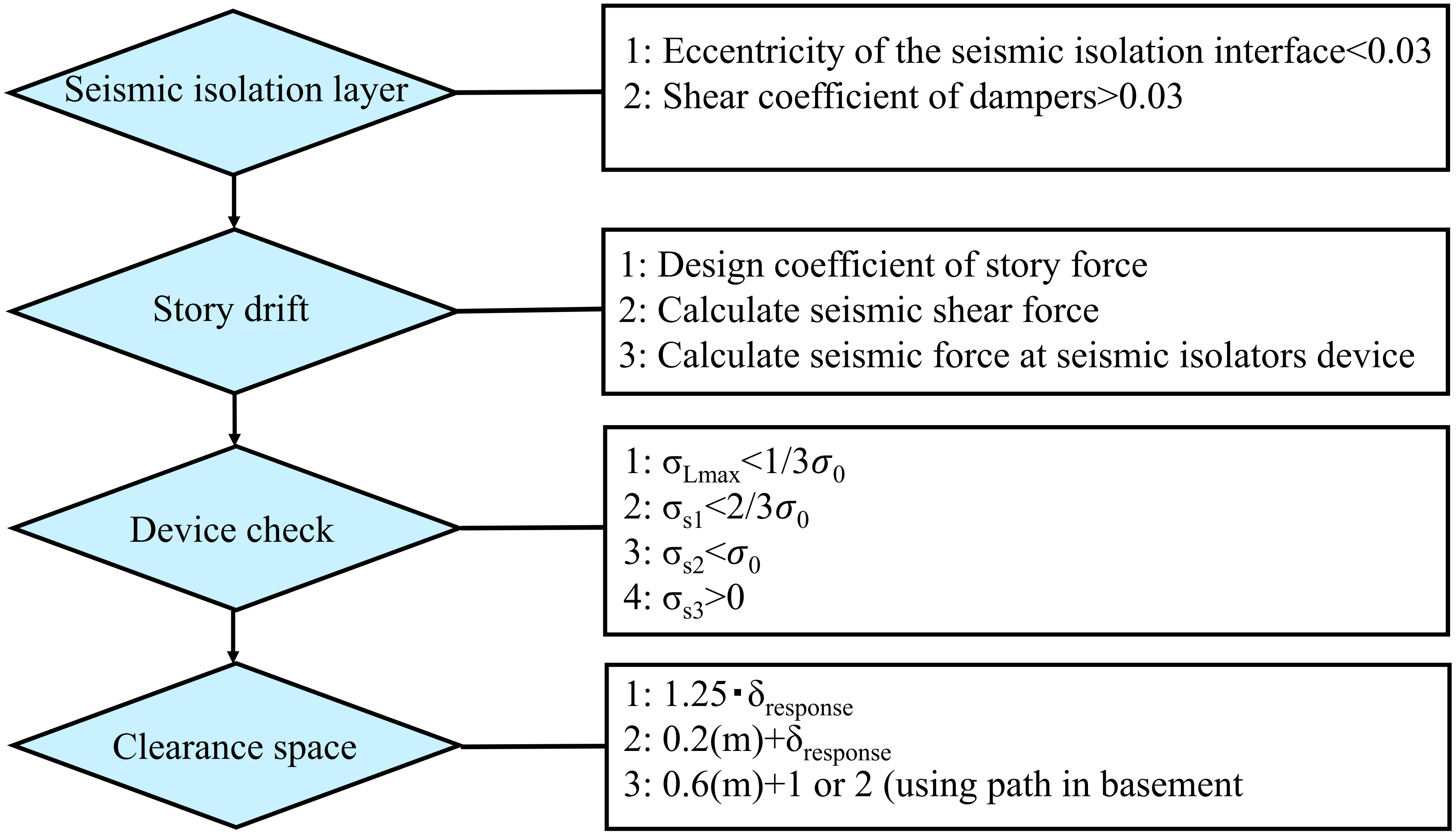


FIGURE.13: Result of the Capacity spectrum method

Requirement :	${}_m\delta_d > \delta_{responce}$	
Result :	437 > 291	(mm)
Judge :	OK	

Design for the superstructure

RSM: Design of superstructure: Design procedures



RSM: Seismic isolation layer : Eccentricity ratio ($R_{ex,ey}$)

Eccentricity ratio

$$R_{ex} = \frac{e_Y}{r_{ex}} \qquad R_{ex} = \frac{0.107}{10.41} = 0.01$$

$$R_{eY} = \frac{e_x}{r_{ey}} \qquad R_{ey} = \frac{0.287}{10.41} = 0.027$$

Less than 0.03→OK

1. Center of gravity

$$X_g = \frac{\sum X_i \cdot N_i}{\sum N_i}$$
$$Y_g = \frac{\sum Y_i \cdot N_i}{\sum N_i}$$

2. Center of rigidity

$$X_k = \frac{\sum X_i \cdot K_{yi}}{\sum K_{yi}}$$
$$Y_k = \frac{\sum Y_i \cdot K_{xi}}{\sum K_{xi}}$$

3. Eccentricity distance

$$e_x = |Y_g - Y_k|$$
$$e_y = |X_g - X_k|$$

4. Rotation stiffness

$$K_T = \sum \{K_{xi} \cdot (Y_i - Y_k)^2 + K_{yi} \cdot (X_i - X_k)^2\}$$

5. Elastic radius

$$r_{ex} = \sqrt{\frac{K_T}{\sum K_{xi}}}$$
$$r_{ey} = \sqrt{\frac{K_T}{\sum K_{yi}}}$$

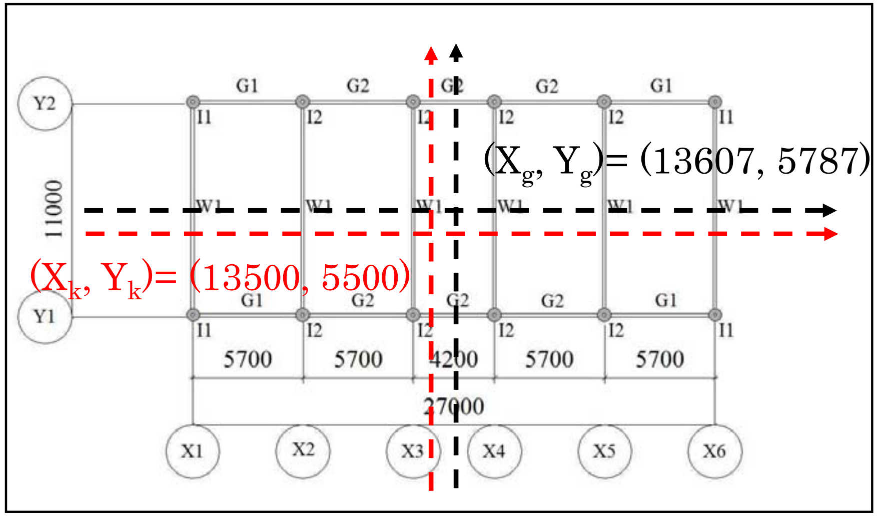
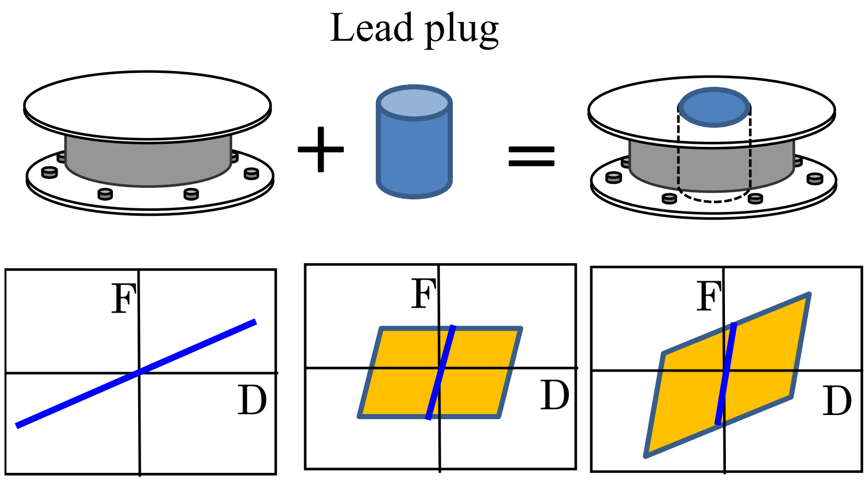


FIGURE.14: Center of the gravity and rigidity

RSM: Shear force at isolation layer



Q_e Q_h

LRBφ650 LRBφ700

$$Q_e = \sum K_1 \cdot \delta$$

Q_e: Shear force at rubber

$$Q_e = 0.823\left(\frac{kN}{mm}\right)\cdot 291(mm)\cdot 4 + 0.94\left(\frac{kN}{mm}\right)\cdot 291(mm)\cdot 8 = 3146(kN)$$

$$Q_h = \sum yield\ load$$

Q_h Shear force at damper (lead plug)

$$Q_h = 122.7(kN)\cdot 4 + 140.9(kN)\cdot 8 = 1618(kN)$$

RSM: Seismic isolation layer : Shear coefficient of dampers(μ)

$$\mu = \frac{Q_h}{M \cdot g} = \frac{1618}{3555 \cdot 9.8} = 0.046 > 0.03$$

Over 0.03→OK

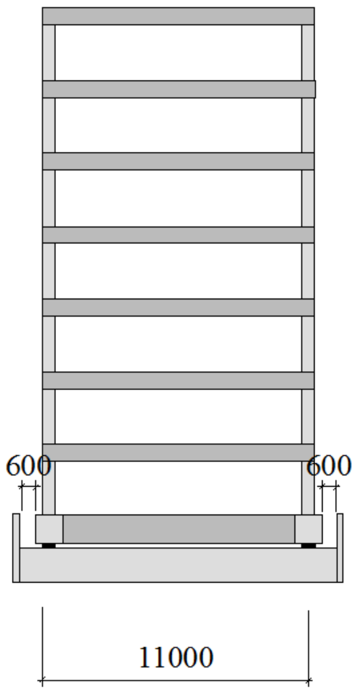
RSM: Story drift : Shear coefficient of superstructure(C_{ri})

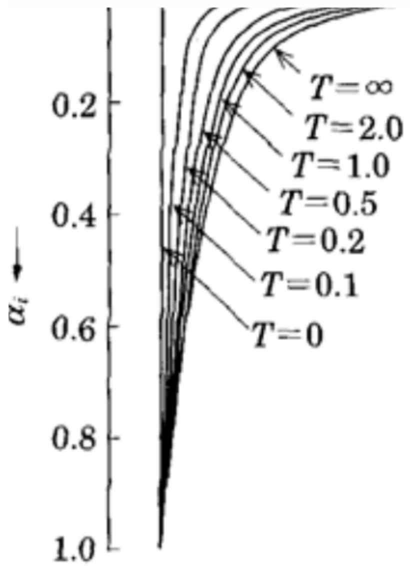
$$A_i = 1 + \left(\frac{1}{\sqrt{\alpha_i}} - \alpha_i \right) \frac{2T}{1+3T}$$

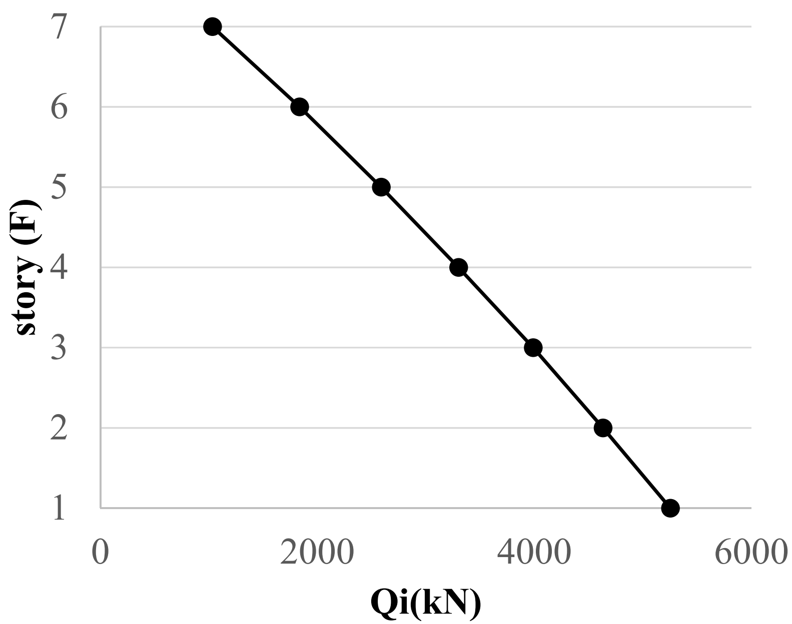
$$C_{ri} = \gamma \frac{A_i \cdot Q_h + Q_e}{M \cdot g}$$

T: The natural period of superstructure with fixed base $(0.02+0.01\alpha)H$

γ: factor considering the variation of material (>=1.3)



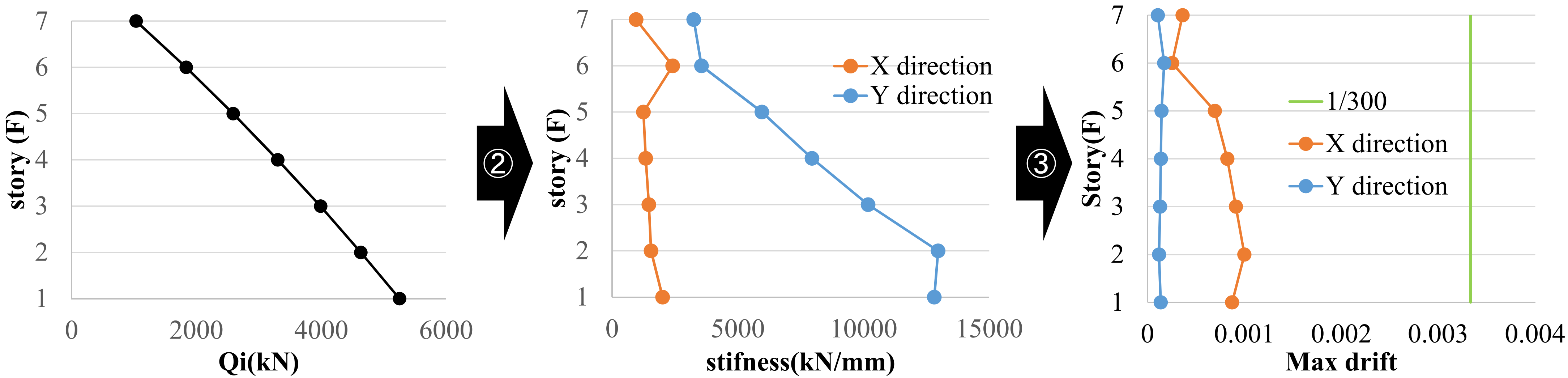




RSM: Story drift

Step ①: Calculate shear force on each floor depend on C_{ri}
Step ②: Estimate horizontal stiffness of the building by frame analysis
Step ③: Shear force divide by stiffness → Max drift

Both directions are not over 1/300→OK



Shear force on each floors | Horizontal stiffness of each directions | Story drift of each directions

FIGURE.14: Procedures to calculate story drift

RSM: Device check ①:Long-term load

$$\sigma_{Lmax} < \frac{1}{3} \cdot \sigma_0$$

Table12: Result of device check

(N/mm^2)	1(LRB650)	2(LRB700)	3(LRB700)	4(LRB700)	5(LRB700)	6(LRB650)
Load	6.81	10.12	8.79	8.79	10.12	7.23
criteria	< 10	< 12	< 12	< 12	< 12	< 10
Judge	**OK**	**OK**	**OK**	**OK**	**OK**	**OK**
Load	6.78	8.8	7.64	7.64	8.8	7.23
criteria	< 10	< 12	< 12	< 12	< 12	< 10
Judge	**OK**	**OK**	**OK**	**OK**	**OK**	**OK**

RSM: Device check ②: Long-term load + seismic force

$$\sigma_{s1} = vertical\ force + seismic\ force$$

$$\sigma_{s1} < \frac{2}{3} \cdot \sigma_0$$

Table13: Result of device check

(N/mm^2)	1(LRB650)	2(LRB700)	3(LRB700)	4(LRB700)	5(LRB700)	6(LRB650)
Load	7.57	10.98	9.65	9.65	10.98	7.99
Criteria	< 20	< 24	< 24	< 24	< 20	> 20
Judge	**OK**	**OK**	**OK**	**OK**	**OK**	**OK**
Load	7.54	9.66	8.50	8.50	9.66	7.99
Criteria	< 20	< 24	< 24	< 24	< 20	> 20
Judge	**OK**	**OK**	**OK**	**OK**	**OK**	**OK**

RSM: Device check ③:1.3・Long-term load + seismic force

$$\sigma_{s2} = 1.3 \cdot (vertical\ force) + seismic\ force$$

$$\sigma_{s2} < \sigma_0$$

Table14: Result of device check

(N/mm^2)	1(LRB650)	2(LRB700)	3(LRB700)	4(LRB700)	5(LRB700)	6(LRB650)
Load	9.61	14.02	12.29	12.29	14.02	10.16
Design	< 30	< 36	< 36	< 36	< 36	< 30
Criteria	**OK**	**OK**	**OK**	**OK**	**OK**	**OK**
Load	9.57	12.30	10.80	10.80	12.30	10.16
Criteria	< 30	< 36	< 36	< 36	< 36	< 30
Judge	**OK**	**OK**	**OK**	**OK**	**OK**	**OK**

RSM: Device check ④:0.7･Long-term load - seismic force

$$\sigma_{s3} = 0.7 \cdot (vertical\ force) - seismic\ force$$

$$\sigma_{s3} > 0$$

Table15: Result of device check

(N/mm²)	1(LRB650)	2(LRB700)	3(LRB700)	4(LRB700)	5(LRB700)	6(LRB650)
Load	4.01	6.22	5.29	5.29	6.22	4.30
Criteria	> 0	> 0	> 0	> 0	> 0	> 0
Judge	**OK**	**OK**	**OK**	**OK**	**OK**	**OK**
Load	3.99	5.30	4.48	4.48	5.30	4.30
Criteria	> 0	> 0	> 0	> 0	> 0	> 0
Judge	**OK**	**OK**	**OK**	**OK**	**OK**	**OK**

RSM: Clearance space

Compare 1) and 2) and bigger value must be taken. In case of using path at seismic isolation layer, it should plus 0.6(m)

1) $1.25 \cdot \delta_{response}$
2) $0.2(\mathrm{m}) + \delta_{response}$
3) $0.6(\mathrm{m}) + 1)$ or $2)$ In case of using to path

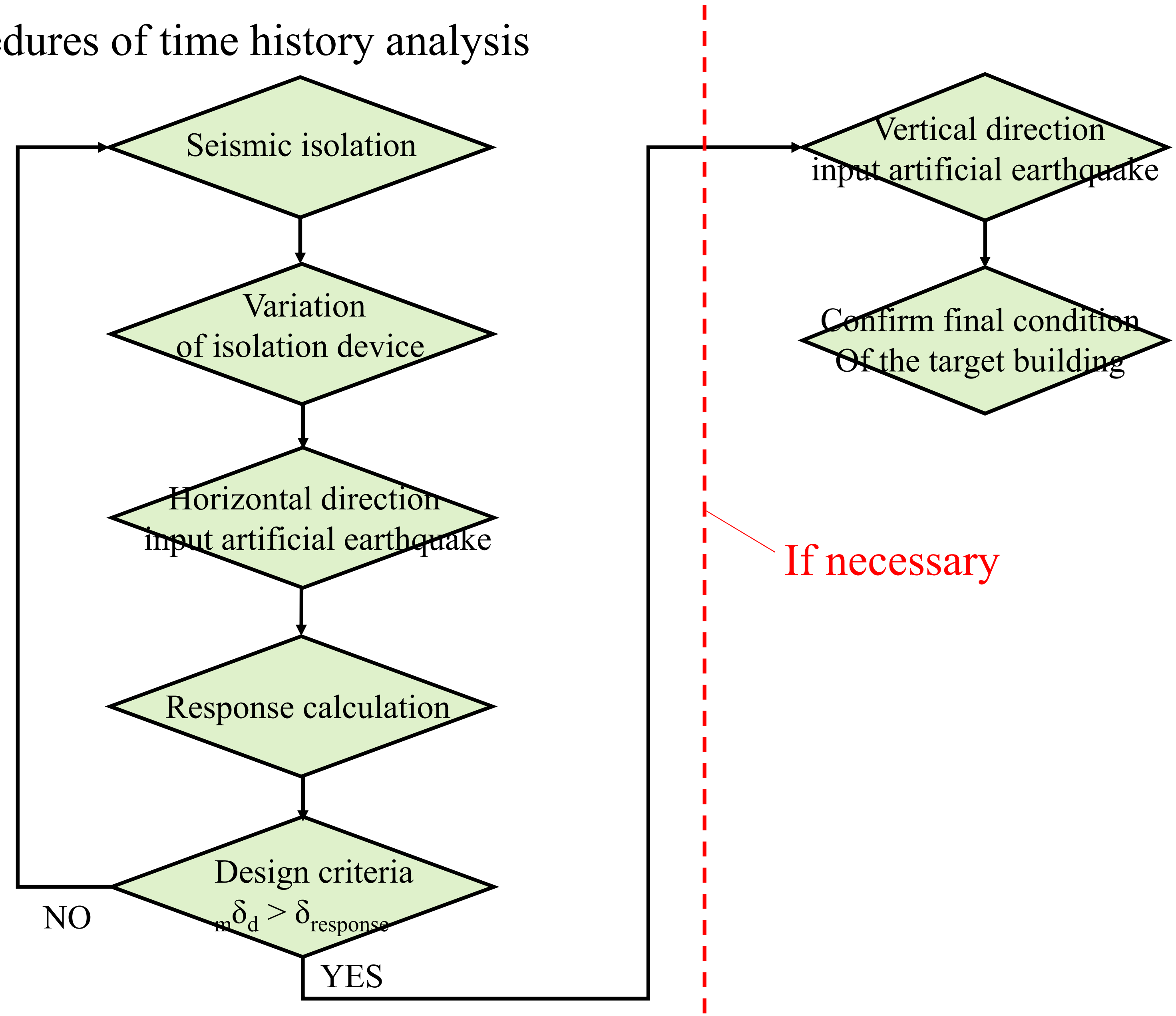
1) $1.25 \cdot \delta_{response} = 1.25 * 0.291(m) = 0.364(m)$
2) $0.2(\mathrm{m}) + \delta_{response} = 0.2(m) + 0.291(m) = 0.491(m)$

In the result, clearance space must secure more than 0.491(m).

Index

1. Introduction for target building
2. Response spectrum method (RSM)
3. Time history analysis (THA)

Design procedures of time history analysis



THA: Variation of isolation device

Table16: Variation of Isolation Device

Isolators	Character of restoring force	Condition	Variation Factor			Variation Ratio
			Product variation	Temperature Dependency	Aging	
Laminated Rubber with Lead Plug	Secondary Stiffness K_2	Upper Limit	10%	6%	11%	27%
		Lower Limit	-10%	-5%	0%	-15%
	Section Load Q_d	Upper Limit	10%	23%	0%	33%
		Lower Limit	-10%	-21%	0%	-31%

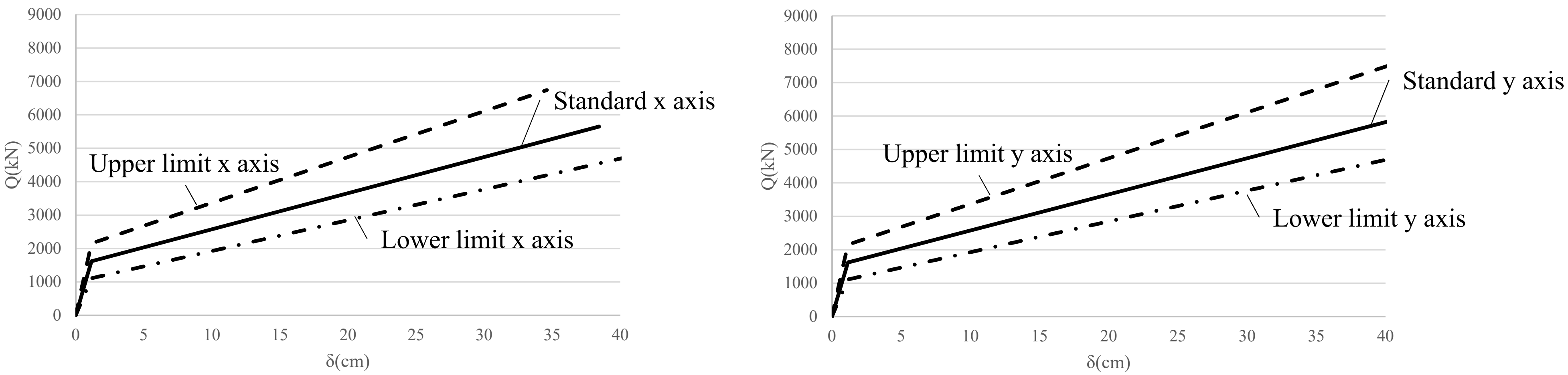
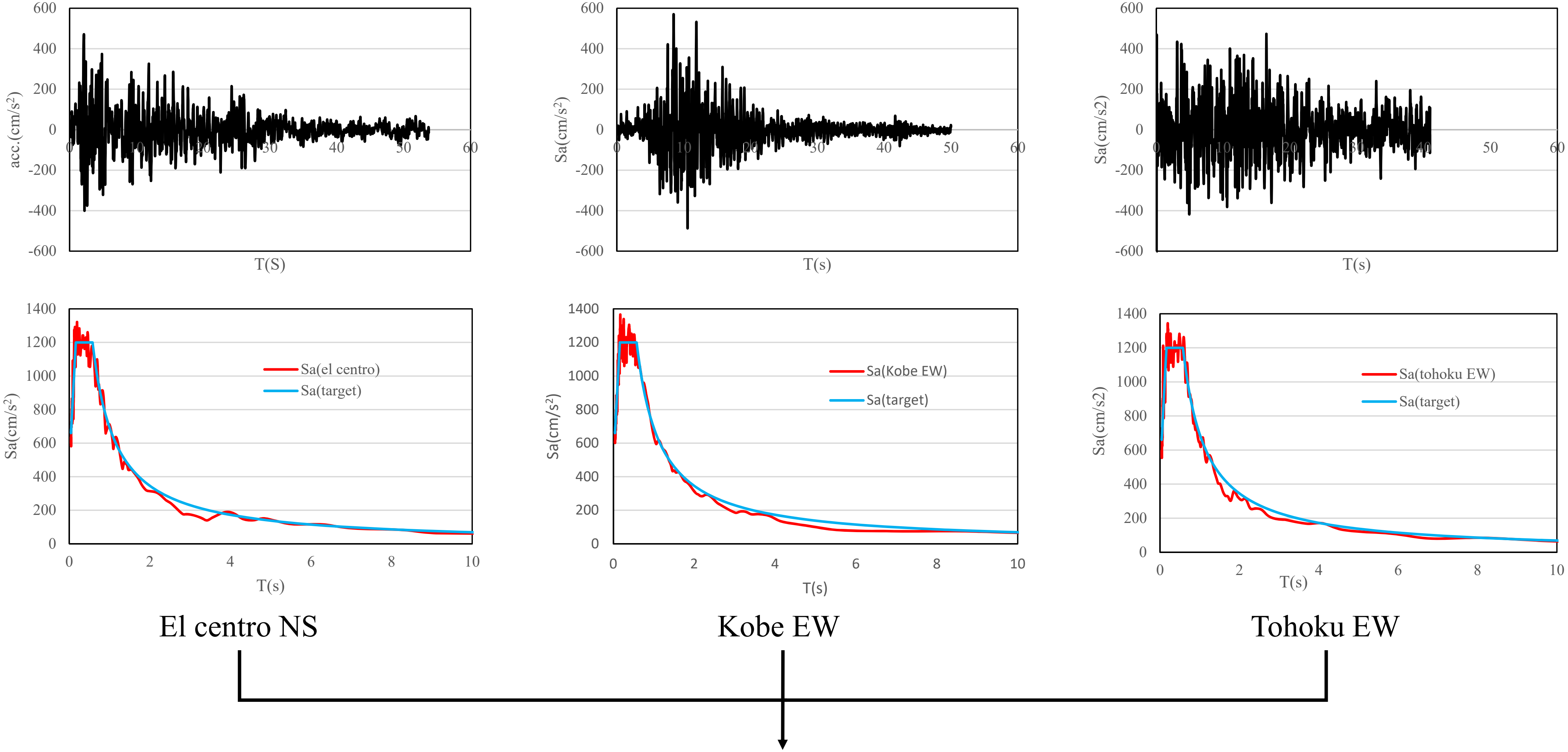


FIGURE.15: Capacity curve which considered variation of Isolation device

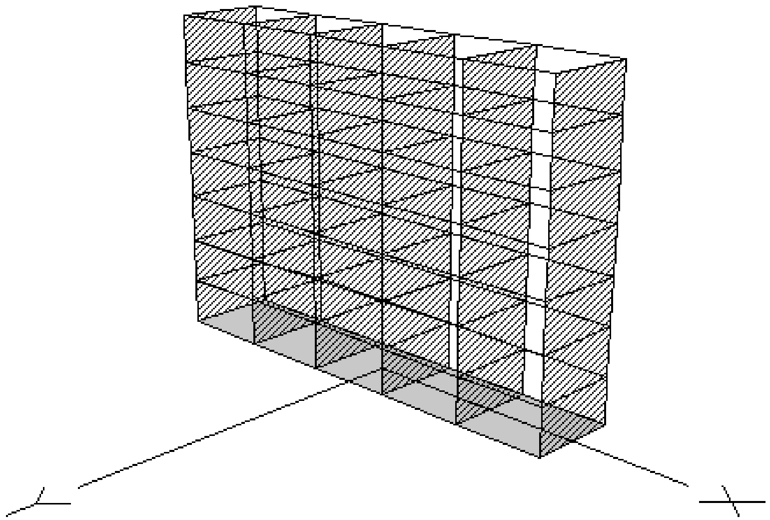
THA: Generate artificial earthquake ground motions in horizontal direction



Input horizontal direction earthquake

THA: Building model

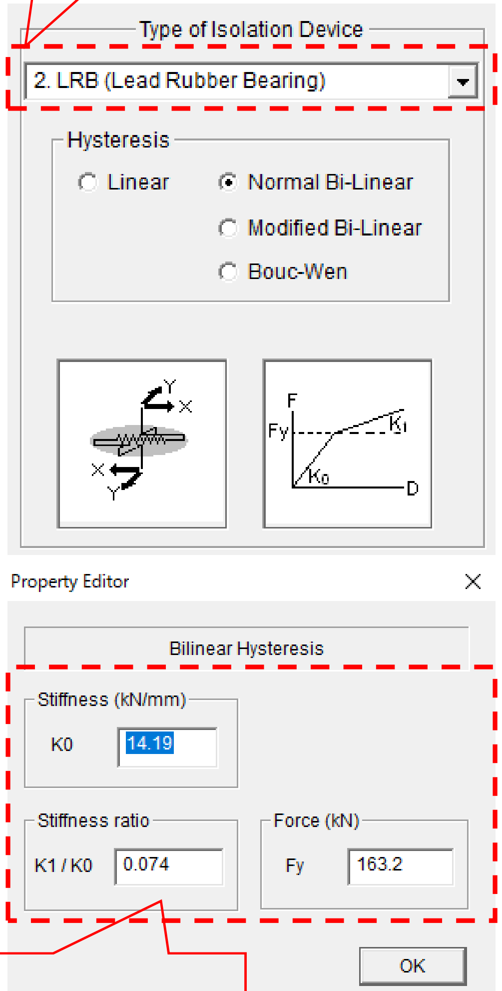
① Create building model based on information



STERA_3D model

② Select type of isolators

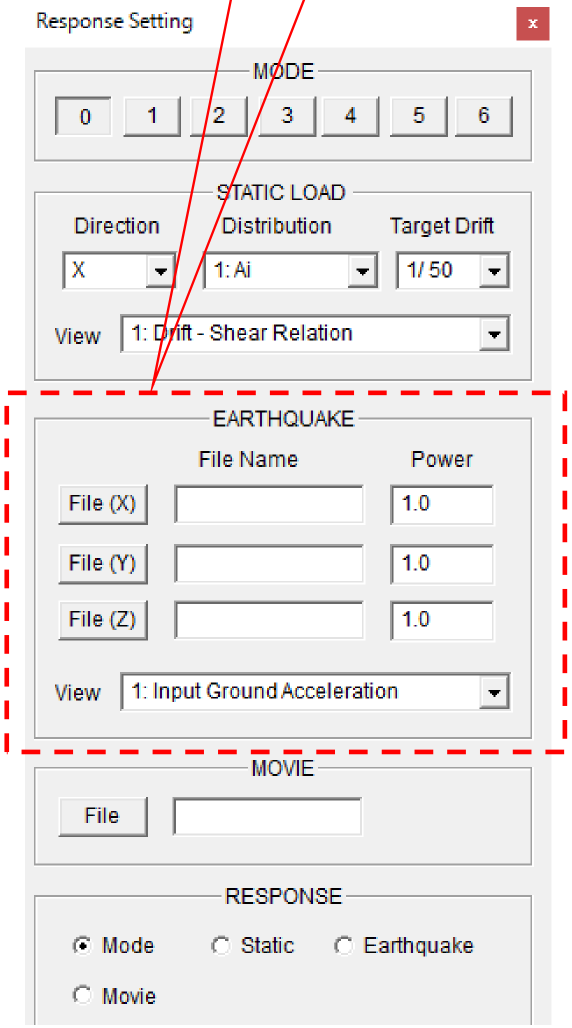
Isolators setting



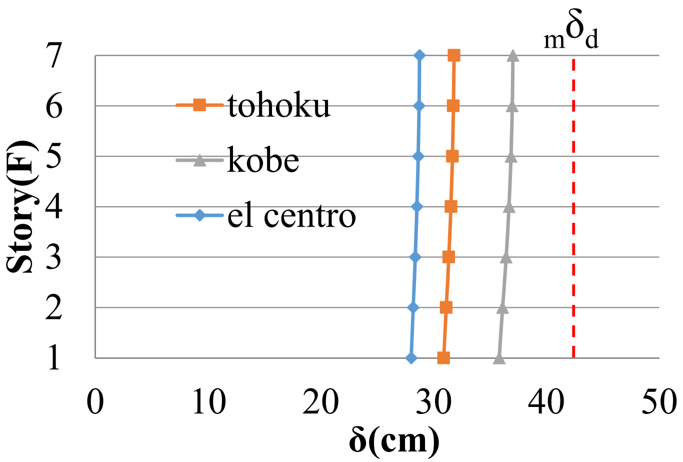
③ set behavior of isolators

④ Input earthquake

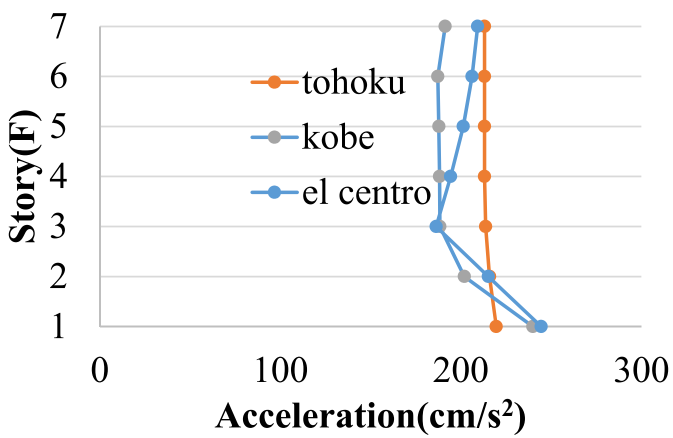
Input earthquake



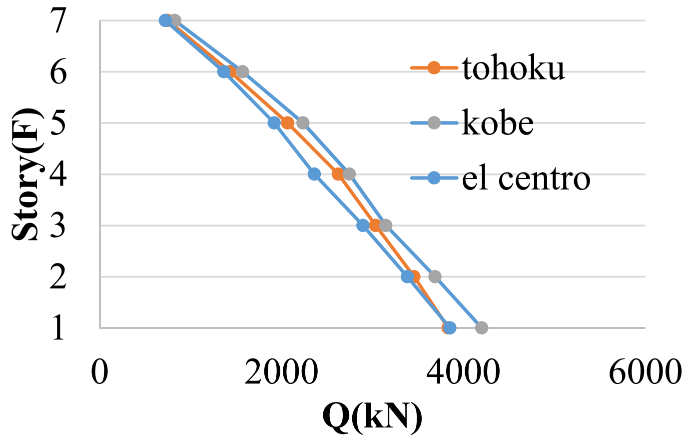
THA: Result of maximum response value in X direction from input horizontal earthquake(El Centro , Kobe , Tohoku)



Lower limit of variation



Upper limit of variation



Upper limit of variation

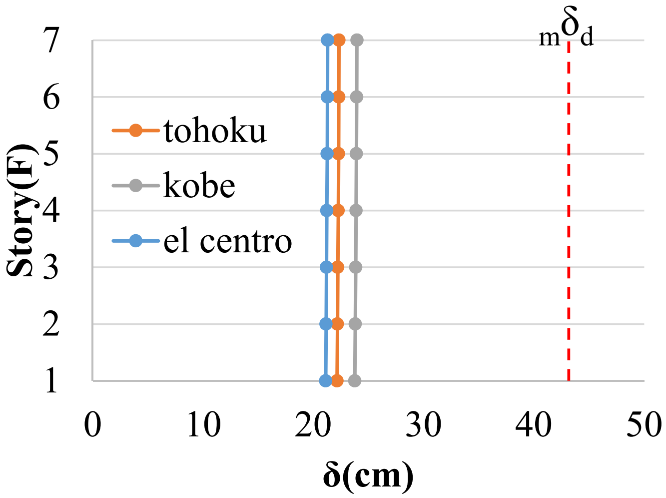
Max response of X direction

$$_m\delta_d > \delta_{responce}$$

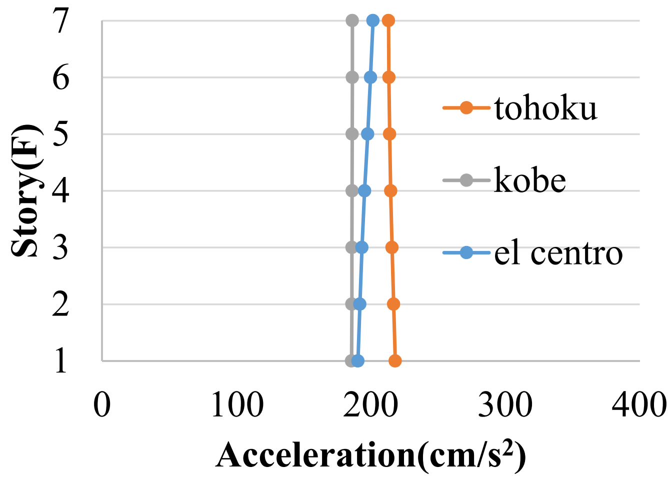
$$_m\delta_d = 437(mm)$$

→ OK

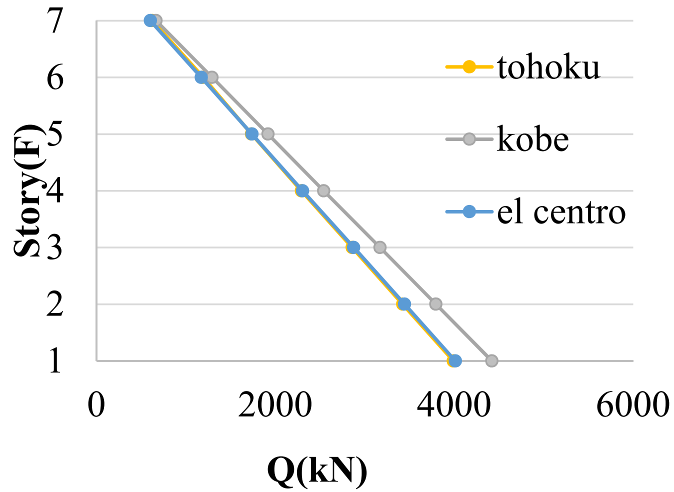
THA: Result of maximum response value in Y direction from input horizontal earthquake(El Centro , Kobe , Tohoku)



Lower limit of variation



Upper limit of variation



Upper limit of variation

Max response of Y direction

$$_m\delta_d > \delta_{responce}$$

$$_m\delta_d = 437(mm)$$

→ OK