Implementation Guidance for Basic Seismic Assessment of Important Cultural Properties (Buildings)

(Approved by the decision of the Director for the Architecture Division,
Cultural Properties Protection Department,
Agency for Cultural Affairs on April 10, 2001)
(Revised on June 12, 2012)

These are revised guidelines which were designed to present the specific methods to conduct the Basic Seismic Assessment according to the "Guidelines for Assessing Seismic Resistance of Important Cultural Properties (Buildings)" published in April, 1999, as specified in 13-Zai-Ken-Zo No. 2, "Notice of Establishing Implementation Guidance for Basic Seismic Assessment Based on the Guidelines for Assessing Seismic Resistance of Important Cultural Properties (Buildings)" issued by the Director for the Architecture Division, Cultural Properties Protection Department, Agency for Cultural Affairs on April 10, 2001.

The calculating formulas, numerical values, etc., specified in these guidelines are based on results of current research, so it should be possible to make successive revisions in the future.

Contents

Chapter 1. General Rules

Section 1. Scope

The Important Cultural Properties (buildings) to be targeted for a Basic Seismic Assessment shall be those that are deemed in need of such an assessment, based on the results of the Preliminary Seismic Assessments. In addition, even if the buildings are not made of wood, if their total floor area exceeds 10 square meters, then they shall, as a matter of principle, be subject to an assessment that is equivalent to the Basic Seismic Assessment.

It should be noted that buildings that shall be subject to these assessments are those that are used by many people and must meet special safety standards, or that are especially required to maintain functionality during a disaster, or other buildings that are acknowledged by prefectural education committees to be in need of assessment.

Section 2. Determining Necessary Seismic Resistance

The necessary seismic resistance shall be established for buildings that are targeted for assessment.

The necessary seismic resistance shall be set by the owners, chief administrators, and administrative organizations (hereinafter referred to as “owners”) in order to maintain the cultural value of the building and to ensure safety while it is being used.

The necessary seismic resistance shall be divided into the following categories, based on the allowable level of damage sustained during a major earthquake (Level 2). One of the following standards shall be set as the necessary seismic resistance. When necessary, an investigation shall be conducted for a moderate earthquake (Level 1).

(1) Standard for maintaining functionality: Functions can be maintained during a major earthquake.
(2) Standard for maintaining safety: There is no collapse during a major earthquake.
(3) Standard for possible restoration: While there is a danger of collapse during a major earthquake, the building can be restored as a cultural property.

Notes:
1) “Major earthquake” refers to the largest scale earthquake that can be expected at the site of the building.
2) “Moderate earthquake” refers to the type of earthquake at the site of the building that has a high probability of occurring at least once during the usable life of a normal building.

When determining necessary seismic resistance, owners may enlist the assistance and advice of the prefectural education committee, and may also seek the opinions of general architects, conservation architects, and other building experts.

For detailed information about determining necessary seismic resistance, please refer to “Chapter 2. Determining Necessary Seismic Resistance.”

Section 3. Assessment

The Basic Seismic Assessment is conducted to determine whether the seismic resistance of the building meets the standards for the necessary seismic resistance. In this assessment, a comparison is made between the maximum predicted value for response displacement and critical deformation to determine whether the set value for necessary seismic resistance is suitable.

Appropriate seismic assessment methods should be selected according to the structural characteristics of buildings. In this guidance, diagnostic methods include the Law of Conservation of Energy and the Equivalent Linearization Method, but it is acceptable to use another suitable diagnostic method depending on the building's properties.

For detailed information about assessment methods, please refer to "Chapter 3. Assessment and Judgment."

Section 4. Judgment

An assessment shall be made to determine whether any of the following items 1 through 3 apply to the seismic resistance of the building, and then a judgment shall be made about whether the standards for necessary seismic resistance are met. When necessary, an investigation shall be conducted for the case of a moderate earthquake.

1) Functionality can be maintained during a major earthquake.
2) No structural failure occurs during a major earthquake.
3) There is a danger of structural failure during a major earthquake.

For detailed information about judgment, please refer to "Chapter 3. Assessment and Judgment."

Section 5. Measures for Improving Seismic Resistance

Measures to enhance seismic resistance should be investigated based on the results of seismic resistance assessments (note that the "Expert Seismic Assessment" is conducted with consideration given to the seismic assessment and reinforcement proposal).

Article 16 in the Guidelines for Assessing Seismic Resistance of Important Cultural Properties (Buildings) should be kept in mind in the investigation.

For detailed information about measures to enhance seismic resistance, please refer to "Chapter 4. Measures for Improving Seismic Resistance."

Chapter 2. Determining Necessary Seismic Resistance

1. The necessary seismic resistance is divided into the following, based on the degree of allowable damage that may occur during a major earthquake, or even during a moderate earthquake:
(1) Standard for maintaining functionality: Functionality can be maintained during a major earthquake.
(2) Standard for ensuring safety: There is no structural failure during a major earthquake.
(3) Standard for possible restoration: There is a danger of structural failure during a major earthquake, but it can be restored as a cultural property.

2. The following should be kept in mind when setting the necessary seismic resistance:
(1) Items related to maintaining value as a cultural property
1) When delicate decorative members that account for most of the cultural value are damaged and may be difficult to restore, or when even only small-scale deformation might result in major loss of cultural value, these cases can be applied to standards for maintaining functionality.
2) Standards for ensuring safety can apply to cases where a wooden structure accounts for most of the cultural value, a certain degree of deformation can be restored, and most of the cultural value will be retained.
3) Standards for possible restoration can be applied to residential areas, where warehouses, storehouses, have major value as part of the residential area and most of the structure can be restored using original materials without major loss of cultural value even after a major deformation.
4) Standards for maintaining functionality or safety in response to conditions can be applied to cases of Buddhist statues, etc., that are kept indoors and cannot be easily restored.

(2) Items related to ensuring safety during use
1) For large-scale buildings that are ordinarily used by many people and which are not easy to evacuate, standards for maintaining functionality and ensuring safety shall be applied based on their respective conditions.
2）For public infrastructure facilities such as electric power plants, bridges, etc., that are necessary for daily life, buildings that engage in disaster mitigation activities, and buildings such as medical facilities that particularly need to maintain functionality at pre-disaster levels, standards for maintaining functionality shall apply.
3) Buildings other than those mentioned in 1) and 2) above that are used on a daily basis should follow standards for ensuring safety.
4) Shrines, warehouses, gates and *torii* (shrine gates), and other structures that are almost never entered or are used only as temporary passageways can follow standards for possible restoration.
5) However, in cases where taking measures to maintain safety can result in a noticeable loss of cultural value, it will be necessary to reconsider standards for necessary seismic resistance, including a review of how the structure is used.

(3) Items related to possible restoration levels

Even in cases where restorable standards can be applied, it would be desirable to increase the seismic resistance to the fullest extent possible while maintaining the cultural value of the building. In such cases, the target values shall be those at which buildings remain standing but may lean with half the force of a major earthquake (Level 2).

Table 1. Standards to determine necessary seismic resistance

			Standard for maintaining functionality	Standard for ensuring safety	Standard for possible restoration
Resistance target			The desired functionality is maintained during a major earthquake.	There is no collapse and no major threat to human life during a major earthquake.	There is a danger of collapse during a major earthquake, but the building's value as a cultural property is not lost and it can be restored.
Type of utilization			Facilities that are currently necessary for daily life (infrastructure), facilities that mitigate damage during a disaster, and large buildings used for daily activities by many people.	Buildings used on a daily basis.	Buildings almost never used, or used only for short periods.
Overview of the damage state of wooden structures	During a major earthquake	Structural Members	Deformation occurs.	Major deformation occurs but there is no collapse (1/30 or less of drift angle).	There is a danger of collapse.
		Safety	Safe	There is no major threat to human life.	Dangerous
		Functionality	Remains functional.	Functionality is lost.	Functionality is lost.
	(For reference) During a moderate earthquake	Framework	There is no damage, but joints can become loose.	Deformation occurs.	Major deformation occurs but there is no collapse.
		Joinery	There may be partial damage.	There is a danger of damage and partial collapse, but it can be restored and reused.	There is a possibility that more than half will be damaged and rendered unfit to use.
		Earthen walls	Almost no damage occurs.	Cracks appear and the wall must be repainted.	There is collapse, and the ground below the wall is damaged.
		Safety	Safe	Can be safely evacuated.	There is no major threat to human life.
		Functionality	Functionality is maintained.	Remains functional.	Functionality is lost.

Chapter 3. Assessment and Judgment

Section 1. Diagnostic Method and Points to Note

An appropriate diagnostic method is selected that is commensurate with the structural characteristics of the building.

Here, diagnostic methods include the law of conservation of energy and the equivalent linearization method, but it is acceptable to use another suitable diagnostic method depending on the structural characteristics of the building.

The law of conservation of energy is discussed in Section 2; the equivalent linearization method is discussed in Section 3.

Eight points to note in the diagnosis are listed below.

(1) Surveys of damage conditions shall be conducted and shall provide the basis for repairing damaged and deteriorating sections, and a diagnosis shall be made with the precondition that the building has its original soundness.

(2) Surveys of the foundation/ground shall be conducted when necessary.

(3) Input seismic force

Major, moderate and other relevant seismic motions are defined according to the Enforcement Order of the Building Standard Law, etc.

(4) Deformation limits

1) The respective deformation limits for a building to remain standing, maintain functionality, and sustain no damage are defined based on the structural characteristics of the building or other structure.

2) The deformation limit used to assess whether a building remains standing (non-collapse limit) is the highest value of deformation at which the vertical load support capacity is not lost on the load-deformation curve for each level and floor which takes repeated loading into account.

The standard story drift angle is about 1/30 in the case of a normal wooden structure. For structures with large deformability, such as traditional Japanese wooden structures, it can be set to about 1/15. However, structures with little deformability sometimes can not even satisfy 1/30. The story drift angle is set to an appropriate value based on the structural characteristics of the building.

3) The deformation limit for maintaining functionality is the maximum value of deformation at which there is no noticeable hindrance of building use due to fallen finishing materials, obstructions to the opening/closing of joinery, etc.

The standard story drift is 1/60 in the case of a normal wooden building, but it is set to an appropriate value based on the structural characteristics of the building.

4) The deformation limit of sustaining no damage is the highest value of the almost linear deformation (in an elastic region) on the load deformation curve for each level and floor.

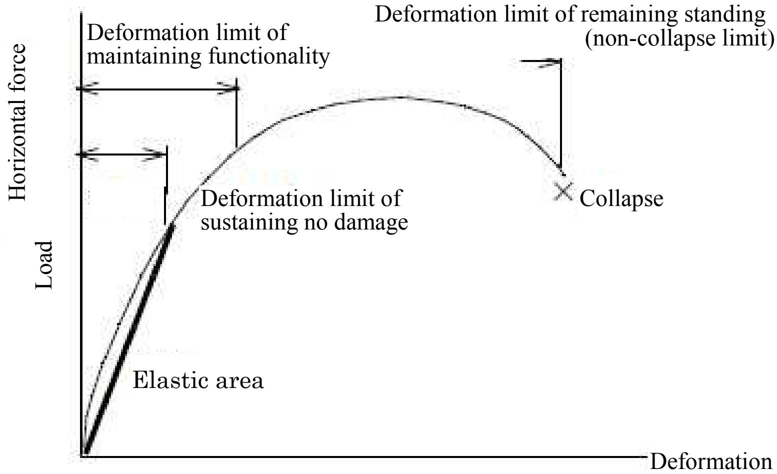


Figure 1. Schematic diagram of deformation limit

(5) Predicting response

1) The value of the maximum response displacement during an earthquake is predicted by appropriate methods based on the load-deformation relationship of each level, which is derived from the load-deformation relationship among the fixed load, live load, snow load, and elements of seismic resistance of each floor of the building in question.

2) When estimating the value of the maximum response displacement, it is necessary to take the influence of the uneven distributions of the rigidity, load, seismic resistance of the horizontal plane and the unevenness of seismic resistance of each floor, etc. into proper consideration.

3) When applying the energy conservation law, the range of the maximum response-displacement is calculated by comparing energy obtained by integrating up to the respective deformation limits for sustaining no damage, maintaining functionality, and remaining standing (non-collapse) in the load-deformation relation of each layer with input energy calculated from the load and initial rigidity of each floor.

4) When applying the equivalent linearization method, structures are replaced by single mass models using load and load-deformation relations of each level, and using equivalent linearization response where reduction in rigidity and historical decay due to plasticization, the maximum response is obtained from the acceleration response spectrum for prediction.

(6) Fixed load

1) In most cases, the fixed load of each floor is calculated by integrating the weight of each member. However, simplified calculations are allowable by estimating the weights per unit of roofs, walls, and floors which depend on the type and size of the building.

2) When calculations take into account matters such as warping and deformation of the horizontal plane, calculations are to be made of the weight of each member that needs to be modeled.

(7) Live load and snow load

The live load of floors and snow load of roofs should be based on the Enforcement Order of the Building Standard Law, but the actual conditions should also be considered.

(8) Elements of seismic resistance

1) The main elements of seismic resistance are pillars, beams, penetrating tie beams, walls, and so on.

It should be noted that reduced resistance based on issues related to rotting, insect damage, warpage, loosening of connectors and joints, differential settling of foundations, durability is not covered here, which assumes that buildings are in sound condition.

2) Each load-deformation relationship of the elements of seismic resistance was determined based on the results of previous experiments.

Section 2. Method Using the Energy Conservation Law

1. Concept

(1) The destructive force of earthquakes is expressed in terms of energy, and thus the maximum response of buildings during earthquakes is evaluated based on the concept that buildings deform until they store energy equal to earthquake energy.

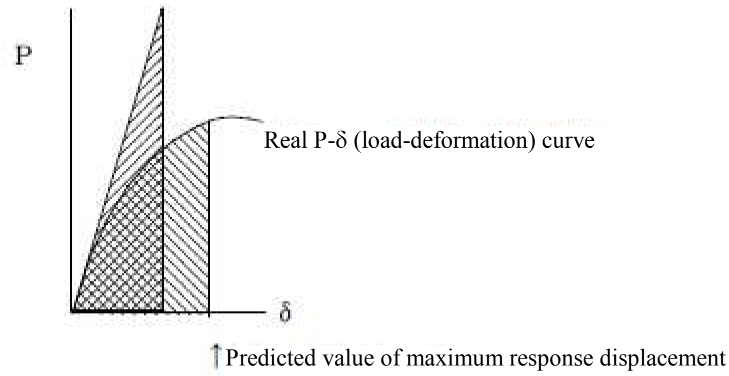


Figure 2. Concept of energy conservation law

2. Calculation of building loads (W)

(1) The expected combinations of building loads during an earthquake are defined as follows:

General region: fixed load (G) + live load (P)

Heavy snow region: fixed load (G) + live load (P) + snow load (S)

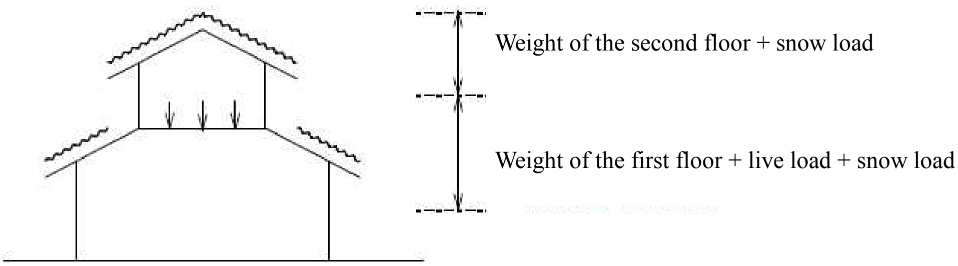


Figure 3. Concept of building loads

(2) Calculation of fixed loads (G)

1) As a rule, the fixed loads of each floor of buildings are the sum of the weights of wooden members, roofs, walls, etc. For buildings with two or more stories, the fixed loads are obtained by adding the loads of wooden members and walls in the upper half of the story height as the weight of the floor in question, and by adding those in the lower half as the load of the lower floor.

(i) Loads of wooden members

The load of wooden members is calculated by determining the total volumes of each kind of member woods and using their relative densities. Wooden board walls and ceilings, rafters and sheathing roof boards of the roof bed are also wooden members.

(ii) Loads of roofs

The loads of roofs are calculated by determining the areas of the roofs and using the weight per unit area of each kind of roofing material.

(iii) Loads of walls

The load of walls is calculated by determining the area of walls and using the weight per unit area of the wall.

2) For standard buildings, the fixed loads are calculated from the values which are obtained by multiplying the load per unit floor area of each part shown in Tables 1-4 by an adjustment factor depending on the type and size of buildings shown in Table 5. For outer and inner walls, their loads in the upper half of the story height are regarded as the loads in question, and those in the lower half are regarded as the loads of the lower floor.

(i) Roof loads

The standard roof loads per unit area are shown in Table 1. However, for floor areas lower than 40 m^2, they are calculated as standard roof load per unit of area, which includes the floor and eaves. For buildings that have multiple kinds of roofs, the loads are adjusted according to the ratio of the area of each kind of roof.

Table 1. Standard roof load per floor area, Wr (unit: N/m^2)

Roofing materials	Standard roof load, Wr
Clay tile roofing	3,300
Pantile roofing (bonding soil)	2,400
Pantile roofing (no bonding soil)	1,300
Cypress bark shingle roofing, wood shingle roofing	1,300
Metal plate roofing	1,000
Thatched roofing (this value corresponds to the thickness of 0.6 m)	1,500
Wooden Plate roofing (in the case of stone-weighted roofing, adding weights of stones)	600

(ii) Loads of outer wall

Standard loads of outer walls per unit floor area are shown in Table 2. For earthen walls, the weights are adjusted corresponding to their coating thickness, where the standard coating thickness is 15 cm for stud walls and 6 cm for plastered walls. For walls with different kinds of materials, the weights are adjusted corresponding to their proportion. For L-shaped buildings, the standard loads are reduced by 30%.

Table 2. Standard load of outer wall per floor area, Wg (unit: N/m^2)

Kind of outer wall	Standard load of outer walls, Wg
Earthen stud wall (earthen wall of plastered storehouse)	2,400
Earthen plastered wall	1,200
Wooden board wall	700

(iii) Loads of inner walls

The standard loads of inner walls per floor area are shown in Table 3. For buildings with different roofs, when the values of the floor area divided by the number of rooms are less than 15 m^2, the standard loads of earthen walls per floor area are 1200 N/m^2.

Table 3. Standard load of inner wall per unit floor area Wn (unit: N/m^2)

Kind of inner wall	Standard load of inner wall, Wn
Earthen wall	450
Wooden board wall	200

(iv) Loads of floors

The standard loads of unit floor area are shown in Table 4. However, earth (for two-storied private houses, earth is sometimes used to cover the 2^{nd} floor) and live loads are not included.

Table 4. Standard loads of unit area of floor Wf (N/m^2)

Kind of floor	Standard load of floor, Wf
Usual floor	600

(v) Adjustment of fixed loads

Adjustment factors for fixed loads are shown in Table 5, where the factors Kd are multiplied by the values in Tables 1 to 4. For temple/shrine buildings such as *shoin* (reception rooms), *yakuden* (guest halls), and *hojo* (residences for head priests), the adjustment factors are the same as private houses. However, for materials other than wood and plaster, such as chimneys of buildings with different roofs, the adjustment factors are separately calculated.

Table 5 Adjustment factors of fixed loads

Kind of building	Scale	Adjustment factor, Kd
Temple/shrine buildings	Height ≤ 10 m	1.6
	10 m < Height ≤12 m	2.0
	12 m < Height ≤15 m	2.3
	15 m < Height	2.5
Private house	Height ≤ 8 m	1.0
	8 m < Height ≤11 m	1.1
	11 m < Height	1.4

(3) Calculation of live loads (P)

1) For buildings with two or more stories, the live loads of floors should be considered, and properly calculated depending on the actual conditions of the buildings.

2) For standard use, the live loads are calculated according to Table 6, and for standard residences, live loads per unit area of floor (P_1) are 600 N/m^2.

Table 6. Standard live load classified by utility, P1 (N/m^2)

Application	Standard live load, P1
Living room	600
Office room	800
School room	1,100
Shop	1,300
Theater, assembly hall, etc. (in the case of immovable chairs)	1,600
Theater, assembly hall, etc. (other cases)	2,100

Note 1: For porches, stairs, and corridors leading to school rooms, shops, and assembly rooms, the live loads are 2,100 N/m^2.
Note 2: For balconies, the live loads are 600 N/m^2. However, for school buildings, the live loads are 1,300 N/m^2.

(4) Calculation of snow loads (S)

Snow loads (S) are calculated using the following equation.

$$S = s_o \times d \times A \times ub$$

where

s_0: unit load of snow, 20 N/cm・m^2, but for heavy snow regions, S is calculated according to a rule set up by the specially designated administrative government.

A: area of roof projected onto horizontal plane

d: snow height, according to values set up by the specially designated administrative government.

ub: shape factor of roof, $ub = \sqrt{\cos(1.5\beta)}$, where β is the slope of the roof (unit: degree).

3. Distribution coefficient of seismic shear forces (A_i)

Distribution coefficients of seismic shear forces A_i are calculated using the following equation:

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

α_i: value of aggregate weight from the top to i-th floors divided by the total weight of building above ground

T: first order natural period for structural design = 0.03h

h: height of building (unit: m)

4. Initial rigidity and storable energy limit

Initial rigidities (St) and current limit energy for the length and width of each floor are expressed by the sum of initial rigidities and the sum of current limit energies of elements of seismic resistance in both directions of each floor (Fig. 4).

Here, the limit energy is defined as the energy that the elements of seismic resistance in both directions of each floor can store until the elements reach a deformation limit. Energy corresponding to damage limit deformation, function limit deformation, and collapse limit deformation are defined as damage limit energy (E_{do}), function limit energy (E_{fo}), and collapse limit energy (E_{uo}).

The input energy shown in Figure 4 indicates earthquake energy input in both directions of each floor by earthquake forces.

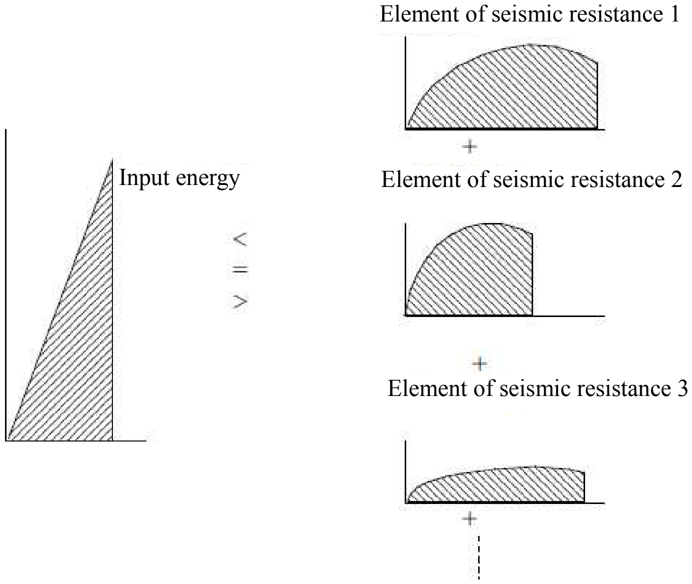


Figure 4. Input energy and amount of storable energy of each element of seismic resistance

(1) Initial rigidity and limit energy of full-length earthen walls

For full-length earthen walls, initial rigidity and fundamental limit energy per unit wall length are values given in Table 7, depending on the wall thickness. Initial rigidity and limit energy are obtained by multiplying these values by the wall length.

Table 7 Initial rigidity and limit energy of earthen wall

Horizontal resisting element	Initial rigidity (N/m/m)	Damage limit energy (N・m/m)	Function limit energy (N・m/m)	Collapse limit energy (N・m/m)
Earthen wall	10,000,000t/h	297th	880th	4,130th

h: story height (unit: m)

t: wall thickness (unit: m)

Note: Although the relationship between loads and deformations of earthen walls has a considerable variation depending on the coating thickness and type of finishing, a standard load-deformation relation is extracted from past experimental results (Fig. 5), with which the limit energy is calculated. However, after reaching a maximum, the strength sometimes shows a relatively rapid decrease due to repeatedly applied force, and thus considering this fact, safer values are taken.

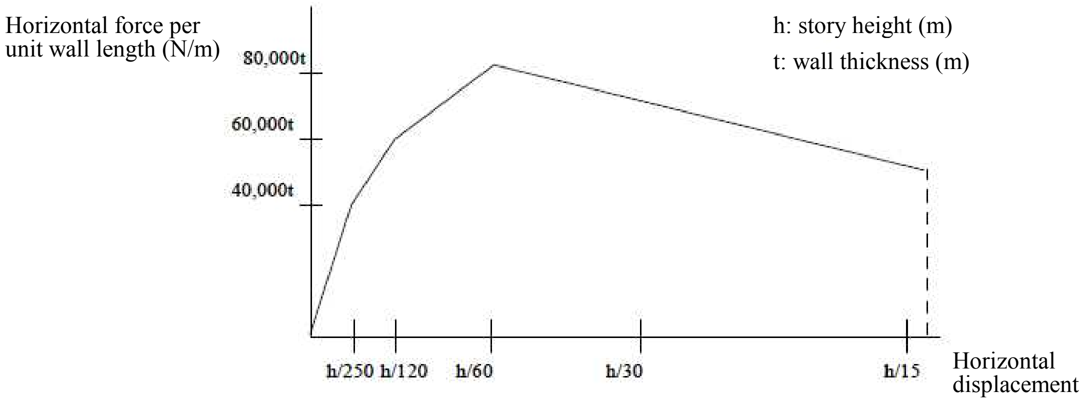


Figure 5. Relationship between load and deformation of earthen wall

(2) Initial rigidity and limit energy of pillars with hanging walls

1) Pillars with hanging walls can be considered horizontal elements of seismic resistance. (Fig. 6). This is only true when the diameter of the pillar is at least approximately 15 cm. Thus, the effect per frame consisting of hanging walls and pillars, initial rigidity and limit energy is considered in the following sections. However, in this case, as the value is per unit frame instead of per wall length, the wall length is not multiplied.

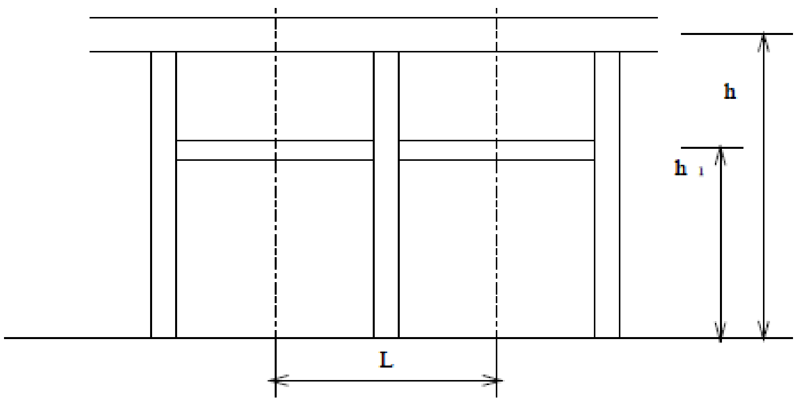


Figure 6. Frame of pillars with hanging walls

2) Initial rigidity (St)

The length of hanging walls which are supported by pillars is the distance from one pillar to the central point between it and the next pillars on both sides. For the pillars with the hanging walls shown in Figure 7, the relationship between the horizontal force and horizontal displacement within the elastic area is given by the following equation, because horizontal displacement of the top side, δ, is the sum of the horizontal shear displacement of the hanging wall, δw, and the bending deformation of the pillar below the hanging wall , δc.

$$\delta = \delta w + \delta c$$

$$\frac{Ph^2}{GLth_2}+\frac{Ph_1{}^3}{3EI}$$

where

P: horizontal force (N)

δ: horizontal displacement at top (m)

E: bending Young's modulus of pillar (N/m^2)

G: shear elastic modulus of hanging wall (soil) (N/m^2),
=10,000,000 N/m^2

I: moment of inertia of area (m^4)

L: length of hanging wall the pillar supports (m)
Note: Half the distance from one pillar to the central point between it and the next pillars on both sides

t: earthen wall thickness (m)

h: story height (m)

h_1: height from pillar base to bottom edge of hanging wall (m)

h_2: height of hanging wall (m)

Thus, the initial rigidity St (N/m) is expressed as follows.

$$S_t=\frac{P}{\delta}=\frac{3EGILth_2}{3EIh^2+GLth_1{}^2h_2}$$

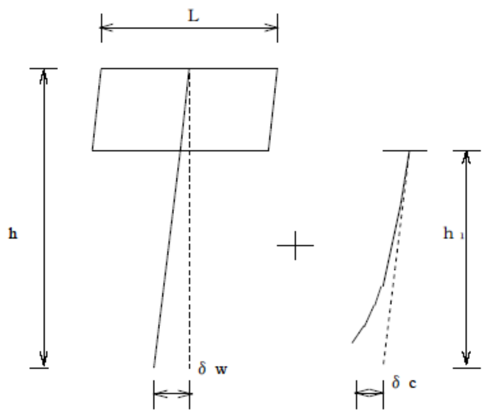


Figure 7. Deformation of pillars with hanging walls

3) Damage limit energy (E_{do})

The relationship between the load and displacement of pillars with hanging walls until the pillars collapse is approximated by the curves in Figure 8, where the maximum deformation varies depending on the magnitude relation between the horizontal force (Pcr) inducing the breaking of pillars and the horizontal force (Pw_3) inducing the breaking of hanging walls.

Here, which case to apply should be decided after comparing 1/120, δ_1, δ_2,and 1/120 (the no damage limit deformation of earthen walls). Since 1/120 cannot be greater than δ_{pb}, cases other than (i) and (ii) are unnecessary.

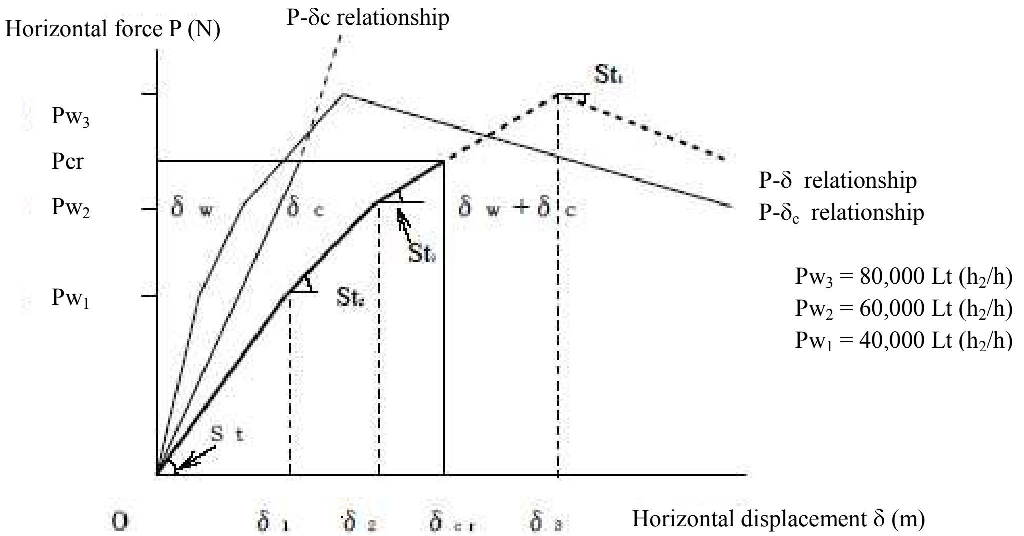


Figure 8. Relationship between load and displacement for pillars with hanging wall

(i) For $h/120 \leqq \delta_1$

$$E_{do} = \frac{S_t h^2}{28{,}800}$$

where $\delta_1 = \dfrac{P_{w1}}{S_t}$

h: story height
E_{do}: damage limit energy
St: initial rigidity of pillar with hanging wall

(ii) For $\delta_1 < h/120 \leqq \delta_2$

$$E_{do} = \frac{1}{2}\left\{P_{w1} \cdot \frac{h}{120} + P_{MAX}\left(\frac{h}{120} - \delta_1\right)\right\}$$

where $P_{Max} = P_{w1} + S_{t2}\left(\dfrac{h}{120} - \delta_1\right)$

$$S_{t2} = \frac{3EG_2 ILth_2}{3EIh^2 + G_2 Lth_1{}^3 h_2} \qquad (\mathrm{N/m})$$

G_2: the second slope for shear stress-strain relation of earthen wall
= 60, 000,000/13 (N/m^2)

4) Function limit energy (E_{f0})

Which case to apply should be decided after comparing δ_1, δ_2, δ_3, and h/60 (function limit deformation of an earthen wall). Since h/60 cannot be greater than δ, cases other than (i), (ii), and (iii) are unnecessary.

(i) For $h/60 \leqq \delta_1$

$$E_{fo} = \frac{S_t h^2}{7{,}200}$$

where E_{fo}: function limit energy

(ii) For $\delta_1 < h/60 \leqq \delta_2$

$$E_{fo} = \frac{1}{2}\left\{P_{w1} \cdot \frac{h}{60} + P_{MAX}\left(\frac{h}{60} - \delta_1\right)\right\}$$

where $P_{Max} = P_{w1} + S_{t2}\left(\frac{h}{60} - \delta_1\right)$

(iii) For $\delta_2 < h/60 \leqq \delta_3$

$$E_{fo} = \frac{1}{2}\left\{P_{w1}\delta_2 + P_{w2}\left(\frac{h}{60} - \delta_1\right) + P_{MAX}\left(\frac{h}{60} - \delta_2\right)\right\}$$

where $P_{Max} = P_{w2} + S_{t3}\left(\frac{h}{60} - \delta_2\right)$

$$\delta_2 = \frac{P_{w1}}{S_t} + \frac{(P_{w2} - P_{w1})}{S_{t2}}$$

$$S_{t3} = \frac{3EG_3ILth_2}{3EIh^2 + G_3Lt{h_1}^3h_2} \quad (\text{N/m})$$

G_3: the third slope for shear stress-strain relation of earthen wall
= 2, 400,000 (N/m^2)

5) Collapse limit energy (E_{uo})

Which case to apply should be decided after comparing P_{cr}, P_{w1}, P_{w2}, and h/15 (non-collapse limit deformation). The horizontal force at which the pillars break, P_{cr}, is calculated as follows.

$$P_{cr} = \frac{3Z_e f_b}{1.1h_1}$$

P_{cr}: horizontal force inducing breaking of pillar (N)
Z_e: the effective section modulus coefficient of pillar (m^3), be assumed to be (3/4)Z.
Z: section modulus of pillar (m^3)
f_b: long-term allowable bending stress of pillar (N/m^2)
h_1: height from pillar base to penetrating beam (m)

(i) For $P_{cr} \leqq P_{w1}$

(a) For $\delta_{cr} \leqq h/15$

$$E_{u0} = \frac{P_{cr} \cdot \delta_{cr}}{2} \quad (N \cdot m)$$

where $\delta_{cr} = \frac{P_{cr}}{S_t}$ (m)

E_{u0}: collapse limit energy

(b) For $h/15 < \delta_{cr}$

$$E_{u0} = \frac{S_t \cdot h^2}{450} \quad (N \cdot m)$$

(ii) For $P_{w1} < P_{cr} \leqq P_{w2}$

(a) For $\delta_{cr} \geqq h/15$

$$E_{u0} = \frac{S_t \cdot h^2}{450} \quad (N \cdot m)$$

(b) For $\delta_{cr} < h/15$

$$E_{u0} = \frac{1}{2}\{P_{w1} \cdot \delta_{cr} + P_{cr}(\delta_{cr} - \delta_1)\} \quad (N \cdot m)$$

where $\delta_{cr} = \delta_1 + \frac{P_{cr} - P_{w1}}{S_{t2}}$ (m)

(c) For $\delta_1 < h/15 \leqq \delta_{cr}$

$$E_{u0} = \frac{1}{2}\left\{P_{w1} \cdot \frac{h}{15} + P_{MAX}\left(\frac{h}{15} - \delta_1\right)\right\} \quad (N \cdot m)$$

where $P_{MAX} = P_{w1} + S_{t2}\left(\frac{h}{15} - \delta_1\right)$ (N)

(iii) For $P_{w2} < P_{cr} \leqq P_{w3}$

(a) For $\delta_1 \geqq h/15$ the same as in (ii) (a)

(b) For $\delta_1 < h/15 \leqq \delta_2$ the same as in (ii) (c)

(c) For $\delta_{cr} < h/15$

$$E_{u0} = \frac{1}{2}\{P_{w1}\delta_2 + P_{w2}(\delta_{cr} - \delta_1) + P_{cr}(\delta_{cr} - \delta_2)\} \quad (N \cdot m)$$

where $\delta_{cr} = \delta_2 + \frac{P_{cr} - P_{w2}}{S_{t3}}$ (m)

(d) For $\delta_2 < h/15 \leqq \delta_{cr}$

$$E_{u0} = \frac{1}{2}\left\{P_{w1}\delta_2 + P_{w2}\left(\frac{h}{15} - \delta_1\right) + P_{MAX}\left(\frac{h}{15} - \delta_2\right)\right\} \quad (N \cdot m)$$

where $P_{MAX} = P_{w2} + S_{t3}\left(\frac{h}{15} - \delta_2\right)$ (N)

(iv) For $P_{w3} < P_{cr}$

(a) For $\delta_1 \geqq h/15$ the same as in (iii) (a)

(b) For $\delta_1 < h/15 \leqq \delta_2$ the same as in (iii) (b)

(c) For $\delta_2 < h/15 \leqq \delta_3$ the same as in (iii) (d)

(d) For $\delta_3 < h/15$

$$E_{u0} = \frac{1}{2}\left\{P_{w1}\delta_2 + P_{w2}(\delta_3 - \delta_1) + P_{w3}\left(\frac{h}{15} - \delta_2\right) + P_{MAX}\left(\frac{h}{15} - \delta_3\right)\right\} (N \cdot m)$$

where $P_{MAX} = P_{w3} + S_{t4}\left(\frac{h}{15} - \delta_3\right)$ (N)

$$\delta_3 = \frac{P_{w1}}{S_t} + \frac{(P_{w2} - P_{w1})}{S_{t2}} + \frac{(P_{w3} - P_{w2})}{S_{t3}}$$

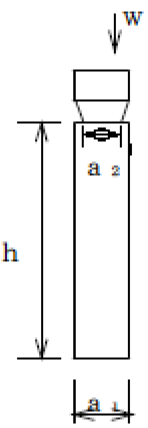
$$S_{t4} = \frac{3EIG_4Lth_2}{3EIh^2 + G_4Lth_1{}^3h_2} \quad (N/m)$$

G4: the fourth slope of shear stress-strain relation of earthen wall
=−600,000 (N/m2)

(3) Initial rigidity and limit energy of thick pillars

1) Pillars whose diameters are comparatively thick, like those of Buddhist temples, have a resistance due to pillar rocking. For the pillar shown in Figure 9, the rocking resistance is considered only when:

$$\frac{a_0}{h} \geqq \frac{1}{15}$$



a_1: Diameter of pillar base
a_2: width of *daito* (capital)

$$a_0 = \frac{a_1 + a_2}{2}$$

Figure 9. Shape of pillar

In Figure 9, assuming that the pillar is a rigid body, the rocking due to the balance of the moment appears when the horizontal force P exceeds

$$P_0 = (a_0/h)W$$

and the relationship between the horizontal force P and horizontal deformation δ is approximated by the following equation:

$$P_0 = W(a_0 - \delta)/h)$$

This corresponds to the dotted line shown in Figure 10. However, since the pillar will become embedded at the top and bottom ends, the load-deformation curve is an arc shape that passes through the origin. Thus, this is represented approximately by a polygon in Figure 10 based on the past experimental results.

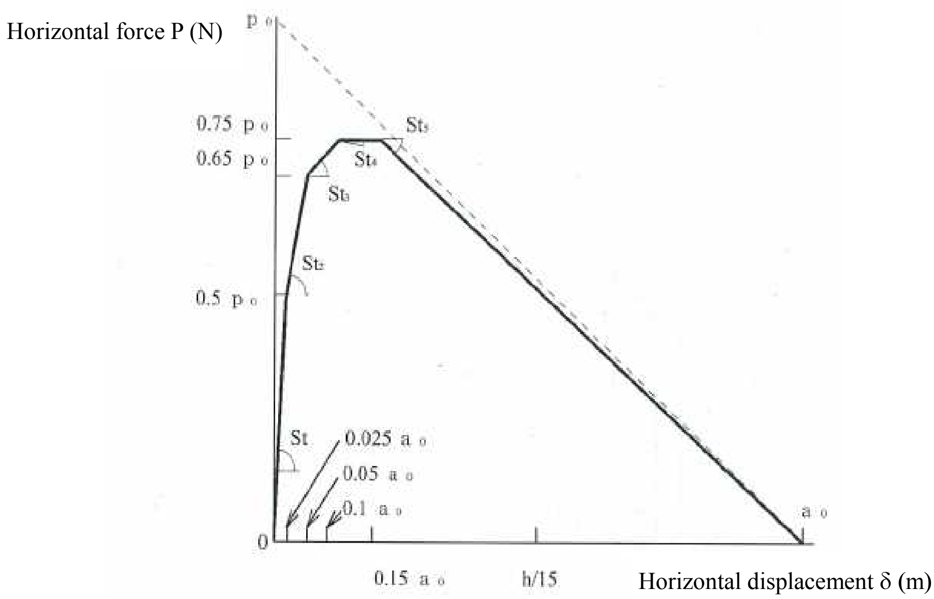


Figure 10. Relationship between load and deformation of rocking resistance of pillar

2) Initial rigidity

As the initial slope of the load-deformation curve shown in Figure 10, initial rigidity is calculated by the following equation:

$$S_t = \frac{P}{\delta} = \frac{0.5P_0}{0.025a_0} = \frac{20W}{h} \quad (\mathrm{N/m})$$

3) Damage limit energy (E_{do})

Which case to apply should be decided after comparing $0.025a_0$, $0.15a_0$, and h/120 (no damage limit deformation).

As h/120 is usually in the range from $0.025a_0$ to $0.15a_0$, the energy is calculated for the following cases (i), (ii) and (iii).

(i) For $0.025a_0 < h/120 \leqq 0.05$

$$E_{d0} = \frac{W}{200}\left(\frac{h}{24} + \frac{7a_0}{12} - \frac{7{a_0}^2}{8h}\right) \quad (\mathrm{N/m})$$

E_{do}: Damage limit energy
W: Axial force of column (N)
a_0: Averaged width of pillar head (or *daito* bottom if *daito* exists) and base (m)
h: Pillar length (m),
where St_2＝6w/h.

(ii) For $0.05a_0 < h/120 \leqq 0.1a_0$

$$E_{d0} = \frac{W}{800}\left(\frac{h}{18} + \frac{11}{3} \cdot a_0 - \frac{15}{2} \cdot \frac{{a_0}^2}{h}\right) \ (N \cdot m)$$

where $S_{t3} = 2W/h$

(iii) For $0.1a_0 < h/120 \leqq 0.15a_0$

$$E_{d0} = \frac{W}{160}\left(a_0 - \frac{31{a_0}^2}{10h}\right) \ (N \cdot m)$$

4) Function limit energy (E_{fo})

Which case to apply should be decided after comparing $0.05a_0$, $0.15a_0$, and 1/60 (failure to function limit deformation).

As h/60 is usually larger than $0.05a_0$, the energy is calculated for the following cases from (i) to (iii).

(i) For $0.05a_0 < h/60 \leqq 0.1a_0$

$$E_{f0} = \frac{W}{400}\left(\frac{h}{9} + \frac{11a_0}{3} - \frac{15}{4} \cdot \frac{{a_0}^2}{h}\right) \ (N \cdot m)$$

E_{fo}: Function limit energy,

where $S_{t3} = 2W/h$

(ii) For $0.1a_0 < h/60 \leqq 0.15a_0$

$$E_{f0} = \frac{W}{80}\left(a_0 - \frac{31}{20} \cdot \frac{{a_0}^2}{h}\right) \ (N \cdot m)$$

where $S_{t4} = 0$

(iii) For $0.15a_0 < h/60$

$$E_{f0} = \frac{W}{68}\left(a_0 - \frac{h}{120} - \frac{797}{400} \cdot \frac{{a_0}^2}{h}\right) \ (N \cdot m)$$

where $S_{t5} = \frac{15W}{17h}$

5) Collapse limit energy (E_{uo})

As h/15 is usually larger than $0.05a_0$, the collapse limit energy (E_{do}) is calculated as follows:

$$E_{u0} = \frac{W}{17}\left(a_0 - \frac{h}{30} - \frac{797}{1600} \cdot \frac{a_0^2}{h}\right) \quad (N \cdot m)$$

E_{uo} : collapse limit energy

5. Form coefficient (Fes)

The form coefficient (Fes) is used to increase the necessary storable horizontal energy of elements of seismic resistance are unbalanced in both the plan and elevation of buildings, and is obtained by the following equation:

Fes＝Fs・Fe

Fes: Form coefficient
Fs: Rigidity coefficient
Fe: Eccentricity coefficient

(1) Rigidity coefficient (Fs)

The rigidity coefficient Fs depends on the rigidity Rs, and is defined as follows:

Fs＝ (−5/3)・Rs＋2.0	(Rs≦0.6)
Fs＝1.0	(Rs＞0.6)

where $Rs = \frac{r_s}{\overline{r_s}}$

Rs: Rigidity of each floor
r_s: Reciprocal of story deformation angle of each floor
$\overline{r_s}$: Arithmetic mean of all r_s $= \frac{\Sigma^n r_{si}}{n}$
n: Number of floors above ground

The reciprocal of story deformation angle of each floor r_{si} is the ratio of the horizontal shear rigidity to the seismic force acting on each floor, and is expressed by the following equation:

$$r_{si} = \frac{1}{P_i/S_{ti}/h} = \frac{h_i \cdot S_{ti}}{P_i}$$

r_{si}: Reciprocal number of story drift angle of each floor
St_i: Horizontal shear rigidity = Initial rigidity
h_i: Story height of floor
P_i: Index of seismic force acting on floor ＝ $A_i \cdot W_i$
A_i: Distribution coefficient of seismic shear force
W_i: Load borne by floor concerned (the sum of loads of upper floors)

(2) Eccentricity coefficient (Fe)

The eccentricity coefficient depends on eccentricity Re, and is given as follows:

Fe = 1.0	(Re＜0.15)
Fe = (10/3)・Re＋0.5	(0.15≦Re≦0.3)
Fe = 1.5	(0.3＜Re)

where $Re = e/r_e$

Re: Eccentricity ratio of each floor

e: Distance between center of gravity and center of rigidity projected onto a plane

r_e: Square of value of torsional rigidity divided by horizontal rigidity

Here, the initial rigidity is used as the rigidity of each element of seismic resistance.

Rigidity coefficient

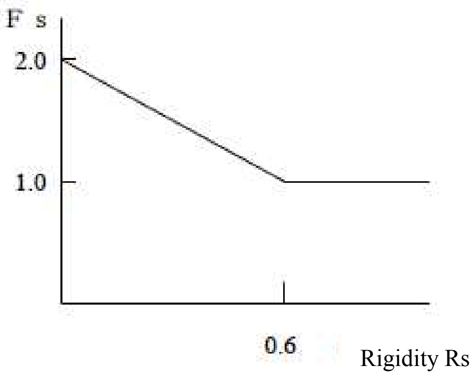


Figure 11. Rigidity and rigidity coefficient (Fs)

Eccentricity coefficient

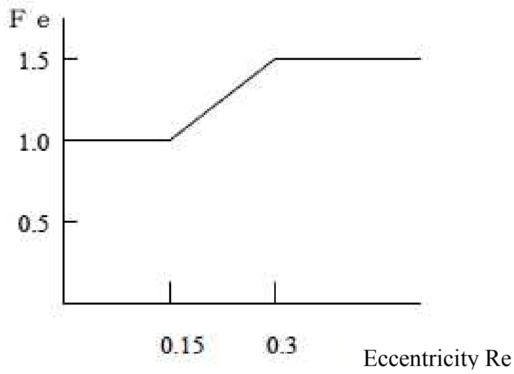


Figure 12. Eccentricity and eccentricity coefficient (Fe)

(3) Calculation of the center of gravity

The distances from the x and y-axes to the center of gravity, y_g and x_g, are calculated using the following equations:

$$x_g = \frac{\sum W_{ij} x_{ij}}{\sum W_{ij}}, \qquad y_g = \frac{\sum W_{ij} y_{ij}}{\sum W_{ij}}$$

Σ: Summation of all following values from the concerned floor to the top floor.

W_{ij}: When each floor is divided into smaller sections, the sum of fixed, live, and snow loads per section.

x_{ij}: The distance of the center of each section from the y-axis.

y_{ij}: The distance of the center of each section from the x-axis.

(4) Calculation of the point of center of rigidity

The distances from x and y-axes to the center of rigidity, y_g, x_g are calculated respectively using the following equations:

$$x_s = \frac{\sum St_{yi} x_i}{\sum St_{yi}}, \qquad y_s = \frac{\sum St_{xi} y_i}{\sum St_{xi}}$$

Σ: Summation in the floor whose center of rigidity is calculated.
St_{xi}: Initial rigidity of element of seismic resistance parallel to x-axis
St_{yi}: Initial rigidity of element of seismic resistance parallel to y-axis
y_i: Distance of element of seismic resistance from x-axis
x_i: Distance of element of seismic resistance from y-axis

6. Calculation of current limit energy

(1) Calculation of current limit energy

Damage limit energy, function limit energy, and collapse limit energy are calculated by the sum of these limit energies of all elements of seismic resistance.

7. Calculation of seismic force and input energy

(1) Earthquake region coefficient (Z)

The region coefficient is classified according to the degree of earthquake disasters, which is based on past records of earthquakes or the extent of the damage predicted by the states of faults, and is shown in Table 8. The region coefficient is defined by the 1980 Ministry of Construction Notification No. 1793-1 (revised to Notification No. 597 in 2007 of the Ministry of Land, Infrastructure, Transport and Tourism) and which is based on the regional classification defined in Article 88, Paragraph 1 of Enforcement Order of the Building Standard Law.

Table 8. Classification of regions

Classification	Prefectures, Cities, Towns	coefficient
I	Region other than classification of II - IV	1.0
II	Prefectures of Akita, Yamagata, Niigata, Shimane, Okayama, Hiroshima, Ehime, Kochi, Miyazaki In Hokkaido, cities of Sapporo, Hakodate, Otaru, Muroran, Kitami, Yubari, Iwamizawa, Abashiri, Tomakomai, Bibai, Ashibetsu, Ebetsu, Akabira, Mikasa, Chitose, Takikawa, Sunagawa, Utashinai, Fukagawa, Furano, Noboribetsu, Eniwa, Date, counties of Sapporo, Ishikari, Atsuta, Hamamasu, Matsumae, Kamiiso, Kameda, Kayabe, Yamakoshi, Hiyama, Nishi, Kudo, Okushiri, Setana, Shimamaki, Suttsu, Isoya, Abuta, Iwanai, Furuu, Shakotan, Furubira, Yoichi, Sorachi, Yubari, Kabato, Uryu, Yufutsu, Abashiri, Shari, Tokoro, Usu, Shiraoi, towns of Higashi-Kagura, Kamikawa, Higashikawa, Biei in Kamikawa County (Kamikawa-Shicho), In Aomori, cities of Aomori, Hirosaki, Kuroishi, Goshogawara, Mutsu, counties of Higashitsugaru, Nishitsugaru, Nakatsugaru, Minamitsugaru, Kitatsugaru, Shimokita	0.9

	In Fukushima, cities of Aizuwakamatsu, Koriyama, Shirakawa, Sukagawa, Kitakata, counties of Iwase, Minamiaizu, Kitaaizu, Yama, Kawanuma, Onuma, Nishishirakawa In Toyama, cities of Uozu, Namerikawa, Kurobe, county of Shimoniikawa In Ishikawa, cities of Wajima, Suzu, counties of Fugeshi, Suzu In Tottori, cities of Yonago, Kurayoshi, Sakaiminato, counties of Tohaku, Saihaku, Hino In Tokushima, counties of Mima, Miyoshi In Kagawa, cities of Takamatsu, Marugame, Sakaide, Zentsuji, Kanonji, counties of Shozu, Kagawa, Ayauta, Nakatado, Mitoyo Prefectures of Kumamoto, Oita (excluding regions in III)	
III	Prefectures of Yamaguchi, Fukuoka, Saga, Nagasaki In Hokkaido, cities of Asahikawa, Rumoi, Wakkanai, Monbetsu, Shibetsu, Nayoro, counties of Nakagawa (Kamikawa-Shicho), Mashike, Rumoi, Tomamae, Teshio, Soya, Esashi, Rebun, Rishiri, Monbetsu, towns of Takasu, Touma, Pippu, Ebetsu, Wassam, Kenbuchi, Asahi, Furen, Shimokawa in Kamikawa County (Kamikawa Shicho) In Kumamoto, Yatsushiro, Arao, Minamata, Tamana, Hondo, Yamaga, Ushibuka, Uto, counties of Hotaku, Uto, Tamana, Kamoto, Ashikita, Amakusa In Oita, cities of Nakatsu, Hita, Bungotakada, Kitsuki, Usa, counties of Nishikunisaki, Higashikunisaki, Hayami, Shimoge, Usa Kagoshima Prefecture (excluding Naze City and Oshima County)	0.8
IV	Okinawa Prefecture	0.7

(2) Soft soil coefficient (Rg)

For soft soils, the seismic force is increased to calculate the increase factor Rg. The values of Rg are defined in Table 9.

Table 9

Type of ground	Condition of ground	Rg
Type I ground	The soil condition is rocky and hard with gravelly layers, etc., and was mostly formed during or prior to the Tertiary, or results of surveys or research have indicated the predominant period at the ground frequency to be at about the same level.	1.0
Type II ground	Neither Type I nor Type III ground	1.2
Type III ground	Consists of humus, mud, or similar soil mainly formed by alluvial deposition (including embankments, if any) and is generally 30 meters or deeper (in the case of reclaimed marshes or swamps, the ground is usually at least 3 meters deep). Additionally, in the case of reclaimed land, not more than about 30 years have passed since reclamation, or results of surveys or research have indicated the predominant period at the ground frequency to be at about the same level.	1.5

(3) Vibration characteristic coefficient (Rt)

Vibration characteristic coefficients change seismic forces by natural periods of buildings and vibration characteristics of concerned buildings, depending on the category of grounds, and are calculated by the method defined in the Ministry of Construction Notification No. 1793-2, based on Article 88, Paragraph 1 of the Constriction Standards Act Enforcement Ordinance. However, when the fundamental natural periods T for designing buildings (= 0.03 h, where h is the height of buildings) are below 0.4 sec, the coefficients are 1.0, being independent of the types of grounds. For wooden buildings, the fundamental natural periods T are generally shorter than 0.4 sec, and thus Rt is usually 1.0. For natural periods longer than 0.4 sec, the values of Rt are specially calculated.

(4) Calculation of initial rigidity

The initial rigidity St in each direction of each floor of the building and other structure is calculated using the following equation:

$$St = \Sigma St_i$$

St: Initial rigidity in each direction on each floor (N/cm)

St_i: Initial rigidity of each element of seismic resistance in each direction on each floor obtained in section 4

(5) Calculation of seismic forces

The seismic force in each direction on each floor of the building is calculated using the following equation:

$$Qd = Rg \cdot Fes \cdot Qud$$

$$Qud = Z \cdot Rt \cdot Ai \cdot C_0 \cdot Wi$$

Rg: Soft soil coefficient

Fes: Form coefficient

Qud: Seismic shear force at each floor

Z: Seismic region coefficient

Rt: Vibration characteristic factor

Ai: Distribution factor of the seismic shear force coefficient in the building height direction

C_0: Standard shear coefficient

$C_0 = 1.0$ for major earthquake motions (Level 1)

$C_0 = 0.2$ for moderate earthquake motions (Level 2)

Wi: Building load above the concerned floor (N)

(6) Calculation of input energy

Input energy due to seismic motions E_d is calculated by the following equation in in each direction on each floor.

$$E_d = \frac{1}{2} \cdot \frac{Qd^2}{St}$$

Qd: Horizontal forces induced by seismic forces at each floor
St: Initial rigidity of each floor

8. Judgment

A judgment is made based on whether the earthquake resistance corresponds to the following items (1)-(3).

(1) Maintenance of functionality during a major earthquake

In each direction of each floor, it is confirmed that the following inequality is satisfied:

Input energy of major earthquake ≤ current limit energy for maintaining functionality

(2) No collapse during a major earthquake

In each direction of each floor, it is confirmed that the following is satisfied:

Input energy of major earthquake ≤ current limit energy for no collapse

(3) Collapse risk during a major earthquake

In each direction of each floor, it is confirmed that the following is satisfied:

Input energy of major earthquake > current limit energy for no collapse.

Section 3. Equivalent Linearization Method

1. Concepts

In this method, elasto-plastic response analyses of structures showing a nonlinear relation between forces and displacements are approximated by elastic response analyses. In such equivalent linear models, elasto-plastic restoring forces are replaced by equivalent rigidity K_E (less than initial rigidity K_I of the elasto-plastic model) and equivalent damping h_{eq} (greater than initial damping h_I of the elasto-plastic model).

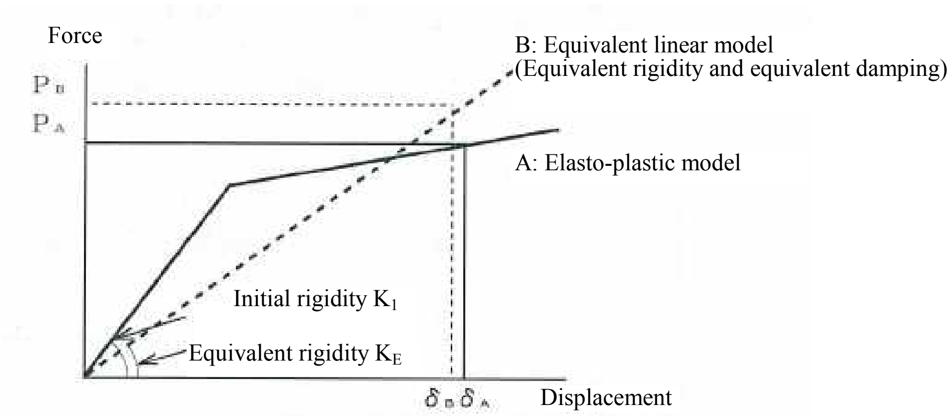


Figure 1. Concept of the equivalent linearization model

2. Earthquake motions

(1) Earthquake motions for verification are determined based on standard earthquake motions of engineering bedrock.

However, for special examinations and investigations, this rule does not apply.

Note: As a rule, engineering bedrock is defined as surface of firm geological layers which have sufficient thickness and shear wave velocities faster than 400 m/s or geological layers with firmness comparable to those.

When the grounds mentioned above do not exist within 30 m of the surface, the deeper one of either the position of 30 m below the surface or the position of the stake apex is adopted.

(2) Standard earthquake motions are defined by the following equation, based on the local earthquake activities, characteristics of past earthquakes, and subsurface soil conditions.

$$S = Z \cdot Gs \cdot S_O$$

S: Standard earthquake motions (m/s^2)

Z: Earthquake region coefficient

S_O: Standard earthquake motions (m/s^2) of engineering bedrock (standard earthquake motions of major and moderate earthquakes are S_{Os} and S_{Od}, respectively)

Gs: Amplification factors of acceleration due to subsurface grounds

1) Earthquake region coefficient (Z)

Refer to “7. Calculation of seismic force and input energy, (1) Earthquake region coefficient (Z)” in Section 2.

2) Amplification factor of acceleration due to subsurface grounds (Gs)

Amplification factors of acceleration due to grounds above engineering bedrock (Gs) are calculated by the equation shown in Table 2 for the regions corresponding to the Type I grounds described in Table 1, and by the equation shown in Table 3 for regions corresponding to Type II and Type III grounds.

Table 1

Type I ground	The ground is rocky and hard with gravelly layers, etc., and was mostly formed during or prior to the Tertiary or results of surveys or research have indicated the predominant period at the ground to be at about the same level.
Type II ground	Neither Type I nor Type III ground
Type III ground	Consists of humus, mud, or similar soil mainly formed by alluvial deposition (including embankments, if any) and is generally 30 meters or deeper. In the case of reclaimed marshes or swamps, the ground is usually at least 3 meters deep. Additionally, in the case of reclaimed land, not more than about 30 years have passed since reclamation, or results of surveys or research have indicated the predominant period at the ground to be at about the same level.

Table 2

$T < 0.576$	$Gs = 1.5$
$0.576 \leqq T < 0.64$	$Gs = 0.864/T$
$0.64 \leqq T$	$Gs = 1.35$

T is the natural period of buildings.

Table 3

$T < 0.64$	$Gs = 1.5$
$0.64 \leqq T < T_u$	$Gs = 1.5\ (T/0.64)$
$T_u \leqq T$	$Gs = q_v$

T_u is the value calculated using the following equations.

$T_u = 0.64\ (q_v/1.5)$

where $q_v = 2.025$ (for the Type II ground)

$= 2.7$ (for the Type III ground)

3) Standard earthquake motions (S_O)

Standard earthquake motions of major and moderate earthquake (S_{OS} and S_{Od}, respectively) are defined corresponding to the natural period T of buildings as follows.

Major earthquake motions $T < 0.16$ $S_{OS} = (3.2 + 30T)$

	$0.16 \leqq T < 0.64$	$S_{OS} = 8$
	$0.64 \leqq T$	$S_{OS} = 5.12/T$
Moderate earthquake motions	$T < 0.16$	$S_{Od} = (0.64 + 6T)$
	$0.16 \leqq T < 0.64$	$S_{Od} = 1.6$
	$0.64 \leqq T$	$S_{Od} = 1.024/T$

where S_{OS}, S_{Od} in m/s^2: response spectra for h=5%

3. Calculation of building load (W)

Refer to "2. Calculation of building load (W)" in Section 2.

4. Distribution coefficients of seismic shear forces (Ai)

Refer to "3. Distribution coefficients of seismic shear forces (Ai)" in Section 2.

5. Relationship between loads and deformations

Refer to "4. Initial rigidity and current limit energy" in Section 2, and then the load-deformation relation, based on the cumulative effects of each element of seismic resistance, is determined in each direction at each floor; however, in advance, the horizontal force loads are divided by the increase factor, Fei, at each floor determined according to the eccentricity ratios determined by "5. Shape factor (Fes)" in Section 2 (Fig. 2).

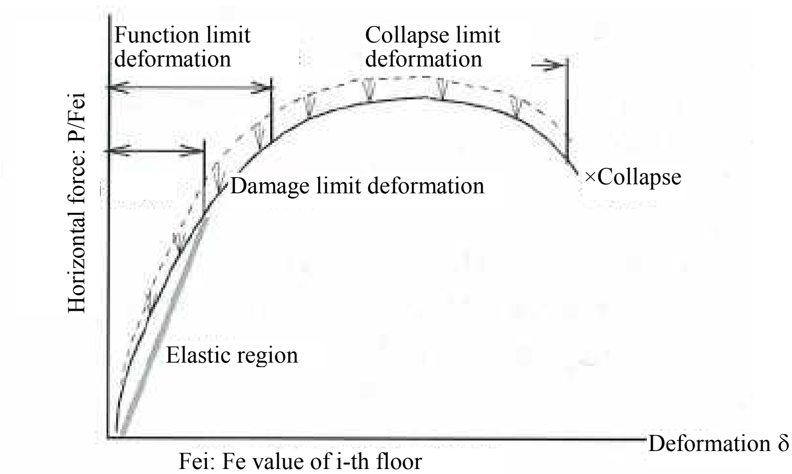


Figure 2. A load-deformation curve in each direction on each floor

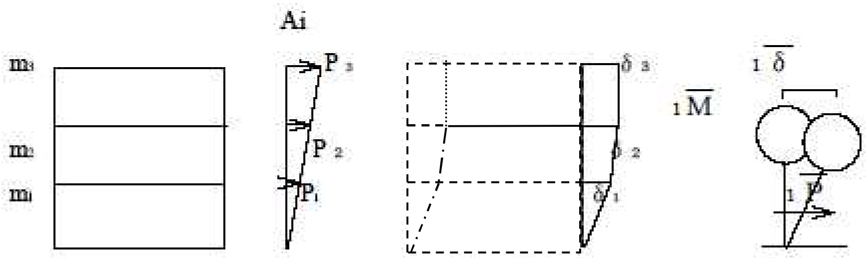
6. Load-deformation relation of equivalent single degree of freedom systems

One storied buildings or multi-storied buildings whose first story rigidity is sufficiently weak compared with other stories can be approximated as an equivalent single degree of freedom system by regarding the total mass above the center of the first story height as an equivalent mass and by using the load-deformation relation of the first floor.

For multi-storied buildings except those mentioned above, the load-deformation relation of equivalent single degree of freedom systems is determined from external forces and deformations of each floor, using the load-deformation relation for external force distributions (corresponding to elasto-plastic deformation) which are approximated as single degree of freedom systems. However, it is known that even if the A_i distributions are used as the external force distributions, the result is about the same, and thus the A_i distributions are used in this work.

When the mass, external force, and displacement at the i-th floor in a loaded state with the A_i distribution are denoted by m_i (ton), P_i (kN), and ${}_1\delta_i$ (m), respectively, the equivalent deformation ${}_1\delta$ (m) and the first order response acceleration ${}_1Sa$ (m/s²) are given as follows (Fig. 3):

$$ {}_1\overline{\delta} = \frac{\sum_{i=1}^{n} m_i \cdot {}_1\delta_i{}^2}{\sum_{i=1}^{n} P_i \cdot {}_1\delta_i} \cdot {}_1S_a \qquad {}_1S_a = \frac{\sum_{i=1}^{n} m_i \cdot {}_1\delta_i{}^2}{\left(\sum_{i=1}^{n} m_i \cdot {}_1\delta_i\right)^2} \cdot \sum_{i=1}^{n} P_i $$



Building model
External force distribution (Ai distribution)
Deformation distribution
Deformation approximated by an equivalent single degree of freedom system

Figure 3. Concept of load-deformation relation for equivalent single degree of freedom system

The acceleration-deformation relation determined as an equivalent single degree of freedom system is plotted on a graph where the ordinate indicates acceleration and the abscissa indicates deformation.

7. Acceleration response spectrum for verification

Predicting the response using the standard earthquake motion (S) shown in section 2, we consider the decrease in acceleration which is induced by the deformation of buildings and other structures by earthquake motions. Namely, when the decreasing rate of acceleration due to the vibration damping is Fh, the coefficient corresponding to the number of stories is p, and the coefficient corresponding to the effective mass ratio is q, the coefficient responding to the acceleration for verification (Sa) is defined as follows:

$$ Sa = Fh \cdot p \cdot q \cdot S \quad (m/s^2) $$

where the acceleration reduction factor Fh due to the vibration damping for equivalent single degree of freedom systems is defined as follows:

$$ Fh = \frac{1.5}{1 + 10heq} $$

$$\mathrm{heq} = 0.25\left(1 - 1/\sqrt{\mu}\right) + 0.05$$

μ = (Equivalent deformation)/(Damage limit deformation)

where when $\mu < 1$, $\mu = 1$.
However, when the pillar rocking is dominant among elements of seismic resistance, the damping heq is 0.1.

p: The coefficient corresponding to the number of stories is obtained from the following table:

Number of stories	1	2	3	4	5 or more
p	0.80	0.85	0.90	0.95	1.00

q: The coefficient corresponding to the effective mass ratio (the ratio of effective mass to total mass of the building) is obtained from the following table:

Effective mass ratio	Less than 0.75	0.75 or more
q	$0.75 \cdot \frac{\sum_{i=1}^{n} m_i}{{}_1\overline{M}}$	1.0

where ${}_1M$: Effective mass of the building (ton)

$${}_1\overline{M} = \frac{\left(\sum_{i=1}^{n} m_i \cdot {}_1\delta_i\right)^2}{\sum_{i=1}^{n} m_i \cdot {}_1\delta_i{}^2}$$

Here, the relation among the deformation Sd (m), the natural period T(s), and the acceleration response spectrum for verification Sa (m/s^2) is expressed as follows:

$$\mathrm{Sd} = \frac{T^2}{4\pi^2}\mathrm{Sa}$$

8. Calculation of response

On the figure obtained in section 6, the acceleration response spectrum for verification (Sa - Sd) obtained in section 7 is superposed, and the cross point is defined as the performance point of the equivalent single degree of freedom system (the response acceleration and the response displacement) (Fig. 4).

When the acceleration-deformation relation of the first story is directly used as an equivalent single degree of freedom system for a one-story building or other structure, the response deformation is the response deformation of buildings.

When multiple degree-of-freedom systems are replaced by equivalent single degree-of-freedom systems, the response deformation of the multiple degree of freedom systems corresponding to the response deformation of the equivalent single degree of freedom system is determined by the reverse of the procedure described in section 6, and is regarded as the response displacement at each floor of a building.

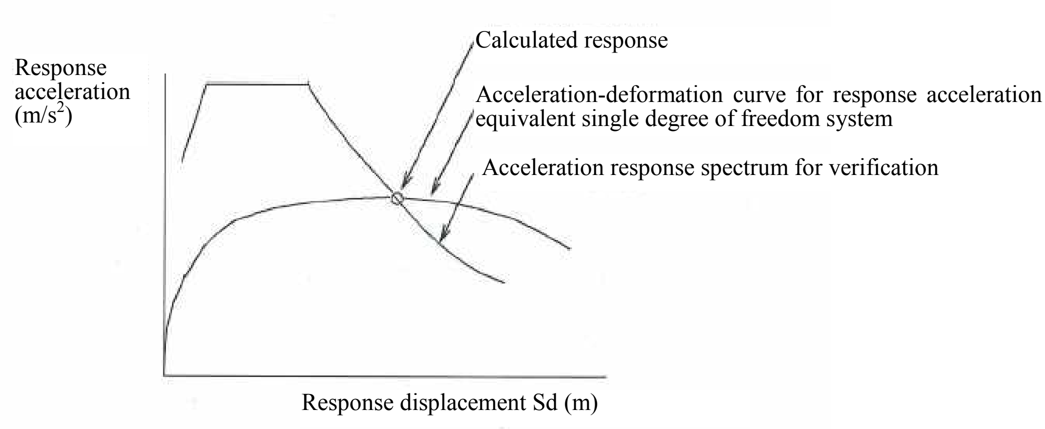


Figure 4. Determining method of response displacement (acceleration)

9. Judgment

A judgment is made about which of the following items (1)-(3) correspond(s) to seismic resistance. For this judgment, the magnitude relation of the response deformation in each direction of each floor and each limit energy obtained in section 8 is examined.

(1) Maintenance of functionality during a major earthquake

In each direction of each floor, it is confirmed that the following inequality is satisfied.

Response displacement during a major earthquake

≤ Function limit deformation.

(2) Non-collapse during a major earthquake

In each direction of each floor, it is confirmed that the following inequality is satisfied.

Response displacement at the time of major earthquake

≤ Non-collapse limit deformation.

(3) Collapse risk during a major earthquake

For any direction of any floor, it is confirmed that the following inequality is satisfied.

Response displacement at the time of major earthquake

> Non-collapse limit deformation.

Chapter 4. Measures for Improving Seismic Resistance

Basic concepts

1. When considering measures to improve seismic resistance based on the results of seismic assessments (note that the “Expert Seismic Assessment” is conducted in conjunction with consideration of the seismic assessment and reinforcement proposal), 16 in the Guidelines for Assessing Seismic Resistance of Important Cultural Properties (Buildings) should be kept in mind.

Improvement of management and utilization methods

2. Improvement of management and utilization methods

(1) Management system

A management system should be set up to manage and maintain the building, prevent fires, ensure safety, and preserve a disaster-prevention environment.

1) It would be desirable to have a permanent manager on the premises to be in charge of daily management.

2) If a permanent manager is not available, efforts should be made to create a system to undertake regular patrols and providing contact during emergencies.

(2) Maintenance and management

In order to ensure that seismic resistance does not decrease due to deterioration and deformation that have occurred over the years, as well as damage from weather, insects, etc., periodic inspections should be made with the following items in mind. In addition, it is necessary to make emergency inspections after the occurrence of a moderate or major earthquake, strong winds, heavy rains, etc.

1) Loosening of connecting joints
2) Damage to structural members
3) Peeling and/or cracking of earthen walls
4) Rain leakage
5) Passage of water through gutters, conduits, etc.
6) Ventilation
7) Insect damage (especially by ants)

(3) Management for fire prevention

1) A review shall be made of the use of flame and the storage of combustible materials, and measures shall be formulated to prevent these materials from igniting during an earthquake.

2) A review shall be made of the state of the fire-fighting equipment and system, and measures shall be formulated for extinguishing fires during an earthquake.

(i) Efforts shall be made to install basic fire-fighting equipment. It would be preferable to have self-contained equipment that can be operated even in the event of electricity and/or water stoppages (pressurized cistern, pump, or water cistern located in high place so it can flow downward naturally).

(ii) Efforts shall be made to ensure the seismic resistance of fire-fighting equipment, and measures shall be formulated to reinforce pipes to prevent breakage, etc.

(iii) Efforts shall be made to meet with relevant organizations and maintain a supply of water for fighting fires.
(iv) Efforts shall be made to form a fire brigade and hold fire-fighting drills.

(4) Safety management
1) Measures shall be formulated to prevent threats to human life. For buildings that are normally used by the public, the following should be kept in mind:
(i) Measures to manage the flow of people shall be formulated, such as clearly showing passageways, the areas that are open to the public, and so on.
(ii) An escape route shall be maintained for emergencies, and shall be marked in such a way as to be clearly recognizable during normal times.
(iii) If evacuation is difficult and/or time-consuming, consideration should be given to securing a temporary evacuation space.
(iv) Measures shall be formulated to limit, when necessary, openness to the public, the number of users, the time and frequency of use, access to indoor areas and surrounding areas, and to indicate the level of hazard..
2) For buildings containing important assets, such as Important Cultural Properties that should be protected from damage, measures shall be formulated to preserve the assets.
(i) Consideration should be given to the possibility of moving assets to other buildings.
(ii) Consideration should be given to protective measures such as installing covers, container boxes, and so on.
(iii) In cases where the measures described above are difficult to formulate but the seismic resistance of the building must still be improved, reconsideration should be made through the Basic and Expert Seismic Assessments.

(5) Environmental preservation
1) Sufficient consideration shall be given to the characteristic form and quality of the land at the site when taking necessary measures shall be taken, such as retaining walls, to prevent secondary damage resulting from landslide, water, to the building.
2) Measures shall be formulated to prevent damages such as structural failure and the spread of fire while considering the site conditions, such as the concentration of houses and the availability of open space, so that there will be no threat of secondary damage arising from the collapse of buildings or outbreak of fire in nearby buildings, structures, walls, trees, etc. (hereafter, “nearby structures”).
3) In the case of a building being damaged by an earthquake, attention should be given to the possibility of damage occurring to local residents and nearby structures to understand the risk of human access to the as area within a radius equal to the eaves height, and necessary measures should be formulated to limit access.

Emergency measures
3. Measures to take during emergency earthquake damage
(1) Emergency measures for preventing the spread of damage and deformation
1) Additional measures for supporting pillars, wires, etc., to prevent tilting, sagging
2) Measures for reinforcing members to prevent peeling or existing damage from progressing,

etc.

(2) Measures to prevent local damage from spreading to the entire structure

1) Retightening of joints and metal reinforcement of connections, etc.

2) Repainting of damaged areas (such as peeling, cracking, etc.) in earthen walls

(3) Simple reinforcement required in local parts

1) Retightening and metal reinforcement of places where there is a danger of structural members breaking, falling off, etc.

2) Addition of braces to supplement the cross-section area of weak structural members

3) Tightening and reinforcement of incidental structures such as signs, chimneys, *udatsu* (projecting gable parapets), etc.

4) Affixing of furniture that might fall or collapse.

5) Joining pillars together by using penetrating beams under the floor.

(4) Miscellaneous reinforcement with only a slight effect on preservation

Comprehensive measures

4. When making comprehensive repairs, including seismic reinforcement, it is important to keep the following in mind:

(1) General items to keep in mind

1) Specialized technicians and architects should be hired to maintain the quality of the work and the design.

2) A survey should be made of previous specifications and traditional specifications should be respected.

3) The construction period should be long enough to allow earthen walls to dry, etc.

4) Repairs to damaged members should be made so as to not only mend the shape but also to maintain as much of the same level of strength as possible.

5) A record should be kept of repairs and surveys.

(2) The following examples of work done in conjunction with comprehensive repairs that are accompanied by repair work that change the shape of buildings, have an effect on preservation, etc., should be considered after the results of the Expert Seismic Assessment have been obtained.

1) Ground reinforcement

2) Changes in the specifications of walls, fittings, etc.

3) Modification of the horizontal rigidity of floor framing, roof framing, etc.

4) Reduction of roof load

5) Changes in room partitions

6) Measures taken in conjunction with major changes in shapes, such as to the building frame, skeleton, etc.

7) Measures that have a major effect on the exterior and interior design

In cases where the present state of Important Cultural Properties is changed or something is done that has an effect on preservation, permission should be obtained beforehand from the

Director-General for Cultural Affairs (Article 43 of the Law of the Protection of the Cultural Properties).

Selection of reinforcement method

5. When reinforcement for seismic resistance is necessary, the reinforcement method should be selected by taking the following items in mind.

(1) Traditional reinforcement of traditional structural members is given priority in the consideration. Traditional methods include reinforcing structural members by splinting or "fish plating," *kanawa* (metal bands), reinforcing wall rigidity by bracing, and reinforcing joints by cleating, *shiguchi* (traditional joints), *kasugai* (iron clamps), among others.

(2) If changes in existing materials or specifications cannot be avoided, a preservation section shall be designed that avoids changing all members with the same materials and/or specifications.

(3) When objects are added to provide reinforcement, consideration shall be given to the detailed specifications for connection with existing areas, while making every effort to ensure that the building's original materials, design, etc., are not lost.

(4) When objects are added to provide reinforcement, a comparative investigation shall be made of the use of new materials and methods using materials having identical properties with the objects in question.

(5) Before new materials, methods, etc., are to be used, their performance shall be verified.

(6) The method and materials shall be given satisfactory consideration so that the reinforcement does not appear to be out of place.

(7) When one or more additional objects are to be installed onto a building's surface, the area for installation shall be selected so that it has the least effect on the cultural value and appearance, but also so that it can be distinguished from the original material.

(8) To facilitate future repairs and to give consideration to advances in seismic engineering and reinforcement techniques, methods and specifications shall be considered for removing or replacing the added object(s).

(9) Methods and specifications shall be considered with ease of installation, maintenance and management in mind.

(10) The maintenance of seismic resistance during repair and reinforcement work should also be taken into consideration.

Items to be kept in mind for reinforcement areas and methods

6. The following is a list of items that should be kept in mind when using various types of reinforcement methods. They are listed by reinforcement area and method.

(1) Reinforcement of ground and foundation

1) It should be known whether there are archaeological features beneath the structure, and if so, whether it is necessary to preserve them.

2) In nearly all cases, efforts shall be made to avoid changing the height of the foundation.

3) If the foundation is weak, it should be integrated using mat foundation, continuous footing, underground beams, etc.

4) Work such as loosely binding the framework with the foundation, making the foundation sufficiently wide, etc., should be done so that the entire framework will not separate from the foundation, even if it moves.

5) It may be necessary to consider connecting the foundation with the building, install an isolation system on the foundation.

(2) Integration of the framework

1) If the building foundation is ground sill, the connection between the ground sill and the pillar(s) shall be strengthened.

2) If the building foundation is made of stone, efforts should be made to mutually integrate the feet of the pillars.

3) When inserting new penetrating beams under the floor, methods shall be considered that do the least damage to pillars, and locations under the floor that are not noticeable shall be given priority.

(3) Strengthening structural members

1) When repairing broken or rotted areas, they should not only be repaired but also strengthened using iron/steel hoops or slats.

2) If the cross-section size of the member(s) is insufficient, priority should be given to methods that can avoid replacing original materials, such as *henzuke* (a frame-like arrangement), the use of *soebashira* (reinforcement post), or *nijubari* (two-tiered transverse beams).

(4) Reinforcing connecting joints

1) After the occurrence of an earthquake or strong winds, connecting parts should be inspected and wedges retightened.

2) When strengthening is made of joints using reinforced metal fittings, carbon fibers, etc., every effort must be made not to damage the original materials.

(5) Strengthening of walls

1) When increasing the resistance of existing walls

(i) Original specifications should be satisfactorily studied in order to gain an accurate understanding of resistance.

(ii) Measures should be taken to prevent the wall from detaching from the framework.

(iii) If a wall is being repainted, the work should be supervised properly to ensure that the wall

has the proper strength.
(iv) If a board wall is being turned into a earthquake-resisting wall, *aikugi* (straight nails with both ends pointed) should be used to connect the boards together.
2) When changing wall specifications to make reinforcements
(i) When changing the specifications of walls such as through the use of diagonal braces, reinforcement frames, reinforcement panels, etc., complete change should be avoided, and places for preserving the original specifications should be selected.
(ii) When changing the specifications of walls, the finish should preferably have a design that closely resembles the original one.
(iii) When installing diagonal braces, efforts should be made to prevent stress from concentrating in connecting sections.
3) When building a new earthquake-resisting wall
(i) When installing a new wall, in most cases no change should be made to the original floor plan.
(ii) When installing a new wall is unavoidable, there should be no major changes to the floor plan, and the location should be where there is as little adverse effect on functionality and design as possible.

(6) Reinforcement of fittings
1) When original fittings are used for earthquake-resisting walls
(i) If a framework is integrated into an earthquake-resisting wall, every effort should be made to avoid damaging structural members.
2) When changing fittings specifications of fittings to make reinforcements
(i) Replaceable items should be appropriately identified to promote preservation.
(ii) When changing fittings specifications, the finish should preferably have a design that closely resembles the original one.

(7) Improving horizontal in-plane rigidity
1) Areas hidden under floors and/or above ceilings should be used
2) If reinforcement boards are to be installed under floors and/or above ceilings, the work should be done with the dual purpose of increasing fire resistance.

(8) Miscellaneous
1) To deal with shaking in overhanging areas, measures should be taken to prevent overhanging parts from falling off the building.
2) Measures should be taken to prevent pillars from coming loose from the foundation as a result of vertical movements.
3) To prevent distortion, earthquake-resisting walls, etc., containing a good balance of elements of seismic resistance should be installed.
4) Usage that lead to noticeable increases in load should be avoided.
5) If it becomes necessary to make a special effort to reduce roof load, work should be done so as not to change the external appearance.

Structural characteristics to be kept in mind

7 The following is a list of structural characteristics for each type of architectural structure that should be kept in mind

(1) Private residences

1) There are many cases where living rooms and dirt floors have different structural characteristics.

2) There is a chance of *sasu* (diagonal roof braces) falling off.

3) There are many cases where wall length is insufficient or the arrangement of walls is uneven.

4) There are some cases where there are not enough *toshibashira* (pillars that extend from the first story of a building, through the second story, to the roof).

(2) Temple residences, such as *shoin* (reception rooms), *kyakuden* (guest halls), *hojo* (residences for head priests), *kuri* (residences for monks) and so on.

1) There are many cases where walls are not long enough and the arrangement of walls is uneven.

2) There are cases where the cross-section area and number of pillars are insufficient for the dimensions or scale of the structure.

3) There are numerous cases of fittings such as *shitomido* (wooden shutters), wooden sliding doors, etc, coming off.

(3) Shinto shrine and Buddhist temple architecture (Buddhist halls, *shaden* (shrine buildings), etc.)

1) The walls of *haiden* (worship halls) and the *honden-oiya* (shelters for main halls) of shrines are particularly lacking in length.

2) There is a possibility that overhanging sections such as *kohai* (step canopies) will shake.

3) There are cases where the foundation stone and independent pillar are not connected tightly.

4) There are also structures such as *romon* (two-storied gates) and high gates that do not have enough wall length on their first floor and may become unstable.

5) There are quite a few cases where roofs are especially heavy and eaves jut far out.

(4) Western wooden architecture

1) There are numerous cases where there is a danger of bricks falling from brick chimneys

2) In the case of a wooden frame and brick walls, there is a possibility of the brick wall falling out from the wooden frame.

3) Sometimes there is a lack of through column.

4) Sometimes diagonal braces are used, but are ineffective.