SECTION 4

SECOND RECOMMENDATION

The integrated behavior of the nonstructural component and its supporting structure has been considered in the formulation of the first recommendation. Hence, explicit information concerning the component, such as its response modification coefficient (R_c) and its period (T_c) is required. In certain situations, component-specific information may not be available. Therefore, a completely structure-driven design methodology for nonstructural components is useful in practice, i.e., parameters such as R_c and T_c do not appear explicitly in the design force equation. This methodology is also supported by the argument that two different light equipment with equal weight, attached to a heavy building floor, will receive approximately the same amount of inertia force except for perfectly tuned cases which have a low probability of occurrence in practice.

By following the same procedure as in the first recommendation, the design force on a mechanical or electrical equipment can be required to satisfy

$$F_p = \frac{A_v a_x a_c P W_c}{R_s} \tag{4.1}$$

where

$$a_c = \begin{cases} 1, & \text{for rigidly-mounted equipment} \\ 2, & \text{for flexibly-mounted equipment} \end{cases} \tag{4.2}$$

which accounts for the tuning effect as well as the reduction effect due to potential component yielding. All the remaining factors in Eq. (4.1) are exactly the same as those in Eq. (3.1)

For the design of architectural components, coefficient a_c in Eq. (4.1) is simply assigned to be unity and the performance criteria factor (P) is taken from Table 3-3.

SECTION 5

THIRD RECOMMENDATION

In this approach, we consider equipment detailing such as specific anchorage design and constraints imposed by the supporting structure, possible ductility capacity in the equipment design, and the transient characteristics of input motion as having major contributions to the assignment of C_c. The supporting building structure effect on the design of mechanical and electrical equipment is considered to be implicitly covered in the determination of C_c values and will not be considered elsewhere in this approach. Therefore, the response modification coefficient (R_c), to be introduced below, is closely related to the C_c values from Tables 8.2.2 and 8.3.2a in [7] for architectural component and equipment design but its values are more uniform than the C_c values for the various components. This is due to the fact that other factors such as location effect on the design force have been sorted out from somewhat arbitrarily assigned C_c values.

5.1 Suggested Revision of the Design Force

5.1.1 Design Force Equation

Mechanical and Electrical Equipment. In this approach, it is proposed that mechanical and electrical equipment and systems be designed for seismic force determined in accordance with the following equation:

$$F_p = C_p W_c \tag{5.1}$$

where

$$C_p = \frac{A_v a_x a_c P}{R_c} \tag{5.2}$$

in which A_v, W_c, a_x and a_c are the same as in the first recommendation. The performance criteria factor (P) is the same as in the current provisions. The response modification coefficient (R_c) is directly transferred from the values of C_c in the current provisions which includes the effect that the supporting structure has on the performance of equipment although this effect is considered to be small. Both the performance criteria factor and the response modification coefficient are tabulated in Table 5-1.

Architectural Components. For architectural component design, the design force required can also be determined by Eq. (5.1) but the amplification factor (a_c) is assigned to be 1.0. The response modification coefficient (R_c) and the performance criteria factor (P) are different from their values for mechanical and electrical components and systems as demonstrated in Table 5-2.

5.1.2 Development of the Design Force Equation

Floor and Equipment Acceleration Coefficients. Floor acceleration is considered to be linearly distributed along the structural height as shown in Fig. 3-1. The floor acceleration coefficient at h_x level is then denoted by $A_v a_x$ and the equipment acceleration coefficient at the same level can subsequently be expressed as $A_v a_x a_c$.

Inertia Force on Equipment. The inertia force acting on the equipment at h_x level can be written as

$$F_p = A_v a_x a_c W_c \tag{5.3}$$

Response Modification Coefficient. As in the design of building structures, the design force for the equipment can be reduced by a factor R_c, i.e.,

$$F_p = \frac{A_v a_x a_c W_c}{R_c} \tag{5.4}$$

due to earthquake variabilities and detailing construction of equipment including small amounts of allowable yielding in equipment anchorage and possible redundant constraint to the equipment.

Performance Criteria Factor. After the performance criteria factor has been considered, the design force on the equipment expressed in Eq. (5.4) becomes

$$F_p = \frac{A_v a_x a_c P W_c}{R_c} \tag{5.5}$$

5.1.3 Determination of Response Modification Coefficient (R_c)

As has been briefly discussed above, the value of R_c is related to the determination of the value of C_c in the current provisions but need to be modified subject to further investigations. In fact, R_c in this recommendation is close to the intermediate result ($\overline{R}_c$) of the first recommendation in deriving the response modification coefficient. In what follows, we simply compare a_x/R_c with C_c in the current provisions to determine the corresponding response modification coefficient (R_c). More specifically, we assign the minimum value of R_c to the most vulnerable components with maximum C_c values. For example, when a communication system is installed on the top floor of a building, the C_c value can be taken from Table 8.3.2a of the current provisions as 2.0 and the amplification factor on the top floor (a_n) is considered to be 3.75. The response modification coefficient is therefore equal to 3.75/2.0 = 1.88. All the R_c values for different mechanical and electrical equipment and architectural components are tabulated in Tables 5-1 and 5-2. For some nonstructural components, such as elevator shaft enclosures, stair enclosures, etc., which can span two or more floors in a building, the response modification coefficient R_c is considered to be the floor amplification factor a_x at 3/5 height divided by the corresponding C_c value. The 3/5 height approximately represents node of the second mode of the building structure and the corresponding response modification coefficient (R_c) implicitly accounts for the second mode contribution to the design force of nonstructural components attached to the upper 2/5-height floors of the building on the conservative side.

TABLE 5-1. Mechanical and Electrical Component and System Response Modification Coefficient (R_c) and Performance Criteria Factor (P)

Mechanical and Electrical Component or System	Response Modification Coefficient (R_c)	Performance Criteria Factor (P) Seismic Hazard Exposure Group I	II	III
Fire protection equipment and systems	1.25	1.5	1.5	1.5
Emergency or standby electrical systems	1.25	1.5	1.5	1.5
Elevator drive, suspension system, and control anchorage	2.0	1.0	1.0	1.5
General equipment Boilers, furnaces, incinerators, water heaters, and other equipment using combustible energy sources or high temperature energy sources chimneys, flues, smokestacks, and vents Communication systems Electrical bus ducts, conduit, and cable trays Electrical motor control centers, motor control devices, switchgears, transformers, and unit substations Reciprocating or rotating equipment Tanks, heat exchangers, and pressure vessels Utility and service interfaces	1.25	0.5	1.0	1.5
Manufacturing and process machinery	4.0	0.5	1.0	1.5
Pipe systems				
Gas and high hazard piping	1.25	1.5	1.5	1.5
Fire suppression piping	1.25	1.5	1.5	1.5
Other pipe systems	4.0	NR	1.0	1.5
HVAC and service ducts	4.0	NR	1.0	1.5
Electrical panel boards and dimmers	4.0	NR	1.0	1.5
Lighting fixtures	4.0	0.5	1.0	1.5
Conveyor systems (nonpersonnel)	4.0	NR	NR	1.5

TABLE 5-2. Architectural Component Response Modification Coefficient (R_c) and Performance Criteria Factor (P)

Architectural Component	Response Modification Coefficient (R_c)	Performance Criteria Factor (P) Seismic Hazard Exposure Group I	II	III
Exterior nonbearing walls	3.0	1.5	1.5	1.5
Interior nonbearing walls				
Stair enclosures	1.8	1.0	1.0	1.5
Elevator shaft enclosures	1.8	0.5	0.5	1.5
Other vertical shaft enclosures	3.0	1 0	1.0	1.5
Other nonbearing walls	3.0	1.0	1.0	1.5
Cantilever elements				
Parapets, chimneys, or stacks	1.0	1.5	1.5	1.5
Wall attachments (see Sec. 8.2.3)	1.0	1.5	1.5	1.5
Veneer connections	1.0	0.5	1.0	1.0
Penthouses	4.5	NR	1.0	1.0
Structural fireproofing	3.0	0.5	1.0	1.5
Ceilings				
Fire-rated membrane	3.0	1.0	1.0	1.5
Nonfire-rated membrane	4.5	0.5	1.0	1.0
Storage racks more than 8 feet in height (content included)	1.8	1.0	1.0	1.5
Access floors (supported equipment included)	1.25	0.5	1.0	1.5
Elevator and counterweight guiderails and supports	2.0	1.0	1.0	1.5
Appendages				
Roofing units	4.5	NR	1.0	1.0
Containers and miscellaneous components (free standing)	1.8	NR	1.0	1.0
Partitions				
Horizontal exits including ceilings	3.0	1.0	1.5	1.5
Public corridors	3.0	0.5	1.0	1.5
Private corridors	4.5	NR	0.5	1.5
Full height area separation partitions	3.0	1.0	1.0	1.5
Full height other partitions	4.5	0.5	0.5	1.5
Partial height partitions	4.5	NR	0.5	1.0

SECTION 6

COMPARISON OF DESIGN FORCES

In this section, two architectural components (parapet and storage rack) and one mechanical or electrical equipment are chosen to demonstrate that the recommended approaches overcome much of the shortcomings in the current provisions as discussed in Section 2.2. They are also used to compare the relative conservativeness of various provisions and design codes. All the comparisons are made based on the determination of the seismic design coefficient for components (C_p) as a function of structural period (T_s).

6.1 Maximum and Minimum Design Forces

It is instructive to make a simple comparison among maximum and minimum design forces specified in different provisions and codes. The maximum and minimum design forces of nonstructural components among three recommended provisions are compared in Table 6-1 and those of the 1991 NEHRP, the 1991 UBC, and the 1985 Tri-Service codes are tabulated in Table 6-2. It can be observed that the recommended force formulas yield maximum forces which are higher than those specified in the UBC and the current NEHRP provisions but are less than those given in the Tri-Service Code. On the other hand, the minimum design forces are consistently less than the values specified in the other provisions and codes. These larger variations in the design force exist since more factors such as soil property, equipment location, and supporting structural characteristics have been taken into account in the recommended formulas, which is a major contribution of the suggested formulation for nonstructural element design. In addition, these extreme forces can not be reached in most cases of practical design because the combination of all the factors contributing to the extreme values hardly occurs in practice.

6.2 Case Studies (Parapets, Storage Racks and General Equipment on Reinforced Concrete Shear Walls)

6.2.1 Effects of Soil Type, Structural Period and Component Location

It is instructive to know how significant the effects of the soil condition, structural period, and component location on nonstructural component design are before comparing design forces of the three recommended approaches with those of current available provisions and codes.

The parapet chosen here is considered to be atop a building structure. The storage rack and mechanical or electrical equipment are considered to be installed either at the top floor or at the middle floor of the building. The parameters used in these case studies are given in Table 6-3.

The seismic design coefficients (C_p) for a parapet determined by the three recommended revisions are presented in Fig. 6-1. It can be seen that C_p is a function of structural period and the soil type. As the building structure becomes more flexible or the soil layer under the structure becomes stiffer, the design force on the parapet decreases.

Figures 6-2, 6-3 and 6-4 present the seismic design coefficients determined by the three recommended approaches for a storage rack installed at the top or middle of the building. As one can see from these plots, the storage rack location in the building has a significant influence on the seismic design force imposed on it. The higher the storage rack location, the larger the required design force. When the storage rack is anchored to the very flexible building structure, the location effect on the design force becomes less significant, since the floor amplification factor (a_x) approaches unity in the limit. As in the case of parapet design, similar effects of structural period and soil type on the design force for the storage rack can be observed.

For seismic design of the mechanical or electrical equipment, the seismic design coefficients determined in accordance with the first recommended revision are respectively shown in Figs. 6-5(a,b) when it is installed at the top and middle of a building structure; those with the second recommended revision are shown in Figs. 6-6(a,b); and those with the third recommended revision are shown in Figs. 6-7(a,b), respectively. An examination of these figures indicates that the tuning effect on the design force is significant and effects of structural period, soil type and equipment location on the design forces are consistent with those found for the parapet and storage rack designs.

6.2.2 Comparisons Among the Three Recommendations

Comparisons among the three recommended revisions may shed more light on their relative merits toward improvement over the 1991 NEHRP provisions. The seismic design coefficients for the parapet, the storage rack, and the mechanical or electrical equipment are presented in Figs. 6-1, 6-8 and 6-9. It can be observed from Figs. 6-1 and 6-9 for the parapet and equipment design that the seismic design coefficient determined by the third recommendation is the highest while the corresponding value produced by the second recommendation is the smallest. This mainly results from the reduction effect due to structural yielding in these examples, i.e., $R_s = 1.5$. In contrast, the second recommendation provides a larger design force for the storage rack design since the response modification coefficient of the structure for the storage rack design ($R_s = 1.5$) is smaller than that of the component ($R_c = 1.8$). It should be noted that the seismic design coefficient calculated by the first recommendation may be larger in other cases than those of the remaining two recommendations. In other words, comparisons among the three recommendations can only be made on individual cases. Anyone of them can produce the most or least conservative design force for a given nonstructural component.

6.2.3 Recommended Revisions vs. U.S. Codes/Provisions

As can be seen from Fig. 6-1, the first and second recommended revisions provide smaller design forces than that given by the 1991 NEHRP provisions for design of the parapet atop a building structure with various flexibility while the third revision requires a larger design force for the same parapet attached to a stiff building structure and a smaller design force to a flexible building than that required by the current NEHRP provisions. Compared with the 1991 UBC or the 1985 Tri-Service Code, the recommended revisions require larger seismic design forces in a broad range of structural periods.

The seismic design coefficients for the storage rack calculated from the recommended revisions are compared in Figs. 6-2, 6-3 and 6-4 with the 1991 NEHRP provisions, the 1991 UBC and 1985 Tri-Service codes when it is installed at the top or middle of a building structure. The seismic design coefficients for the storage rack attached to the top floor, calculated by the recommended formulas, are greater in the case of a stiff building and smaller in the case of a flexible building than the corresponding coefficient provided in the current NEHRP provisions. The second recommended revision requires a slightly greater seismic design force for the storage rack design than that given by the 1991 UBC for the middle attachment as in the case of top attachment; whereas the first and third recommended revisions require smaller seismic design forces than the current NEHRP values but larger design forces than the 1991 UBC or the 1985 Tri-Service values when the storage rack is supported by a stiff building.

The seismic design coefficients of the mechanical or electrical equipment installed at the top of a building, calculated by the recommended revisions, are compared in Figs. 6-5(a), 6-6(a), 6-7(a) and 6-9 with those specified in the current NEHRP provisions, UBC and Tri-Service codes. In the tuned case, as shown in Fig. 6-9, the seismic design coefficients from the suggested approaches are larger for stiff building structures and smaller for flexible building structures than the corresponding values provided by the 1991 NEHRP and the 1985 Tri-Service codes but consistently larger than the design coefficient given by the 1991 UBC code. In the detuned case as shown in Figs. 6-5(a), 6-6(a) and 6-7(a), the recommended seismic design coefficients are also larger for a stiff structure and smaller for a flexible structure than the 1991 NEHRP values, but those provided by the second and third recommendations are consistently larger than the 1991 UBC and the 1985 Tri-Service values.

It is worth noting that, for a nonstructural component attached to a very flexible structure, the recommended design forces are in many cases smaller than those provided by the 1991 UBC and the 1985 Tri-Service codes. This seems contradictory to the design philosophies employed in the NEHRP provisions and UBC (or Tri-Service) Code (strength design vs. stress design). In fact, this phenomenon only indicates the over conservativeness involved in the UBC and Tri-Service codes for this case since the recommended revisions in this report are justified to a certain degree by analyses, experimental results and observation data from past earthquakes.

TABLE 6-1. Maximum and Minimum Design Forces (1)

	first recommendation		second recommendation		third recommendation	
Design Code	Architectural	Mechanical & Electrical	Architectural	Mechanical & Electrical	Architectural	Mechanical & Electrical
Basic Equation	$F_p = \frac{A_v a_x P W_c}{R_s R_c}$	$F_p = \frac{A_v a_x a_c P W_c}{R_s R_c}$	$F_p = \frac{A_v a_x P W_c}{R_s}$	$F_p = \frac{A_v a_x a_c P W_c}{R_s}$	$F_p = \frac{A_v a_x P W_c}{R_c}$	$F_p = \frac{A_v a_x a_c P W_c}{R_c}$
Basis	Strength Design	Strength Design	Strength Design	Strength Design	Strength Design	Strength Design
Maximum Value	$\frac{0.4 \times 3.75 \times 1.2 W_c}{1.0 \times 1.0}$ $= 1.80\ W_c$	$\frac{0.4 \times 3.75 \times 2.5 \times 1.2 W_c}{1.0 \times 1.1}$ $= 4.09\ W_c$	$\frac{0.4 \times 3.75 \times 1.2 W_c}{1.0}$ $= 1.80\ W_c$	$\frac{0.4 \times 3.75 \times 2.0 \times 1.2 W}{1.0}$ $= 3.60\ W_c$	$\frac{0.4 \times 3.75 \times 1.5 W_c}{1.0}$ $= 2.25 W_c$	$\frac{0.4 \times 3.75 \times 2.5 \times 1.5 W}{1.25}$ $= 4.50 W_c$
Minimum Value	$\frac{0.05 \times 1.0 \times 0.8 W_c}{2.0 \times 3.0}$ $= 0.007\ W_c$	$\frac{0.05 \times 1.0 \times 1.0 \times 0.8 W}{2.0 \times 2.7}$ $= 0.007\ W_c$	$\frac{0.05 \times 1.0 \times 0.8 W_c}{2.0}$ $= 0.020 W_c$	$\frac{0.05 \times 1.0 \times 1.0 \times 0.8 W}{2.0}$ $= 0.020 W_c$	$\frac{0.05 \times 1.0 \times 0.5 W_c}{4.5}$ $= 0.006 W_c$	$\frac{0.05 \times 1.0 \times 1.0 \times 0.5 W}{4.0}$ $= 0.006 W_c$

TABLE 6-2. Maximum and Minimum Design Forces (2)

	1991 NEHRP		1991 UBC	1985 Tri-Service	
Design Code	Architectural	Mechanical & Electrical	Nonstructural	Architectural	Mechanical & Electrical
Basic Equation	$F_p = A_v C_c P W_c$	$F_p = A_v C_c P a_c W_c$	$F_p = Z I C_p W_p$	$F_p = Z I C_p W_p$	$F_p = Z I A_p C_p W$
Basis	Strength Design	Strength Design	Allowable Stress	Allowable Stress	Allowable Stress
Maximum Value	$0.4 \times 3.0 \times 1.5 W_c$ $= 1.80\ W_c$	$0.4 \times 2.0 \times 1.5 \times 2.0 W_c$ $= 2.40\ W_c$	$0.4 \times 1.5 \times 2.0 W_p$ $= 1.20\ W_p$	$1.0 \times 1.5 \times 0.8 W_p$ $= 1.20\ W_p$	$1.0 \times 1.5 \times 5.0 \times 0.8 W_p$ $= 6.00\ W_p$
Minimum Value	$0.05 \times 0.6 \times 0.5 W_c$ $= 0.015\ W_c$	$0.05 \times 0.67 \times 0.5 \times 1 W_c$ $= 0.017\ W_c$	$\frac{2}{3} \times 0.05 \times 1.0 \times 0.75 W_p$ $= 0.025\ W_p$	$\frac{3}{16} \times 1.0 \times 0.3 W_p$ $= 0.056\ W_p$	$\frac{3}{16} \times 1.0 \times 1.0 \times 0.3 W_p$ $= 0.056\ W_p$

TABLE 6-3. Parameters Used in Case Studies

Provisions/Codes	Parapet (a_c=A_p=1.0)	Storage Rack (a_c=A_p=1.0, P=I=1.0)	Equipment (P=I=1.0) (a_c=detuned/ tuned)
first Recommendation	A_v=0 2, P=1.2, R_s=1.5, R_c=1.0	A_v=0.2, R_s=1.5, R_c=1.5	A_v=0.2, R_s=1.5, R_c=1.1, a_c= 1.0/2.5
second recommendation	A_v=0.2, P=1.2, R_s=1.5	A_v=0.2, R_s=1.5	A_v=0.2, R_s=1.5, a_c= 1.0/2.0
third Recommendation	A_v=0.2, P=1.5, R_c=1.0	A_v=0.2, R_c=1.8	A_v=0.2, R_c=1.25, a_c= 1.0/2.5
1991 NEHRP	A_v=0.2, P=1.5, C_c=3.0	A_v=0.2, C_c=1.5	A_v=0.2, C_c=2 0, a_c= 1.0/2.0
1991 UBC	Z=0.2, I=1.25, C_p=2.0	Z=0.2, C_p=0.75	Z=0.2, C_p=0.75
1985 Tri-Service	Z=0.5, I=1.25, C_p=0.8	Z=0.5, C_p=0.3	Z=0.5, C_p=0.3, A_p= 1.0/5.0

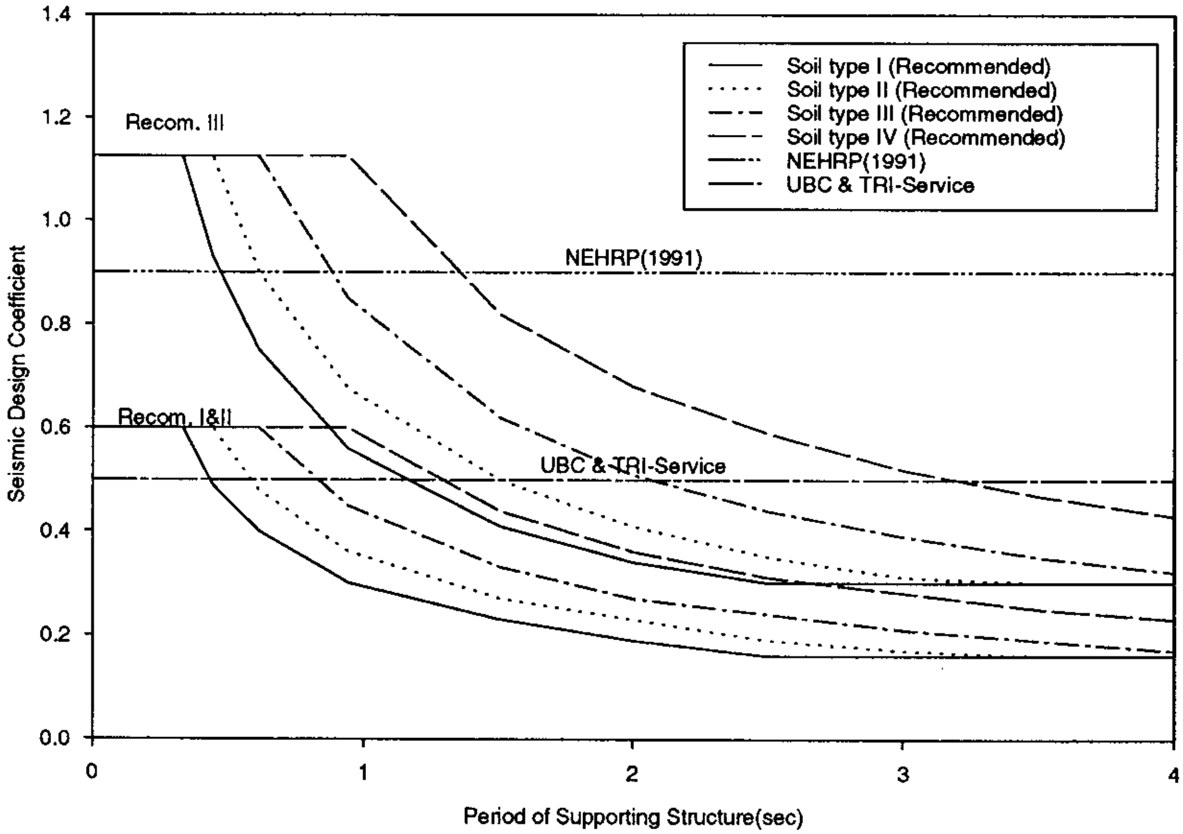

Fig. 6-1 Seismic Design Coefficient for Parapet at Top of Building

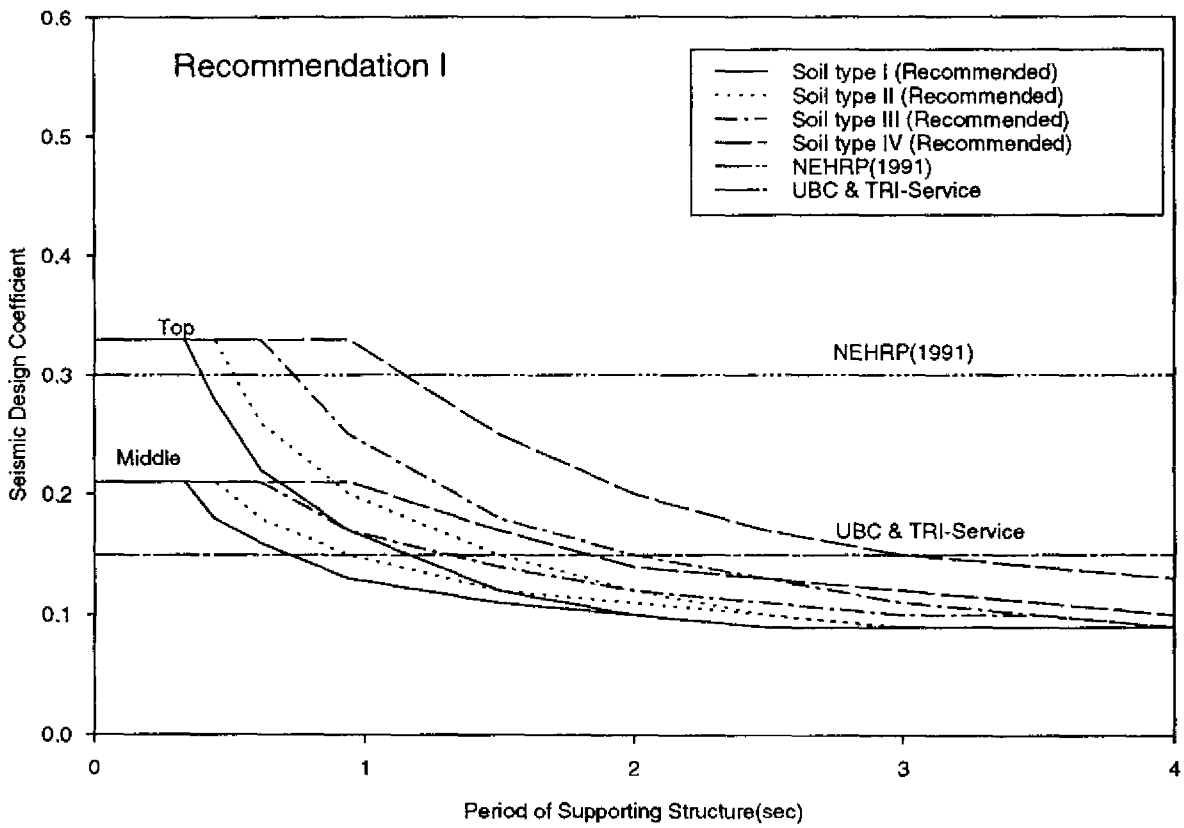

Fig. 6-2 Seismic Design Coefficient for Storage Rack at Different Locations (First Recommendation)

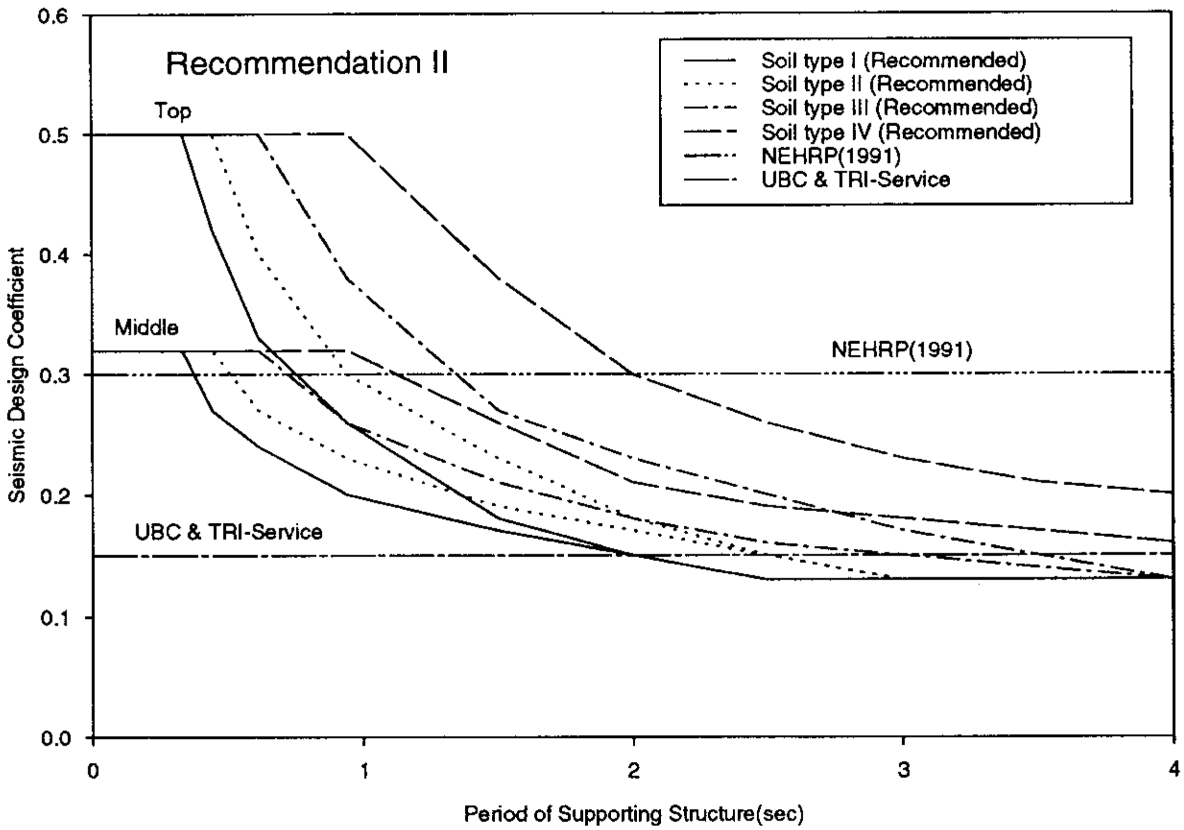

Fig. 6-3 Seismic Design Coefficient for Storage Rack at Different Locations (Second Recommendation)

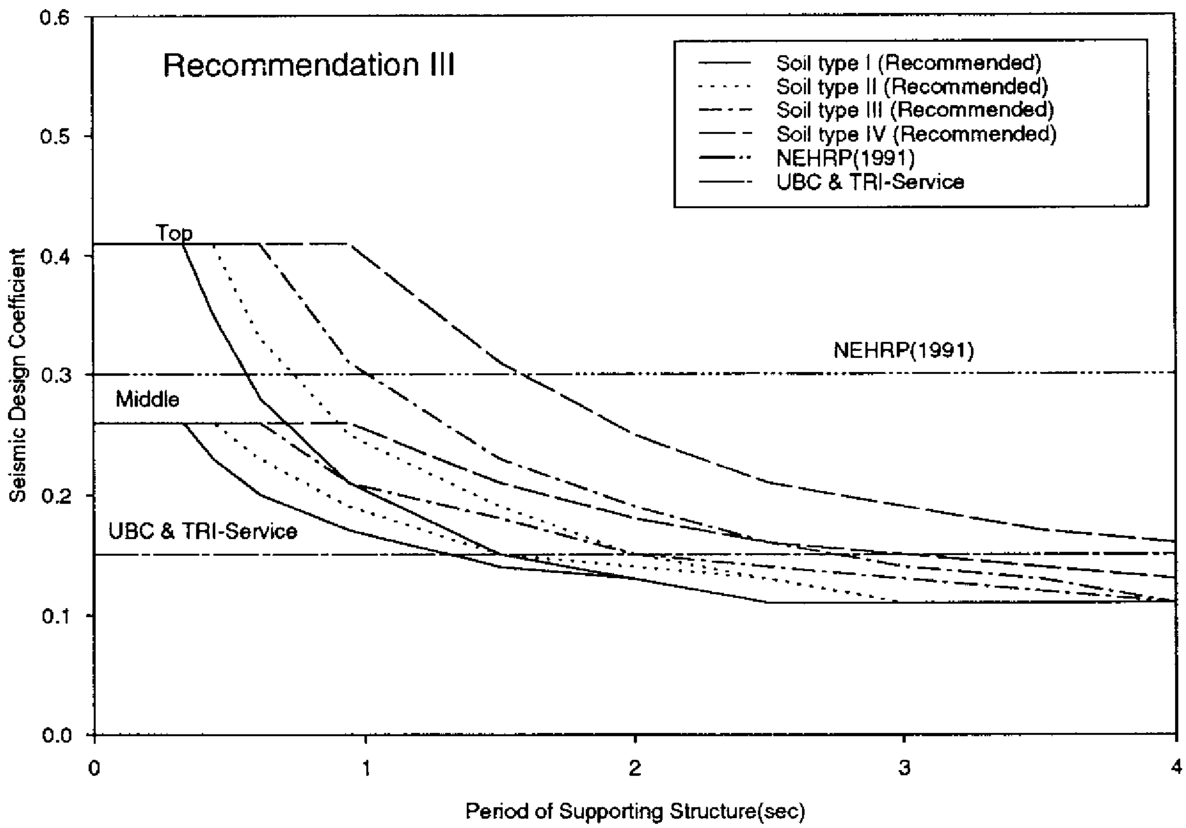

Fig. 6-4 Seismic Design Coefficient for Storage Rack at Different Locations (Third Recommendation)

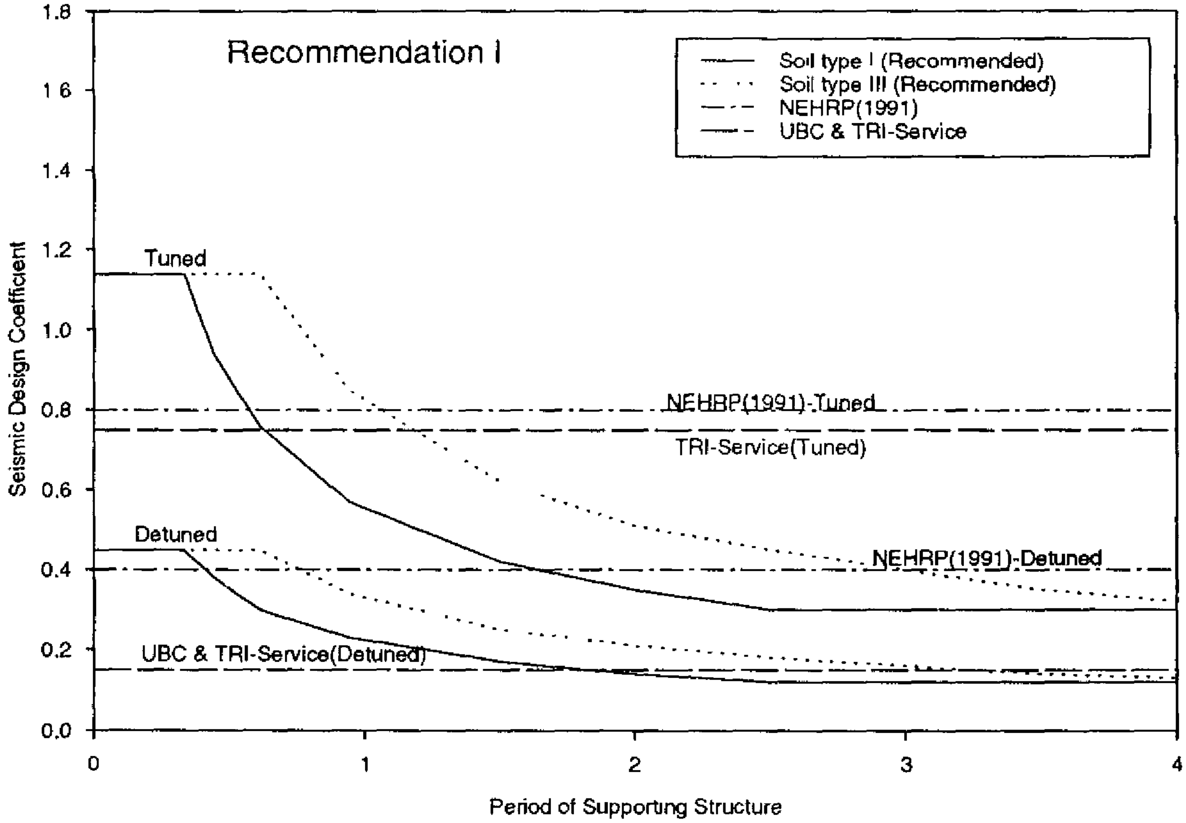

Fig. 6-5(a) Seismic Design Coefficient of Equipment at Top of Building (First Recommendation)

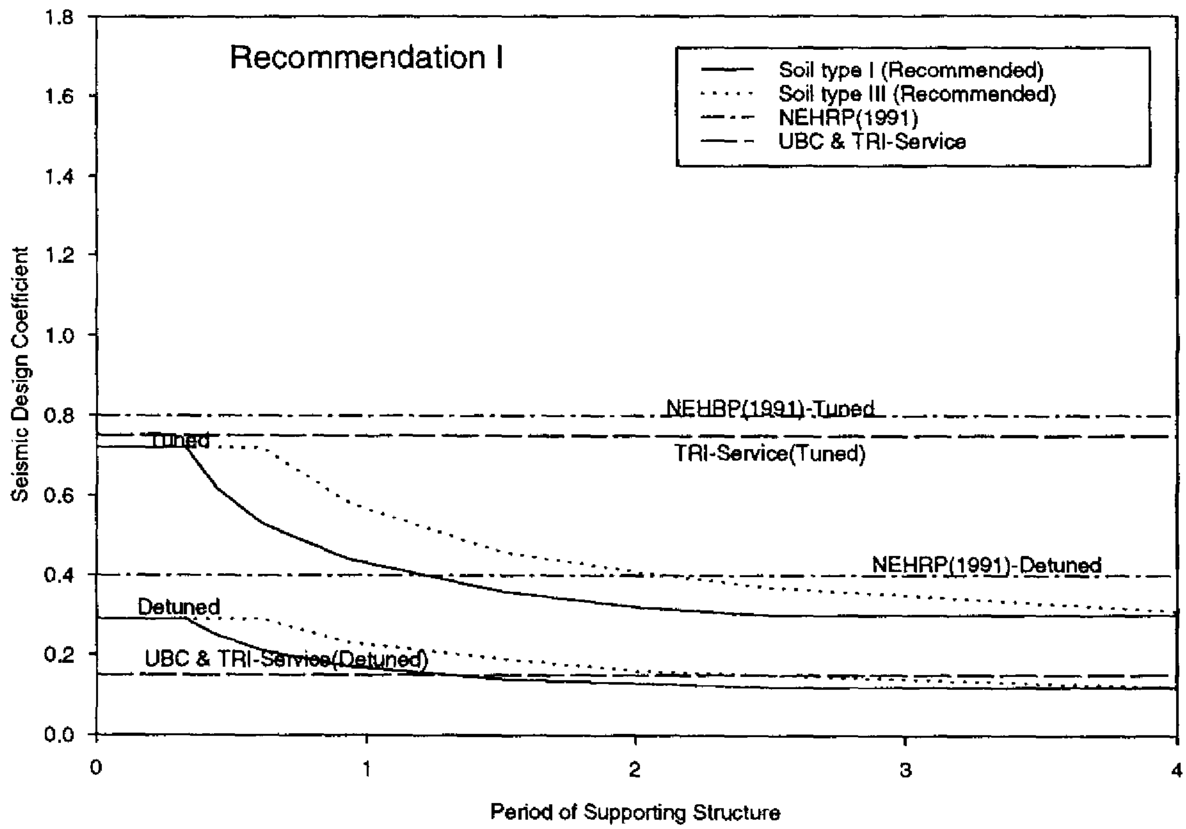

Fig. 6-5(b) Seismic Design Coefficient of Equipment at Middle of Building (First Recommendation)

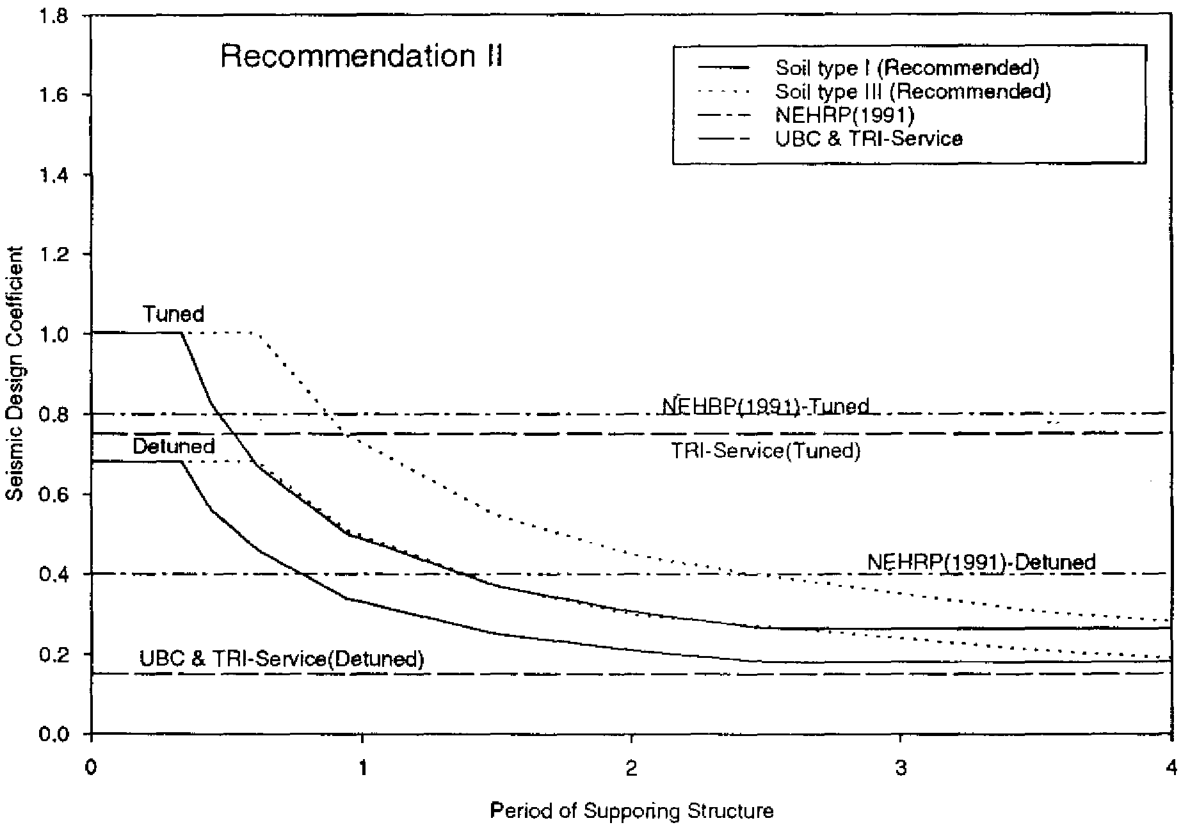

Fig. 6-6(a) Seismic Design Coefficient of Equipment at Top of Building (Second Recommendation)

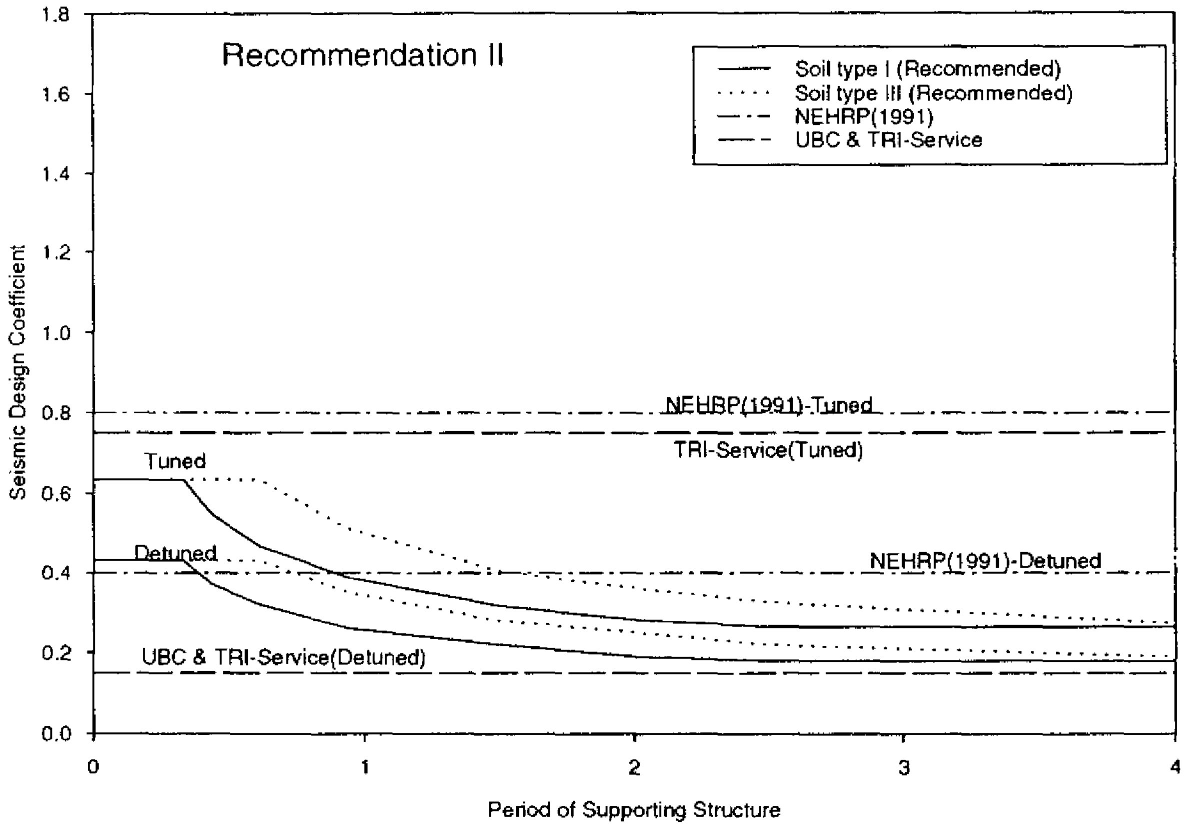

Fig. 6-6(b) Seismic Design Coefficient of Equipment at Middle of Building (Second Recommendation)

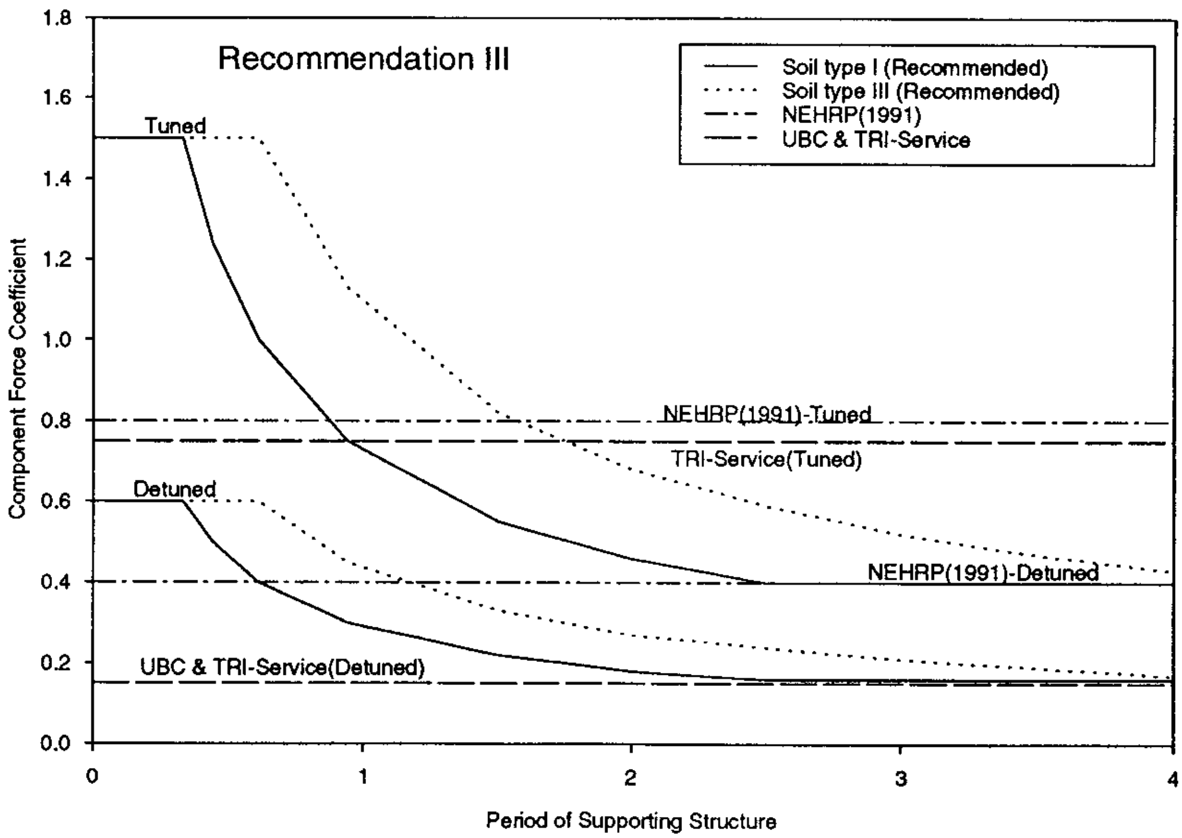

Fig. 6-7(a) Seismic Design Coefficient of Equipment at Top of Building (Third Recommendation)

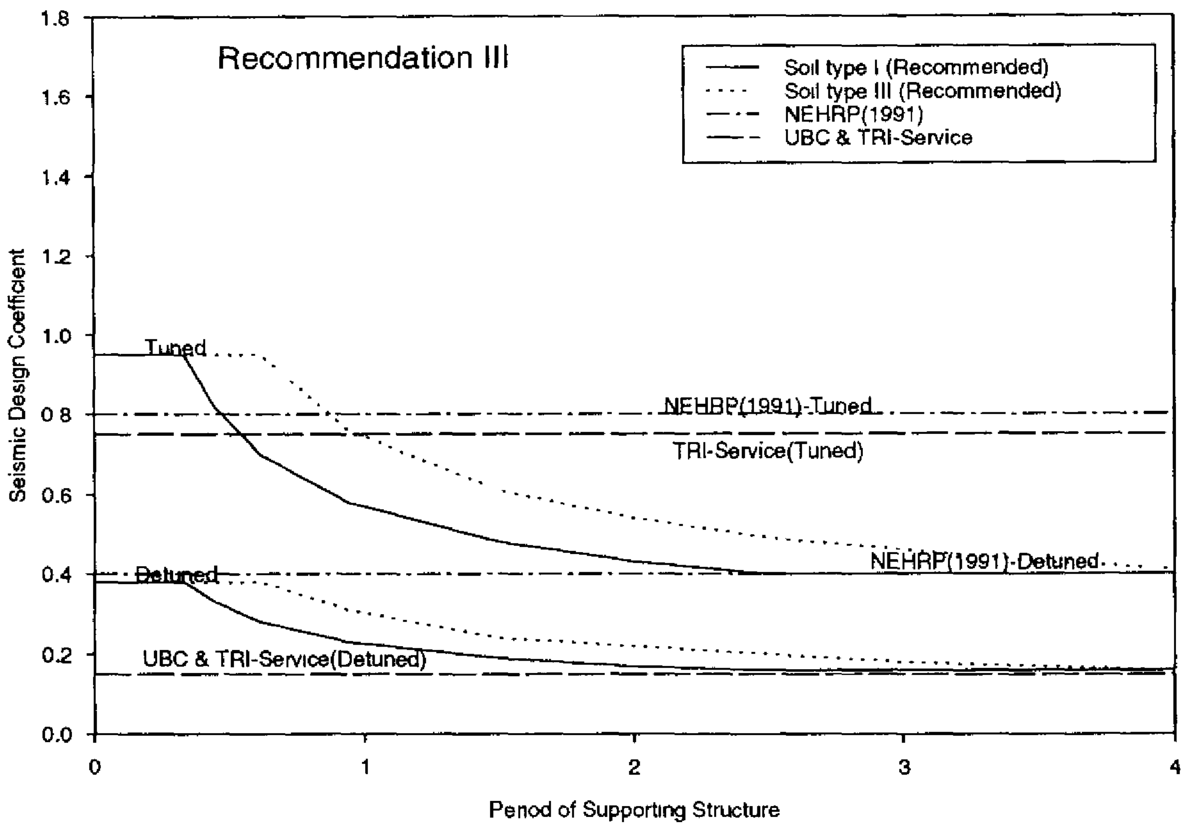

Fig. 6-7(b) Seismic Design Coefficient of Equipment at Middle of Building (Third Recommendation)

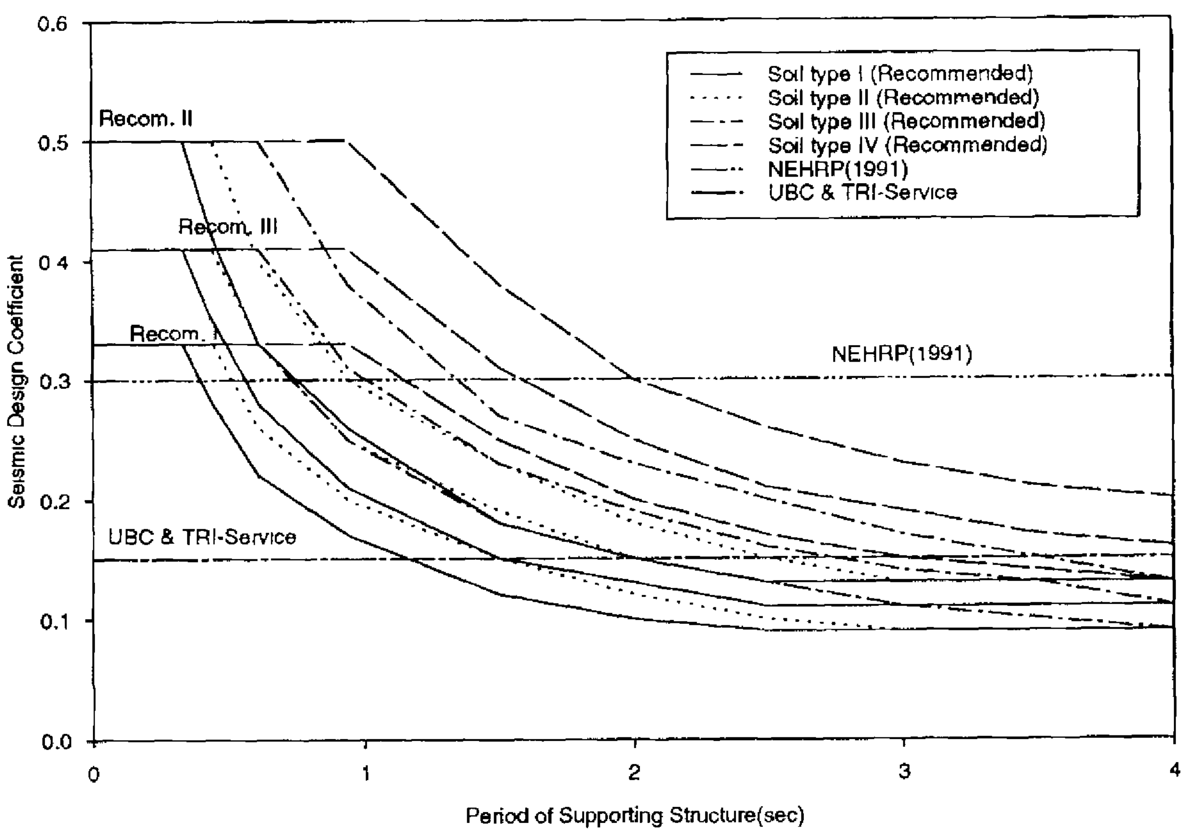

Fig. 6-8 Seismic Design Coefficient for Storage Rack at Top of Building

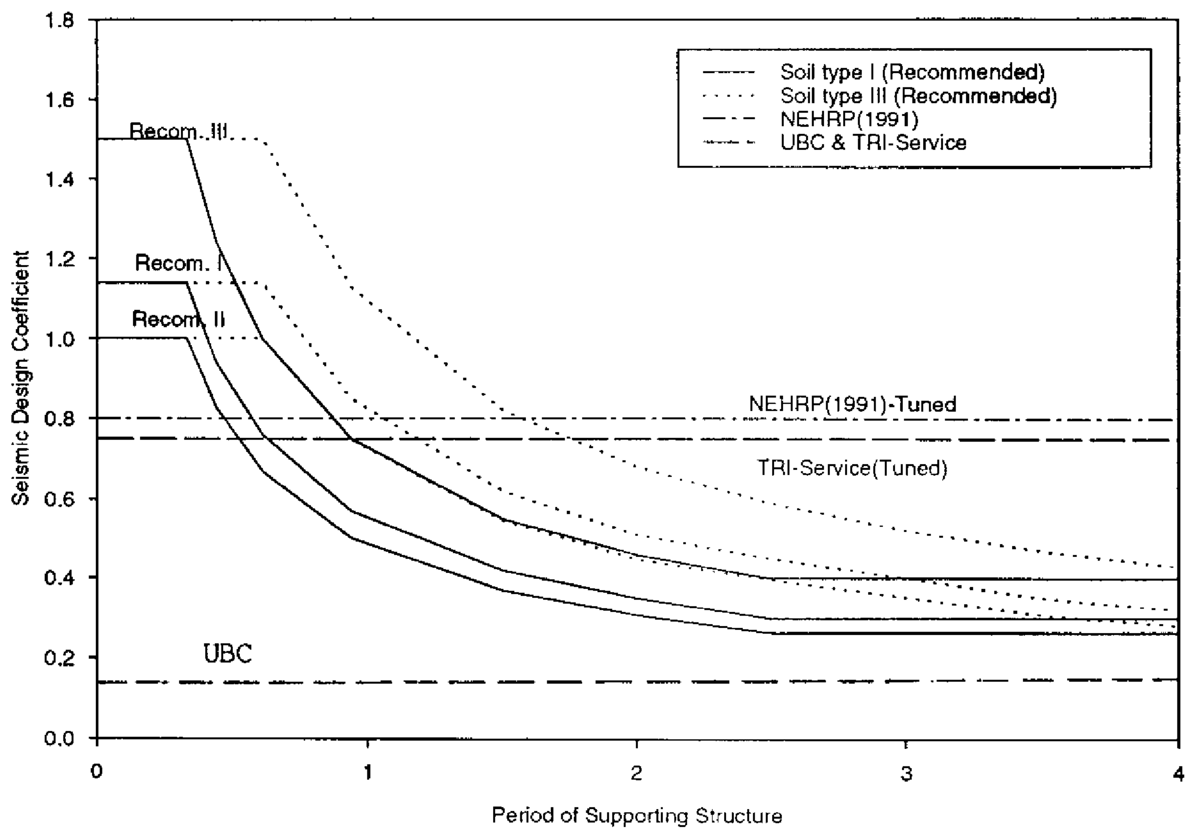

Fig. 6-9 Seismic Design Coefficient of Equipment at Top (Tuned Case)

SECTION 7

DESIGN DISPLACEMENT

There are three types of displacements involved in the design of mechanical and electrical equipment, i.e., flexible support deformation, sliding displacement and interstory distortion. The flexible support deformation is defined as the relative displacement of the equipment with respect to its attached floor. The sliding displacement of an equipment with low center of gravity occurs when bolts (if exist) connecting the equipment anchorage to the building floor are damaged or when the maximum friction force between the equipment and floor (no bolts) is exceeded. The interstory distortion of one building structure or between two adjacent buildings is relevant to the design of equipment such as piping systems installed over two or more floors of the building structure or between two building structures.

For seismic design of architectural components, only interstory distortion is of interest.

7.1 Flexible Support Deformation

In order to suppress vibrational levels of a mechanical or electrical equipment, flexible anchorage of the equipment is generally required. When flexibility of the equipment anchorage is relatively large, the design force on the equipment may not be critical. However, the relative displacement of the equipment with respect to its attached floor may exceed an allowable level, which will also cause anchorage damage. In addition, when anchorage ductility is taken into account as in the first and third recommendations, the design force on the equipment would also be small. Nevertheless, the inelastic deformation in this case may be excessive. For these reasons, a displacement equation for flexibly-supported equipment which provides support deformation information is of practical value.

7.1.1 Displacement Equation

From Eq. (3.1), the relative displacement of an equipment with respect to its supporting floor can be formulated as

$$\Delta_p = \frac{F_p}{K_c} = \frac{A_v a_x a_c P g T_c^2}{4\pi^2 R_s R_c} \tag{7 1}$$

in which g is the gravitational acceleration. The response modification coefficient (R_c) should be assigned to be 1.0 to obtain the maximum displacement.

7.1.2 Example: A General Equipment

The same type of general equipment as in Section 6 is used here to show the magnitude of its relative displacement with respect to the floor. The calculated displacements for different equipment periods are presented in Table 7-1. As one can observe, the relative displacement increases as the anchorage becomes flexible.

7.2 Sliding Displacement

As indicated in the brief introduction of this section, sliding of a rigid body which is not bolted to the floor occurs when seismic load acting on the rigid body exceeds friction force between the rigid body and its supporting floor. Sliding of a general equipment which is bolted to the floor could also occur when bolts fail when the seismic load is excessive.

It is noted that only equipment with low centers of gravity are considered here so that the possibility of overturning of the equipment is ignored.

7.2.1 Displacement Equation

The sliding distance of a rigid body along its supporting building floor can be approximately determined in accordance with

$$\Delta_p = C_\delta \delta_s \tag{7.2}$$

in which δ_s is the relative displacement of the building floor with respect to ground and can be determined from the building structural analysis exclusively. The sliding coefficient C_δ can be calculated from

$$C_\delta = \left| \frac{\eta\gamma^2}{2} - \frac{1-\cos\gamma}{\eta} \right| \tag{7.3}$$

where

$$\gamma = \frac{2\pi(t_3 - t_1)}{T_s} \tag{7.4}$$

and satisfies the following equation:

$$\gamma = \frac{\sqrt{1-\eta^2}(1-\cos\gamma)}{\eta} + \sin\gamma \tag{7.5}$$

Here, $t_3 - t_1$ represents the time interval during which the rigid body moves within a half cycle of seismic input from the building floor. The parameter η represents the relative strength of resistance (friction force) and load (seismic force) which can be simply expressed as

$$\eta = \frac{\mu(1-a_v)}{A_v a_x} \tag{7.6}$$

in which μ is the friction coefficient between the rigid body and its supporting floor, and a_v represents vertical acceleration of the supporting floor that is approximately equal to $A_v/3$ if floor amplification effect of the vertical acceleration is insignificant.

7.2.2 Development of the Displacement Equation

For the purpose of developing a simple sliding distance equation, the absolute acceleration of a building floor to which a mechanical or electrical equipment is attached can be simply considered as a harmonic motion with the fundamental period of the building structure. In the case of a mechanical or electrical equipment installed on the upper floors of a building structure, which is usually of practical interest, the contribution of the first mode of the structure to the seismic response of the equipment is predominant and therefore accelerations of the upper floors appear to be harmonic, i.e.,

$$\ddot{x}_f(t) = A_v a_x g \sin\left(\frac{2\pi t}{T_s}\right) \tag{7.7}$$

The rigid body begins to slide when the inertia force $m_c\ddot{x}_f(t)$ acting on it exceeds the effective friction force and it stops again when $m_c\ddot{x}_f(t)$ is less than the friction force as shown in Fig. 7-1. The rigid body will move back and forth along a perfectly horizontal building floor during earthquakes and only a half cycle of seismic excitation $\ddot{x}_f(t)$ is needed to obtain maximum sliding distance of the rigid body.

The equation of motion of the rigid body ($W_c = m_c g$) can be written as

$$\dot{z}(t) = \begin{cases} 0, & m_c\dot{x}_f(t) < F_f \\ \frac{F_f'}{m_c} - \ddot{x}_f(t), & m_c\dot{x}_f(t) \geq F_f \end{cases} \tag{7.8}$$

in which $z(t)$ denotes the sliding displacement of the rigid body, and F_f and F_f' are static and dynamic friction forces, respectively. The dynamic friction force (F_f') is considered to be approximately equal to the static friction (F_f) for simplicity. Both of them can be represented by

$$F_f' = F_f = \mu m_c g(1 - a_v) \tag{7.9}$$

The initial conditions for sliding of the rigid body can be expressed as

$$z(t) = \dot{z}(t) = 0 \tag{7.10}$$

By substituting Eq. (7.9) for F_f' in Eq. (7.8), the equation of motion can be rewritten as

$$\dot{z}(t) = \mu g(1 - a_v) - A_v a_x g \sin\frac{2\pi t}{T_s} \qquad (t_1 \leq t \leq t_3) \tag{7.11}$$

with the solution of

$$\dot{z}(t) = \mu g(1 - a_v)(t - t_1) + \frac{T_s}{2\pi} A_v a_x g \left(\cos\frac{2\pi t}{T_s} - \cos\frac{2\pi t_1}{T_s} \right) \tag{7.12}$$

$$z(t) = 0.5\mu g(1 - a_v)(t - t_1)^2 + \frac{T_s}{2\pi} A_v a_x g \left[\frac{T_s}{2\pi} \left(\sin\frac{2\pi t}{T_s} - \sin\frac{2\pi t_1}{T_s} \right) - (t - t_1)\cos\frac{2\pi t_1}{T_s} \right] \tag{7.13}$$

To determine the starting and ending time instants (t_1 and t_3), the following conditions are introduced:

$$\ddot{z}(t_1) = 0 \tag{7.14}$$

$$\dot{z}(t_3) = 0 \tag{7.15}$$

Solving these two equations simultaneously yields Eq. (7.5). The maximum sliding distance can then be calculated by

$$\Delta_p = |z(t_3)| = \frac{A_v a_x g T_s^2}{4\pi^2} C_\delta = C_\delta \delta_s \tag{7.16}$$

The values of C_δ for different values of the parameter η in Eq. (7.6) are tabulated in Table 7-2.

7.3 Interstory Distortion

An architectural component such as a wall system is often subjected to distortion action due to story drift of its supporting building structure. A piping system inside a building structure is also restrained by story drift and a piping system attached to two adjacent buildings may be subjected to their differential movement. Therefore, interstory distortions inside a building structure or between two adjacent buildings are important to the design of this type of nonstructural components. However, constraint displacements of this type for nonstructural components can be exclusively calculated from structural analysis when the nonstructural components are considered to be relatively light. For this reason, explicit expressions for these interstory distortions are not discussed here.

TABLE 7-1. Displacement of Flexibly-Mounted Equipment at Top of Building (Soil Type I)

T_s (seconds)		0.0	0.33	0.44	0.61	0.94
Tuned $T_c = T_s$	first recommendation	0.0	0.034	0.050	0.077	0.137
	second recommendation	0.0	0.037	0.054	0.084	0.149
	third recommendation	0.0	0.051	0.075	0.115	0.201
Detuned $T_c < 0.5\ T_s$ or $T_c > 2.0\ T_s$	first recommendation	0.0	0.0034	0.0050	0.0077	0.0137
	second recommendation	0.0	0.0046	0.0067	0.0105	0.0186
	third recommendation	0.0	0.0051	0.0075	0.0115	0.0201
R_c in the first and third recommendations are taken as 1.0 for displacement determination to obtain the maximum elastic deformation presented above.						

TABLE 7-2. Sliding Coefficient

η	0.4	0.5	0.6	0.7	0.8	0.9	1.0
C_δ	1.8780	1.2658	0.7884	0.4325	0.1878	0.0460	0.0

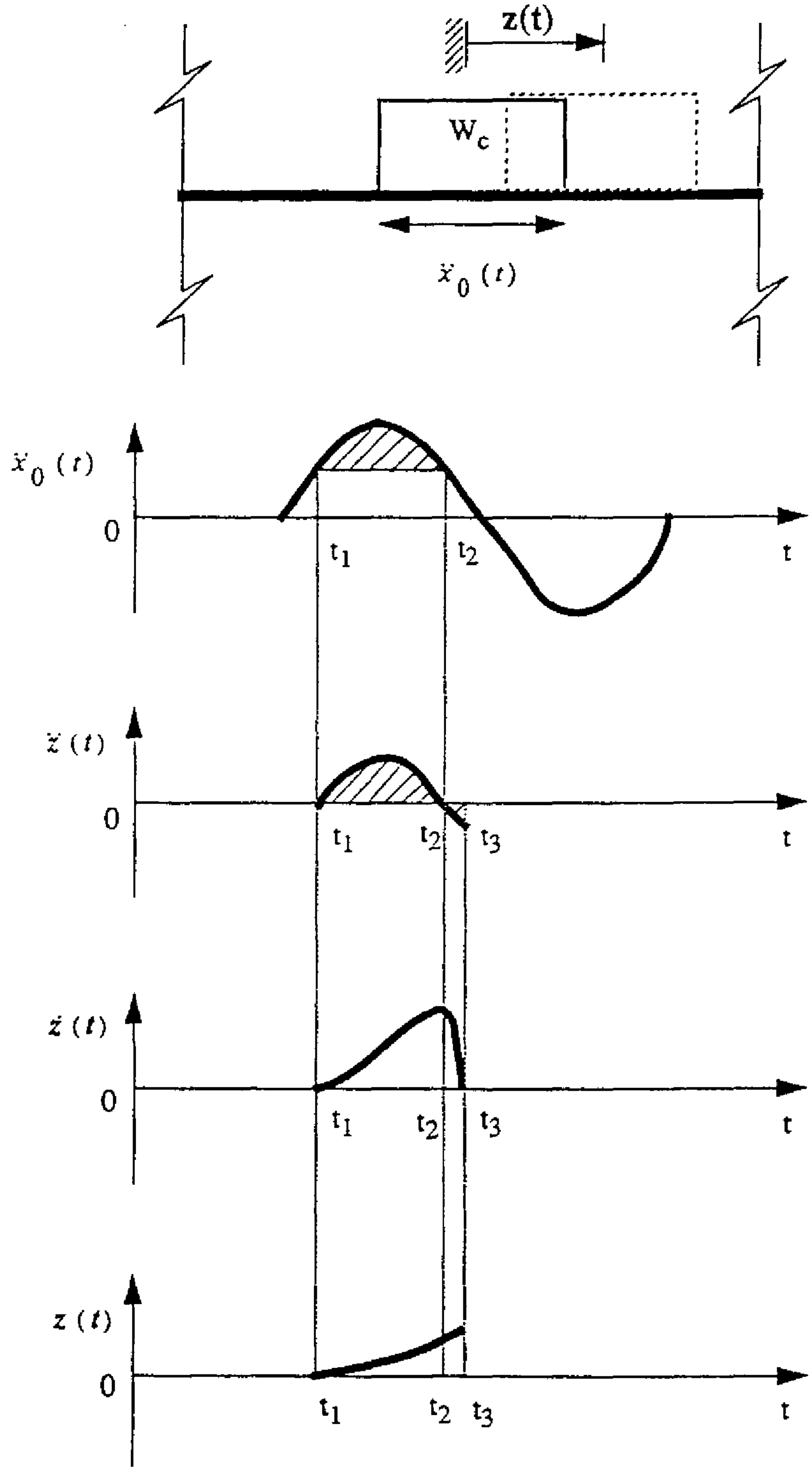

Fig. 7-1 Sliding Displacement

SECTION 8
CONCLUDING REMARKS

Three approaches to the modification of the 1991 NEHRP design force equations for nonstructural components have been developed by incorporating different levels of consideration for structural and component effects. In the first recommendation, structural and component characteristics are jointly taken into account, which is no doubt the most comprehensive. The second recommendation is basically a structure-driven type modification to the current provisions. The third recommendation mainly concerns the effect of different types of components on the force, representing the least modified version.

Design force equations recommended in this report preserve the equivalent lateral force concept, a static procedure in which all the dynamic characteristics such as modal contribution, damping ratio, and response spectrum are not explicitly included. However, these statics-based equations can be justified based on dynamic analysis of the first mode representation of MDOF systems with 5% modal damping following the cascade (decoupled) procedure.

The values of the component response modification coefficient (R_c) in this report are basically transferred from those of the seismic coefficient (C_c) of the current provisions. They are subjected to further modification by practitioners.

An attempt was made to consider the structural yielding effect on the acceleration or inertia force distribution along building height. In general, the larger the structural inelastic deformation or the larger the seismic input, the more uniform the distribution of the maximum acceleration along the building height. However, it was decided in this revision to ignore the structural yielding effect on the acceleration distribution due to simplicity requirements for practical design and insufficient observed data for statistical analysis.

Overall, the recommended modifications of the 1991 NEHRP design force equations for nonstructural components represent a major effort which, on the one hand, preserves the equivalent lateral force format for practical applicability and, on the other, identifies and corrects deficiencies in the current provisions to the extent feasible. It has been shown that these recommended revisions can be justified on the basis of analyses, experimental results, and observation data from past earthquakes; and they represent a significant improvement over the 1991 NEHRP design force formulas.

Current provisions do not include design guidelines based on displacements or deformations on the part of nonstructural components. Since excessive displacements or movements are causes of a significant number of past nonstructural failures, simple equations have also been presented which can be used to estimate flexible support deformation and the amount of sliding a nonstructural component can experience during a seismic event. The inclusion of this type of displacement equations in future codes and provisions is recommended.

SECTION 9

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