CE-412: STRUCTURAL ENGINEERING

(Seismic analysis & design of structures using UBC-97)

Design of structures to withstand the maximum intensity earthquake is highly expensive and may not even be possible due to the following factors:

- The magnitude, intensity and other characteristics of future earthquakes are not precisely known.
- Stiffer structures attract more earthquake loads.
- These structures cannot dissipate energy and all the energy is stored in them making them unstable.
- Heavier design means more mass of the structure.
- Due to larger mass, more inertial forces are produced during the ground excitation.

STRUCTURAL DYNAMICS:- Seismic Design

- Damage to multistory structures due to earth-quake result in loss of lives and infrastructure at massive level.

- Earthquake forces are random in nature and are unpredictable, so, these forces are required to be carefully analyzed and modeled to assess the real response behavior of structure with damages.

- Seismic response analysis are performed on the basis of external action, the behavior of structure , structural materials, or the type of structural model selected.

STRUCTURAL DYNAMICS:- Seismic Design Methods

- Based on the type of external action and behavior of structure, the analysis can be further classified as:
- (1) Linear Static Analysis,
- (2) Nonlinear Static Analysis,
- (3) Linear Dynamic Analysis; and
- (4) Nonlinear Dynamic Analysis.

- ***Linear static analysis or equivalent static or Eqt. lateral load analysis:***

This is generally used for regular structure with limited height. Equivalent Static analysis procedure does not require dynamic analysis, however, it accounts for the dynamics of building in an approximate manner.

- This *equivalent lateral load method* is the simplest one. It requires less computational efforts and is based on formulate given in different codes of practices.

- First, the design base shear is computed for the whole building, and is then distributed along the height of the building.

- The lateral forces at each floor levels thus obtained are distributed to individual lateral load resisting elements. The moments are then calculated at each level as usual.

- In ***Linear dynamic analysis or Response spectrum method (RSM),*** the peak response of structure during an earthquake is obtained directly from the earthquake response.

- The difference between linear static and linear dynamic analysis is the level of the forces and their distribution along the height of structure. Structural design is generally based on peak response values rather than detailed time history.

- This procedure is not an exact predictor of peak response, but it provides an estimate that is sufficiently accurate for structural design applications.

Concept of Response Spectrum

- Extremely useful concept in earthquake engineering research and in applying the seismological knowledge of strong earthquake to the design of structures

- Hugo Benioff initiated in 1934
- M. A. Biot extended its application to earthquake engineering in 1941

Use of Response Spectrum

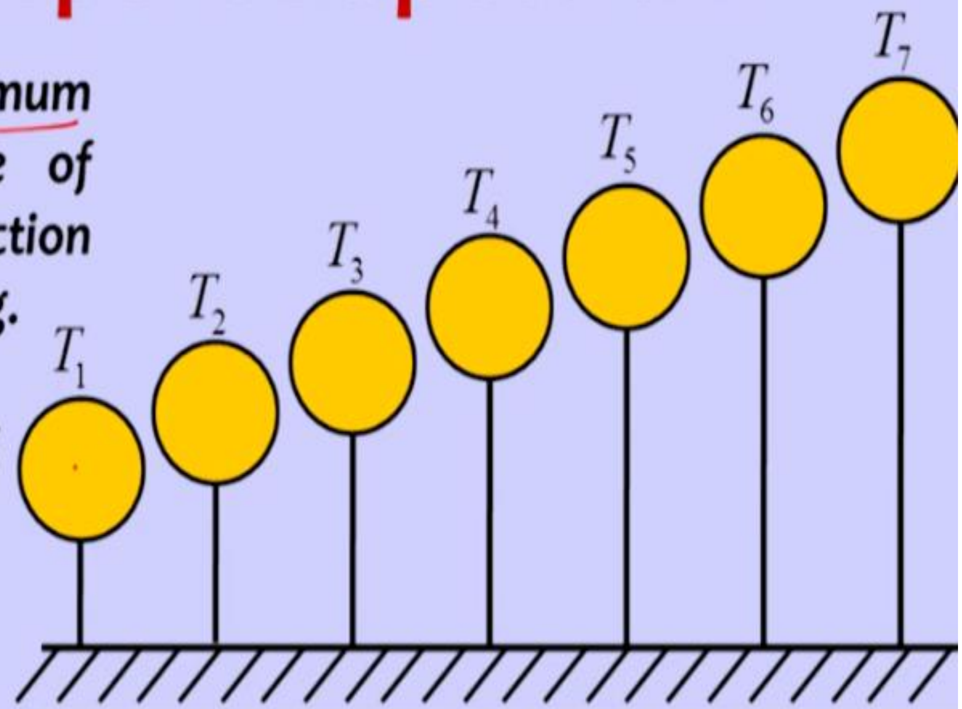
- For engineering purposes, we are not especially concerned with the time variation of the response parameters
- Rather, it is their extreme value that convey the crucial information
- They are related to the maximum forces, maximum displacement and maximum deformation that structures must be able to endure

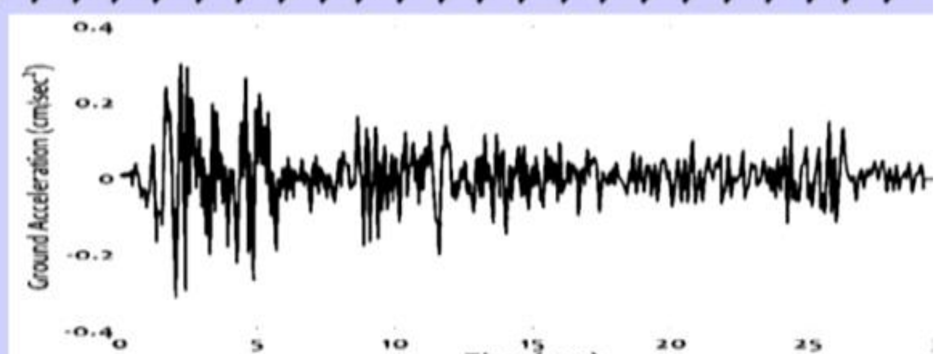
Construction of Response Spectrum

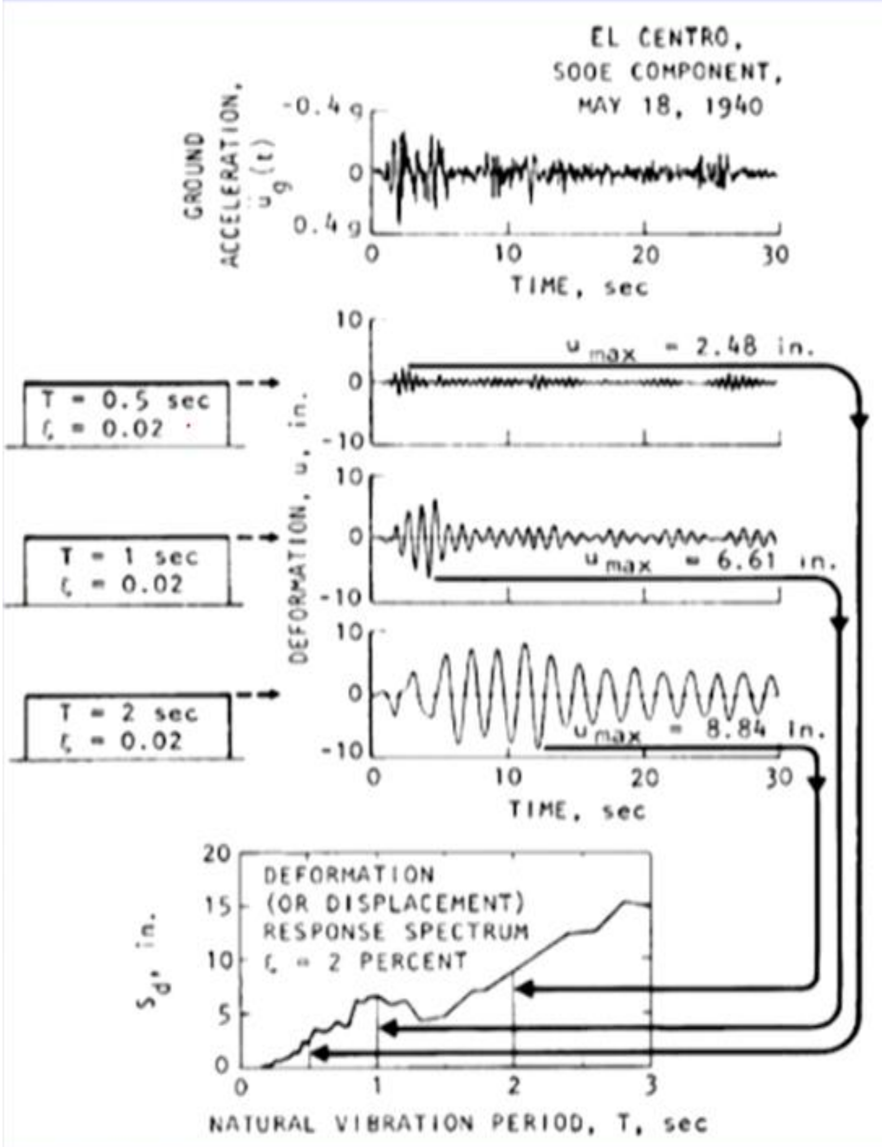
Response spectrum is a plot of maximum response of linear single degree of freedom system oscillators as a function of natural period for a given damping.

Response can be any of the following

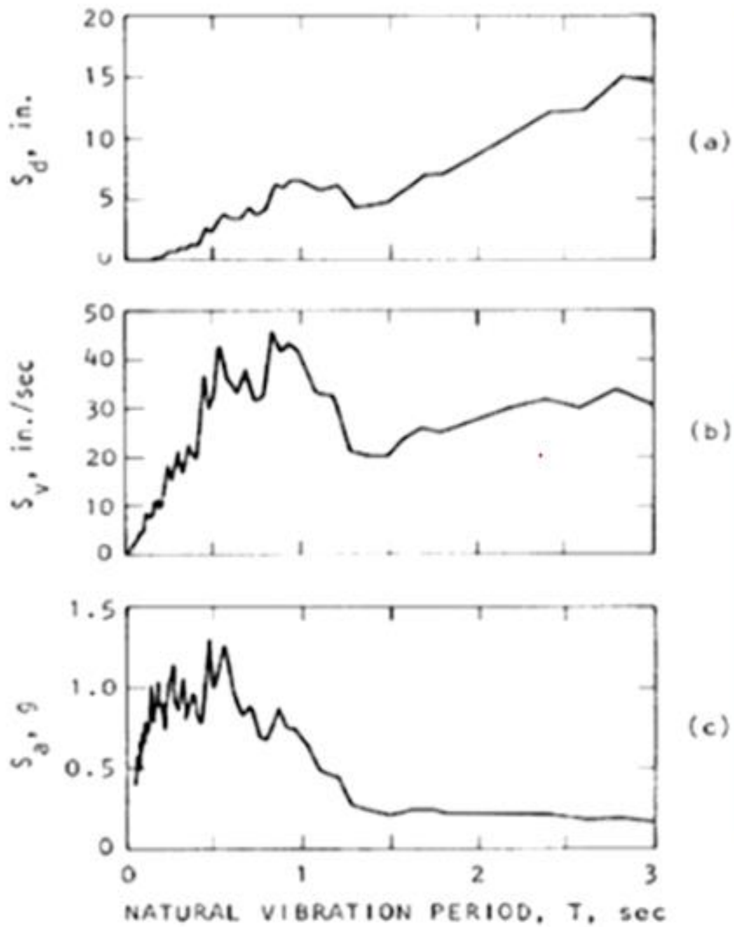
1. Displacement
2. Velocity
3. Acceleration







- **If we calculate the maximum response for a range of values of frequency and damping and portray the results graphically, we then have a spectrum chart that shows the maximum response of all possible single degree of freedom systems to that component of earthquake.**



(a) Deformation (or Displacement), (b) pseudo-velocity and (c) pseudoacceleration response spectra. El Centro ground motion—S00°E component. Damping ratio ξ = 2 percent

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Response may be defined as displacemen velocity or acceleration

and, all the three responses can be shown in one plot called Tripartite plot

Procedure To Use Response Spectra For SDOF Systems

- The procedure to use response spectrum to calculate the earthquake lateral forces for single degree of freedom systems is summarized as under:
  1) Calculate angular speed ω and time period T for the structure.
  2) Estimate the damping ratio ξ.
  3) Use applicable response spectrum for a particular area and find S_d or S_v or S_a (the values are inter-convertible) against the time period.
  4) Find shear force in each column as:
  5) S.F = $S_d \times k$
  6) Find the total lateral force by adding shear forces in all the columns.
  7) The lateral forces may be scaled to the values given by the equivalent static method. This scaling depends upon the types of frames and their ductility

Procedure To Use Response Spectra For MDOF Systems

- The procedure to use response spectrum for the calculation of the earthquake lateral forces in case of multiple degrees of freedom systems is summarized as under:
- Calculate angular speed ω and time period T for the desired mode of vibration of the structure.
- Find the mode shape a_i.
- Estimate the damping ratio ξ.
- Find S_d, S_v and S_a from the response spectrum or calculate others after knowing one out of these.

- Calculate the effective weight as follows:

$$W^E = \frac{\left(\sum W_i a_i\right)^2}{\left(\sum W_i a_i^2\right)}$$

- Calculate the base shear as follows:

$$V = W^E S_a / g$$

- Find the lateral force at each level as follows:

$$F_i = V \frac{W_i a_i}{\sum W_i a_i}$$

- The lateral forces may be scaled to the values given by the equivalent static method. This scaling depends upon the types of frames and their ductility.

- Although the response spectrum should be developed for a particular site based on geologic, seismological and soil properties at a specific site.
- In the absence of such response spectrum, ***the UBC design response spectrum may effectively be used.***

Response Spectrum Analysis

- According to **UBC,** response spectrum analysis is defined as an elastic dynamic analysis of a structure utilizing the peak dynamic response of all modes having a significant contribution to total structural response.

STRUCTURAL DYNAMICS:- Seismic Design Methods

- ***Nonlinear static analysis or Pushover analysis*** is an improvement over linear static *or* dynamic analysis in the sense that it allows inelastic behavior of structure.

- A nonlinear dynamic analysis is the only method to describe the actual behavior of a structure during an earthquake.

- The method is based on the direct numerical integration of the differential equations of motion by considering the elasto-plastic deformation of the structural element.

- It is practical method in which analysis is carried out under permanent vertical loads and gradually increasing lateral loads to estimate deformation and damage pattern of structure.

- The behavior of the structure is characterized by capacity curve that represents the relation between the base shear force and the displacement of the roof.

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STRUCTURAL DYNAMICS:- Seismic Design Methods

- ***Nonlinear dynamic analysis or Time history or response history analysis (RHA)***:

- An important technique for structural seismic analysis especially when the evaluated structural response is nonlinear. A representative earthquake time history is required for a structure being evaluated and it is a step-by-step analysis of the dynamic response of a structure to a specified loading that may vary with time. Time history analysis is used to determine the seismic response of a structure under dynamic loading of representative earthquake.

- Structural response is calculated as a function of time when the system is subjected to a given ground acceleration $\ddot{u}_g(t)$

STRUCTURAL DYNAMICS:- ***Seismic loads***

- Earthquakes often occur due to slip between tectonic plates along a geological fault in the earth's crust.
- Earthquakes result in various types of ground motion as seismic waves propagate through the earth. As these waves pass the location of a structure, the associated ground motion subjects the structure to lateral forces (primarily) and vertical forces (to a lesser degree).
- Ground motion at the base of a structure results in dynamic loads (forces) distributed throughout the structure based on the stiffnesses of structural elements (restoring forces) and the distribution of mass (inertial forces). The most accurate methods of design for seismic loads involve comprehensive dynamic analyses of structures.

STRUCTURAL DYNAMICS:- ***Seismic loads***

- However, simplified analytical techniques (typically referred to as equivalent static force or equivalent lateral force procedures) are provided in model building codes for the design of general building structures subjected to seismic loads.
- Calculation of seismic loads for analysis of structure is required when earthquake resistant structure is to be designed. Structural Engineers use different design codes/guidelines for calculation of earthquake loads.
- Widely accepted codes for calculation of seismic loads are, Uniform Building Code 1997 (UBC-97), International building code (IBC-2000), ASCE-7-10, Building code of Pakistan (seismic provisions).

STRUCTURAL DYNAMICS:- (*EQUIVALENT LATERAL LOAD METHOD)*

- ***Equivalent static lateral force*** procedure is to place static loads on a structure with magnitudes and direction that closely approximate the effects of dynamic loading caused by earthquakes.
- Concentrated lateral forces due to dynamic loading tend to occur at floor and ceiling/roof levels in buildings, where concentration of mass is the highest.
- Furthermore, concentrated lateral forces tend to be larger at higher elevations in the structure.
- In general, the distribution of lateral story forces is associated with the first (fundamental) mode of vibration of a cantilevered structure. (In this case, a typical structure is idealized as a vertical cantilever, rigidly attached to the ground.)

STRUCTURAL DYNAMICS:- (***EQUIVALENT LATERAL LOAD METHOD)***

- The effects of higher modes of vibration are approximated in the UBC by considering an additional lateral force, Ft, applied to the top level of a structure.
- In both the ***IBC and the UBC***, the summation of the lateral story forces (plus the additional lateral force at the top, Ft, in the UBC) must be equivalent to the base shear (V) force applied to the structure due to seismic ground motion.

STRUCTURAL DYNAMICS:- **UBC-General Terms**

- ***BASE*** is the level at which the earthquake motions are considered to be imparted to the structure or the level at which the structure as a dynamic vibrator is supported.
- ***Base shear*** is an estimate of the maximum expected lateral force due to seismic ground motion at the base of a structure.
- ***BRACED FRAME*** is an essentially vertical truss system of the concentric or eccentric type that is provided to resist lateral forces.
- ***BUILDING FRAME SYSTEM*** is an essentially complete space frame that provides support for gravity loads.
- ***CANTILEVERED COLUMN ELEMENT*** is a column element in a lateral-force-resisting system that cantilevers from a fixed base and has minimal moment capacity at the top, with lateral forces applied essentially at the top.

STRUCTURAL DYNAMICS:- **UBC-General Terms**

- ***COLLECTOR*** is a member or element provided to transfer lateral forces from a portion of a structure to vertical elements of the lateral-force-resisting system.
- ***COMPONENT*** is a part or element of an architectural, electrical, mechanical or structural system.
- ***DESIGN-BASIS GROUND MOTION*** is that ground motion that has a 10 percent chance of being exceeded in 50 years as determined by a site-specific hazard analysis or may be determined from a hazard map. A suite of ground motion time histories with dynamic properties representative of the site characteristics shall be used to represent this ground motion. The dynamic effects of the Design Basis Ground Motion may be represented by the Design Response Spectrum

- ***DIAPHRAGM*** is a horizontal or nearly horizontal system acting to transmit lateral forces to the vertical-resisting elements. The term "diaphragm" includes horizontal bracing systems.
- ***LATERAL-FORCE-RESISTING SYSTEM*** is that part of the structural system designed to resist the Design Seismic Forces.
- ***MOMENT-RESISTING FRAME*** is a frame in which members and joints are capable of resisting forces primarily by flexure.
- ***MOMENT-RESISTING WALL FRAME (MRWF)*** is a masonry wall frame especially detailed to provide ductile behavior and designed in conformance with Section 2108.2.5.
- ***ORDINARY BRACED FRAME (OBF)*** is a steel-braced frame designed in accordance With the provisions of Section 2-9

STRUCTURAL DYNAMICS:- **UBC-General Terms**

- ***STORY*** is the space between levels. Story x is the story below Level x.
- ***STORY DRIFT*** is the lateral displacement of one level relative to the level above or below.
- ***STORY DRIFT RATIO*** is the story drift divided by the story height.
- ***STORY SHEAR,*** is the summation of design lateral forces above the story under consideration.
- ***STRENGTH*** is the capacity of an element or a member to resist factored load as specified in Chapters 16, 18, 19, 21 and 22.
- ***STRUCTURE*** is an assemblage of framing members designed to support gravity loads and resist lateral forces. Structures may be categorized as building structures or non-building structures.

STRUCTURAL DYNAMICS:- **Basis for Design**

(1629.1- Base Shear–UBC)

The procedures and the limitations for the design of structures shall be determined considering;

1) occupancy configuration,
2) site characteristics
3) seismic zoning
4) structural system and
5) height in accordance with this section

Basis for Design (1629.1- UBC)

- Structures shall be designed with adequate strength to withstand the lateral displacements induced by the Design-Basis Ground Motion, considering the inelastic response of the structure and the inherent redundancy, over-strength and ductility of the lateral-force- resisting system.
- The minimum design strength shall be based on the Design Seismic Forces determined in accordance with the static lateral force procedure of Section 1630, except as modified by Section 1631.5.4.

STRUCTURAL DYNAMICS:- **Base Shear - (UBC)**

Calculations of base shear (**V**) depends on:

- Site soil conditions at the site,
- Proximity to potential sources of seismic activity (geological faults)
- Probability of significant seismic ground motion
- Level of ductility and over-strength associated with various structural configurations and the total weight of the structure
- Fundamental (natural) period of vibration due to dynamic loading
- UBC addresses the probability of ***significant seismic activity*** in various locations by categorizing geographic regions as Seismic Zones 0 through 4 (See UBC Figure 16-2).
- Seismic Zone 0 indicates a geographic location where no seismic activity is expected to occur. Seismic Zone 4 indicates a geographic location with a high probability of significant seismic activity.

STRUCTURAL DYNAMICS:- 1. 1629.2 -Occupancy Categories

- For purposes of earthquake resistant design, each structure shall be placed in one of the occupancy categories listed in Table 16-K.

1. -Occupancy Categories

TABLE 16-K—OCCUPANCY CATEGORY

OCCUPANCY CATEGORY	OCCUPANCY OR FUNCTIONS OF STRUCTURE	SEISMIC IMPORTANCE FACTOR, I
1. Essential facilities[2]	Group I, Division 1 Occupancies having surgery and emergency treatment areas Fire and police stations Garages and shelters for emergency vehicles and emergency aircraft Structures and shelters in emergency-preparedness centers Aviation control towers Structures and equipment in government communication centers and other facilities required for emergency response Standby power-generating equipment for Category 1 facilities Tanks or other structures containing housing or supporting water or other fire-suppression material or equipment required for the protection of Category 1, 2 or 3 structures	1.25
2. Hazardous facilities	Group H, Divisions 1, 2, 6 and 7 Occupancies and structures therein housing or supporting toxic or explosive chemicals or substances Nonbuilding structures housing, supporting or containing quantities of toxic or explosive substances that, if contained within a building, would cause that building to be classified as a Group H, Division 1, 2 or 7 Occupancy	1.25
3. Special occupancy structures[3]	Group A, Divisions 1, 2 and 2.1 Occupancies Buildings housing Group E, Divisions 1 and 3 Occupancies with a capacity greater than 300 students Buildings housing Group B Occupancies used for college or adult education with a capacity greater than 500 students Group I, Divisions 1 and 2 Occupancies with 50 or more resident incapacitated patients, but not included in Category 1 Group I, Division 3 Occupancies All structures with an occupancy greater than 5,000 persons Structures and equipment in power-generating stations, and other public utility facilities not included in Category 1 or Category 2 above, and required for continued operation	1.00
4. Standard occupancy structures[3]	All structures housing occupancies or having functions not listed in Category 1, 2 or 3 and Group U Occupancy towers	1.00
5. Miscellaneous structures	Group U Occupancies except for towers	1.00

- **1629.3 Site Geology and Soil Characteristics**.
- Each site shall be assigned a soil profile type based on properly substantiated geotechnical data using the site categorization procedure set forth in Division V, Section 1636 and Table 16-J.

- *EXCEPTION: When the soil properties are not known in sufficient detail to determine the soil profile type, Type S_D shall be used. Soil Profile Type S_E or S_F need not be assumed unless the building official determines that Type S_E or S_F may be present at the site.*

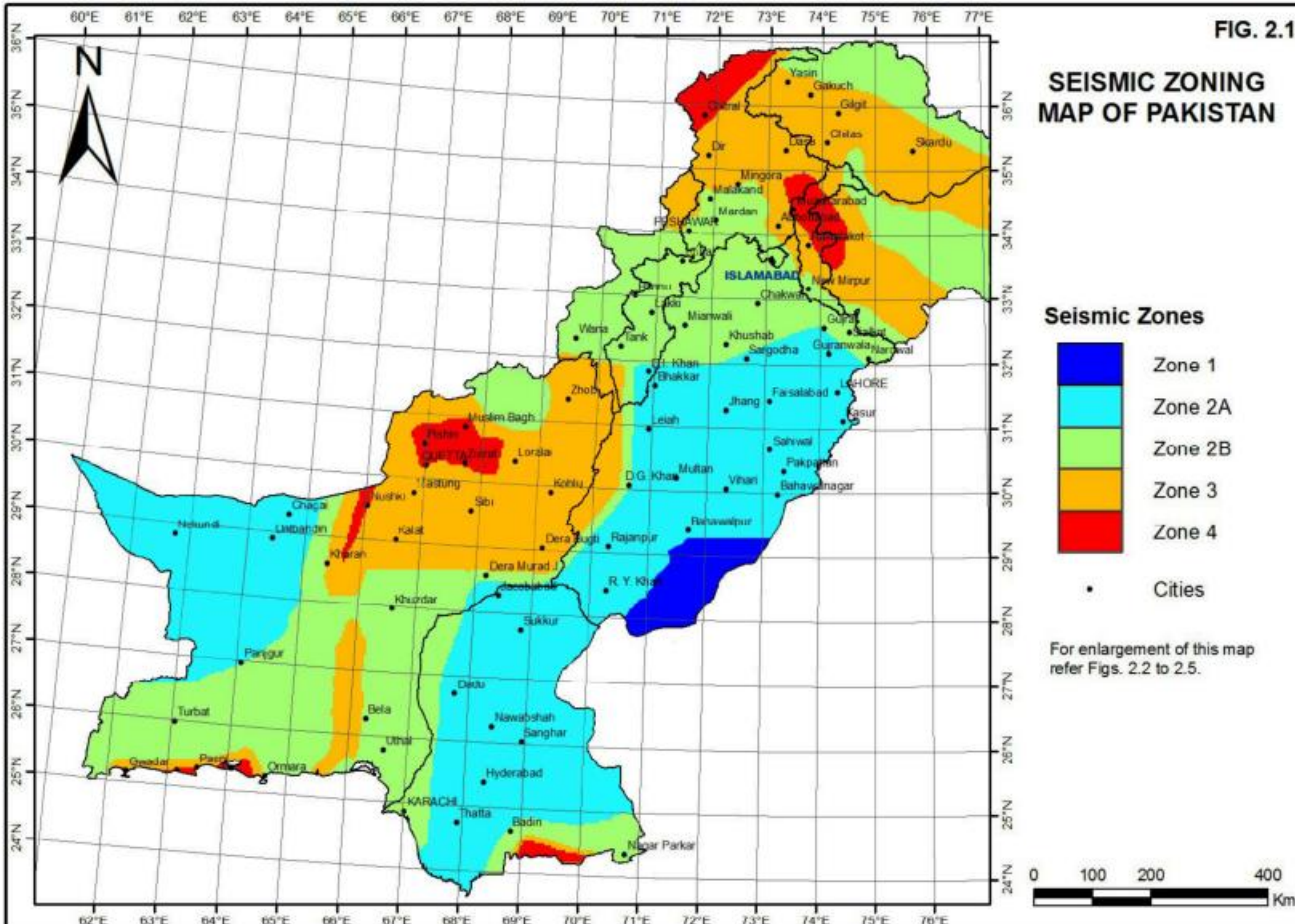
TABLE 16-J—SOIL PROFILE TYPES

SOIL PROFILE TYPE	SOIL PROFILE NAME/GENERIC DESCRIPTION	AVERAGE SOIL PROPERTIES FOR TOP 100 FEET (30 480 mm) OF SOIL PROFILE		
		Shear Wave Velocity, $\bar{v}_s$ feet/second (m/s)	Standard Penetration Test, $\bar{N}$ [or $\bar{N}_{CH}$ for cohesionless soil layers] (blows/foot)	Undrained Shear Strength, $\bar{s}_u$ psf (kPa)
S_A	Hard Rock	> 5,000 (1,500)	—	—
S_B	Rock	2,500 to 5,000 (760 to 1,500)		
S_C	Very Dense Soil and Soft Rock	1,200 to 2,500 (360 to 760)	> 50	> 2,000 (100)
S_D	Stiff Soil Profile	600 to 1,200 (180 to 360)	15 to 50	1,000 to 2,000 (50 to 100)
S_E[1]	Soft Soil Profile	< 600 (180)	< 15	< 1,000 (50)
S_F	Soil Requiring Site-specific Evaluation. See Section 1629.3.1.			

- **1629.4 Site Seismic Hazard Characteristics.**
- Seismic hazard characteristics for the site shall be established based on the seismic zone and proximity of the site to active seismic sources, site soil profile characteristics and the structure's importance factor.

- **1629.4.1 Seismic zone**.
- Each site shall be assigned a seismic zone in accordance with. UBC defined probability of significant seismic activity in various locations by categorizing geographic regions as Seismic Zones 0 through 4 (Figure 16-2).
- Seismic Zone 0 indicates a geographic location where no seismic activity is expected to occur. Seismic Zone 4 indicates a geographic location with a high probability of significant seismic activity. Each structure shall be assigned a seismic zone factor Z in accordance with Table 16-I.

STRUCTURAL DYNAMICS:- 3. Seismic Zone factor



- **1629.4.2 Seismic Zone 4-near-source factor**.
- For sites located in Zone 4, ***additional lower bound*** for calculating base shear (**V**) includes factors associated with (**Z**) and near source factors N_a and N_v assigned according to seismic source type and distance from the seismic source. Seismic source type is defined in Table 16-U. Values for N_a and N_v are provided in tables 16-S and 16-T, respectively. These factors are then used to calculate seismic response coefficients C_a & C_v for zone-4.

TABLE 16-U—SEISMIC SOURCE TYPE[1]

SEISMIC SOURCE TYPE	SEISMIC SOURCE DESCRIPTION	SEISMIC SOURCE DEFINITION[2]	
		Maximum Moment Magnitude, *M*	Slip Rate, *SR* (mm/year)
A	Faults that are capable of producing large magnitude events and that have a high rate of seismic activity	$M \geq 7.0$	$SR \geq 5$
B	All faults other than Types A and C	$M \geq 7.0$ $M < 7.0$ $M \geq 6.5$	$SR < 5$ $SR > 2$ $SR < 2$
C	Faults that are not capable of producing large magnitude earthquakes and that have a relatively low rate of seismic activity	$M < 6.5$	$SR \leq 2$

STRUCTURAL DYNAMICS:- 4 near-source factors

TABLE 16-S—NEAR-SOURCE FACTOR N_a[1]

SEISMIC SOURCE TYPE	CLOSEST DISTANCE TO KNOWN SEISMIC SOURCE[2,3]		
	≤ 2 km	5 km	≥ 10 km
A	1.5	1.2	1.0
B	1.3	1.0	1.0
C	1.0	1.0	1.0

[1]The Near-Source Factor may be based on the linear interpolation of values for distances other than those shown in the table.

[2]The location and type of seismic sources to be used for design shall be established based on approved geotechnical data (e.g., most recent mapping of active faults by the United States Geological Survey or the California Division of Mines and Geology).

[3]The closest distance to seismic source shall be taken as the minimum distance between the site and the area described by the vertical projection of the source on the surface (i.e., surface projection of fault plane). The surface projection need not include portions of the source at depths of 10 km or greater. The largest value of the Near-Source Factor considering all sources shall be used for design.

TABLE 16-T—NEAR-SOURCE FACTOR N_v[1]

SEISMIC SOURCE TYPE	CLOSEST DISTANCE TO KNOWN SEISMIC SOURCE[2,3]			
	≤ 2 km	5 km	10 km	≥ 15 km
A	2.0	1.6	1.2	1.0
B	1.6	1.2	1.0	1.0
C	1.0	1.0	1.0	1.0

STRUCTURAL DYNAMICS:- 5. Seismic Response Coefficients

- C_v and C_a are seismic coefficients associated with structural sensitivity to the velocity and acceleration (respectively) of seismic ground motion.

- C_v and C_a are based on the geographic location of the structure (seismic zone) and soil conditions at the site.

- Values for C_v and C_a are specified in UBC Tables 16-R and 16-Q.

TABLE 16-Q—SEISMIC COEFFICIENT C_a

SOIL PROFILE TYPE	SEISMIC ZONE FACTOR, Z				
	$Z = 0.075$	$Z = 0.15$	$Z = 0.2$	$Z = 0.3$	$Z = 0.4$
S_A	0.06	0.12	0.16	0.24	$0.32N_a$
S_B	0.08	0.15	0.20	0.30	$0.40N_a$
S_C	0.09	0.18	0.24	0.33	$0.40N_a$
S_D	0.12	0.22	0.28	0.36	$0.44N_a$
S_E	0.19	0.30	0.34	0.36	$0.36N_a$
S_F	See Footnote 1				

TABLE 16-R—SEISMIC COEFFICIENT C_v

SOIL PROFILE TYPE	SEISMIC ZONE FACTOR, Z				
	$Z = 0.075$	$Z = 0.15$	$Z = 0.2$	$Z = 0.3$	$Z = 0.4$
S_A	0.06	0.12	0.16	0.24	$0.32N_v$
S_B	0.08	0.15	0.20	0.30	$0.40N_v$
S_C	0.13	0.25	0.32	0.45	$0.56N_v$
S_D	0.18	0.32	0.40	0.54	$0.64N_v$
S_E	0.26	0.50	0.64	0.84	$0.96N_v$
S_F	See Footnote 1				

- **1629.7 Height Limits**.
- Height limits for the various structural systems in Seismic Zones 3 and 4 are given in Table 16-N.

TABLE 16-N—STRUCTURAL SYSTEMS[1]

BASIC STRUCTURAL SYSTEM[2]	LATERAL-FORCE-RESISTING SYSTEM DESCRIPTION	R	Ω_o	HEIGHT LIMIT FOR SEISMIC ZONES 3 AND 4 (feet) × 304.8 for mm
1. Bearing wall system	1. Light-framed walls with shear panels			
	a. Wood structural panel walls for structures three stories or less	5.5	2.8	65
	b. All other light-framed walls	4.5	2.8	65
	2. Shear walls			
	a. Concrete	4.5	2.8	160
	b. Masonry	4.5	2.8	160
	3. Light steel-framed bearing walls with tension-only bracing	2.8	2.2	65
	4. Braced frames where bracing carries gravity load			
	a. Steel	4.4	2.2	160
	b. Concrete[3]	2.8	2.2	—
	c. Heavy timber	2.8	2.2	65
2. Building frame system	1. Steel eccentrically braced frame (EBF)	7.0	2.8	240
	2. Light-framed walls with shear panels			
	a. Wood structural panel walls for structures three stories or less	6.5	2.8	65
	b. All other light-framed walls	5.0	2.8	65
	3. Shear walls			
	a. Concrete	5.5	2.8	240
	b. Masonry	5.5	2.8	160
	4. Ordinary braced frames			
	a. Steel	5.6	2.2	160
	b. Concrete[3]	5.6	2.2	—
	c. Heavy timber	5.6	2.2	65
	5. Special concentrically braced frames			
	a. Steel	6.4	2.2	240
3. Moment-resisting frame system	1. Special moment-resisting frame (SMRF)			
	a. Steel	8.5	2.8	N.L.
	b. Concrete[4]	8.5	2.8	N.L.
	2. Masonry moment-resisting wall frame (MMRWF)	6.5	2.8	160
	3. Concrete intermediate moment-resisting frame (IMRF)[5]	5.5	2.8	—
	4. Ordinary moment-resisting frame (OMRF)			
	a. Steel[6]	4.5	2.8	160
	b. Concrete[7]	3.5	2.8	—
	5. Special truss moment frames of steel (STMF)	6.5	2.8	240

1629.8.3- Static Lateral Force (Base shear) Procedure

The procedure may be used for the following structures:

1. All structures, regular or irregular, in Seismic Zone 1 and in occupancy categories 4 and 5 in Seismic Zone 2.
2. Regular structures under 240 feet (73152 mm) in height with lateral force resistance provided by systems listed in Table 16-N,
3. Irregular structures not more than five stories or 65 feet (19 812 mm) in height.

Seismic dead load W, is total load plus other loads as listed below:

- In storage and warehouse occupancies, a min. of 25% of the floor live load shall be applicable.
- Where a partition load is used in the floor design , a load of not less than 10psf (0.48kN/m2) shall be included.
- Design snow load of 30psf (1,44kN/m^2) or less need not be included. Where design snow loads exceed 30psf(1.44kN/m^2),the design snow load shall be included, but may be reduced up to 75% where consideration of siting, configuration and load duration warrant when approved by the building official.
- Total weight of permanent equipment shall be included.

Static Lateral Force Procedure, UBC 1630.2

- UBC specifies the following formula for calculating base shear **(V)**:

1630.2.1 Design base shear. The total design base shear in a given direction shall be determined from the following formula:

$$V = \frac{C_v I}{R T} W \quad ---(30\text{-}4)$$

The total design base shear need not exceed the following:

$$V = \frac{2.5 C_a I}{R} W \quad ---(30\text{-}5)$$

The total design base shear shall not be less than the following:

$$V = 0.11 C_a I W \quad ---(30\text{-}6)$$

In addition, for Seismic Zone 4, the total base shear shall also not be less than the following:

- The upper bound value for base shear tends to govern for relatively stiff structures that exhibit a small (short) fundamental period of vibration (T).
- The lower bound values for base shear tend to govern for relatively flexible structures that exhibit a large (long) fundamental period of vibration (T).

C_v = Seismic Coefficient, See Table 16-R
I = Seismic Importance Factor, See Table 16-K
R = Ductility Coefficient, See Table 16-N
T = Natural time period of the building
W = Story dead load

Static Lateral Force Procedure

$$V = \frac{0.8 \; Z N_v \; I}{R} W \qquad (30\text{-}7)$$

1630.2.2 Structure period. The value of T shall be determined from one of the following methods:

1. **Method A:** For all buildings, the value T may be approximated from the following formula:

$$T = C_t (h_n)^{3/4} \qquad (30\text{-}8)$$

WHERE:

C_t = 0.035 (0.0853) for steel moment-resisting frames.

C_t = 0.030 (0.0731) for reinforced concrete moment-resisting frames and eccentrically braced frames.

C_t = 0.020 (0.0488) for all other buildings.

For structures with flat roofs, h_n is the distance from the ground to the roof/ceiling system. For structures with sloped (pitched) roofs, h_n may be taken as either the height of the ceiling system above the ground or as the mean roof height.

Static Lateral Force Procedure

1630.5 Vertical Distribution of Force. The total force shall be distributed over the height of the structure in conformance with Formulas (30-13), (30-14) and (30-15) in the absence of a more rigorous procedure.

$$V = F_t + \sum_{i=1}^{n} F_i \qquad (30\text{-}13)$$

The concentrated force F_t at the top, which is in addition to F_n, shall be determined from the formula:

$$F_t = 0.07\ T\ V \qquad (30\text{-}14)$$

The value of T used for the purpose of calculating F_t shall be the period that corresponds with the design base shear as computed using Formula (30-4). F_t need not exceed $0.25V$ and may be considered as zero where T is 0.7 second or less.

Static Lateral Force Procedure

Ft is an additional lateral force assumed to act at the top of a structure. This force is intended to approximate the effects of higher modes of structural vibration. The magnitude of Ft is determined based on the natural (fundamental) period of vibration of the structure, T:

Ft = 0, when T < 0.7s
Ft = 0.07 T V, when 0.7s < T < 3.57s
Ft = 0.25 V, when T > 3.57s,

Since $\mathbf{F_t}$ = 0 when **T** < 0.7s, it is apparent from UBC Equation 30-8 that $\mathbf{F_t}$ = 0 for buildings less than 114.5 ft tall.

Static Lateral Force Procedure

The remaining base shear shall be distributed over the height of the structure, including Level n, according to the following formula:

$$F_x = \frac{(V - F_t)\, w_x h_x}{\sum_{i=1}^{n} w_i h_i} \qquad (30\text{-}15)$$

At each level designated as x, the force F_x shall be applied over the area of the building in accordance with the mass distribution at that level. Structural displacements and design seismic forces shall be calculated as the effect of forces F_x and F_t applied at the appropriate levels above the base.

- **h_x** is the height from the base of the structure to level x,
- **w_x** is the portion of the building weight assumed to be “lumped” at level x.
- w_x typically includes the total weight of the floor or ceiling/roof system at level x, plus half the weight of the vertical elements (walls; columns) located immediately below level x and half the weight of the vertical elements located immediately above level x.

Problem-1

Determine the UBC-97 design seismic forces for a three-story concrete shear Wall office building. It is located in Dir District KPK province on rock with a shear Wave velocity of 3000 ft/sec. The story heights are 13 feet for the first floor and 11 feet for the second and third floors. The story dead loads are 2200, 2000 and 1700 kips from the bottom up. The plan dimensions are 180 feet by 120 feet. The Walls in the direction under consideration are 120 feet long and are Without openings. The shear walls do not carry vertical loads.

Problem-1

Level	h_x (ft)	w_x (k)	$w_X h_X$ x10^{-3}	F_i+F_t (k)	V_X (k)	M_x (ft-k)
3	35	1700.	59.5	351.7	351.7	3869.
2	24	2000.	48.0	283.7	635.4	10858
1	13	2200.	28.6	169.1	804.5	21317.
Σ		5900.	136.1	804.5		

Problem-2

Determine the UBC-97 design seismic forces for a nine story ductile moment resisting steel frame office building located in Muzaffarabad on very dense soil and soft rock. The building is located **5km** from a fault capable of large magnitude earthquakes and that has a moderate slip rate (M>7, SR>2mm/yr). The story heights are all thirteen feet. The plan area is 100 feet by 170 feet. The total dead load is 100 pounds per square foot at all levels.

Problem-2

Level	h_x (ft)	w_x (k)	$w_x h_x$ $x10^{-3}$	F_i+F_t (k)	V_x (k)	M_x (ft-k)
9	117	1700.	198.9	260.1	260.1	3381.
8	104	1700.	176.8	156.2	416.6	8793.
7	91	1700.	155.7	137.6	553.9	15994.
6	78	1700.	132.6	117.2	671.1	24718.
5	65	1700.	110.5	97.6	768.7	34711.
4	52	1700.	88.4	78.1	846.8	45720.
3	39	1700.	66.3	58.6	905.4	57490.
2	26	1700.	45.2	39.9	945.3	69779.
1	13	1700.	22.1	19.5	964.8	82321.
Σ		15300.	996.5	964.8		

- Determine the base shear for the fundamental mode of the Frame shown in Fig. 35 by using response spectrum of Fig. 33 with $\xi = 0.05$. Also determine the lateral load at each level for the fundamental mode.

Solution:

Dead Loads:

Level 1 & 3 = (880)(30)(30) = 7770 kN

Level 2 = (590)(30)(30) = 5209 kN

ω = 15.1 rad/sec

$T = 2\pi / \omega$ = 0.416 sec

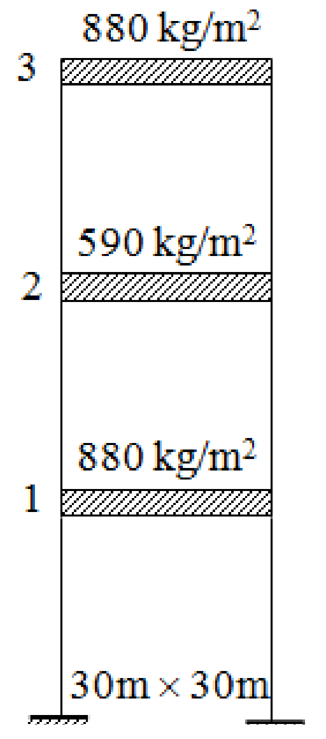


Fig. 35. Frame for Example 10.9.

STRUCTURAL DYNAMICS- Example 10.9 using Response Spectrum

$S_a = \omega S_v = 5285 \text{ mm/sec}^2 = 5.285 \text{ m/sec}^2$

The calculations are made in Table 10.6 using the following expressions:

$$W^E = \frac{\left(\sum W_i a_i\right)^2}{\left(\sum W_i a_i^2\right)}$$

$$V = W^E S_a / g \text{ and}$$

$$F_i = V \frac{W_i a_i}{\sum W_i a_i}$$

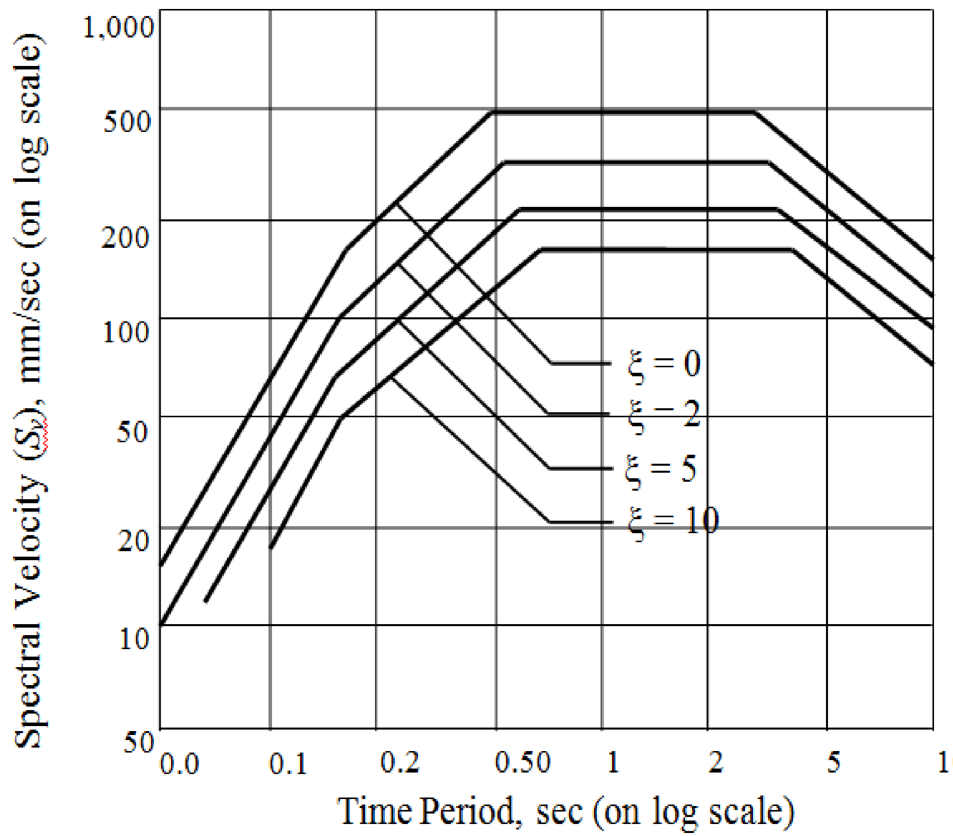


Fig. 33. A Typical Out-of-Scale Response Spectrum.

Table 10.6. Calculation Sheet for Example 10.9.

Level	W_i kN	a_i mm	$W_i a_i$ kN-mm	$W_i a_i^2$ kN-mm²	F_i kN
1	7770	1.00	7770	7770	1844
2	5209	1.95	10158	19807	2411
3	7770	2.86	22222	63555	5275
Total	20749		40150	91132	9530

$$W^E = \frac{(40150)^2}{(91132)} = 17689 \text{ kN} \qquad V = \frac{17689 \times 5.285}{9.81} = 9530 \text{ kN}$$

STRUCTURAL DYNAMICS- General Considerations for Seismic Design

- Buildings are designed to withstand moderate earthquakes without damage and severe earthquakes without collapse. Earthquake movements impose deformations on the structures.
- We find inertial forces due to these earthquake movements depending upon the structure.
- Dynamic effects like resonance are also important to be considered.
- Due to availability of limited data, the design is generally based on statistical studies of the previous earthquakes.
- As more and more earthquake data become available and understanding of the structural behavior is improved, Building Codes undergo modifications to cover the weaknesses in design criteria of the previous codes.
- Further, the safety of a structure subjected to earthquake loading also depends on the designer's understanding of the response of the structure to ground motion.
- It is prohibitively expensive to design the structure in the elastic range. Overall structural ductility is very important in such designs.

STRUCTURAL DYNAMICS- General Considerations for Seismic Design

- Following are the general considerations for the seismic design of structures:
    1. Design for earthquakes differ from the design for gravity and wind loads particular with respect to greater sensitivity of earthquake-induced forces to the geometry of the structure. Most structures, which are not extremely tall, are designed by the equivalent static loading (up to about 20 stories). This is applicable for regular buildings with center of mass and center of resistance very near to each other (Fig. 36).

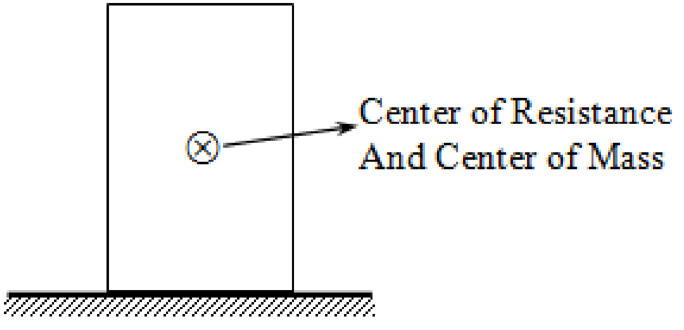


Fig. 36. Center of Resistance against Earthquake and Center of Mass of a Regular Structure.

2. Design is made for loads that are a function of weight/mass of the structure.
   - Bulk of mass is located at floor levels, so forces are considered at these levels.
   - Triangular variation of forces is generally assumed. Without careful design, for an irregular structure, forces and displacements can be concentrated in portions of the structure that may not be capable of providing the adequate strength or ductility.
   - The configuration of a structure has a major effect on its response to an earthquake.
   - Structures with a discontinuity in stiffness or geometry can be subjected to very high displacements and forces.
   - the absence of shear walls, infill walls or even cladding at a particular story level, as compared to other stories, causes concentration of displacements at this story.

- The ground floor of a shopping center generally has this weakness, as shown in Fig.37. This weak story compared with rest of the structure is termed as ***open or soft story***.
- The larger displacements require a considerably larger ductility at the level of soft story.
- If this amount of ductility is not available, the structure fails locally at this level. Such a design is not recommended and the stiffening members must be continued to the foundations.

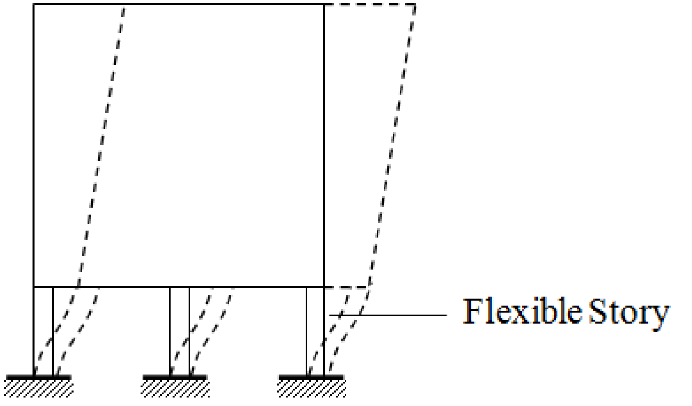
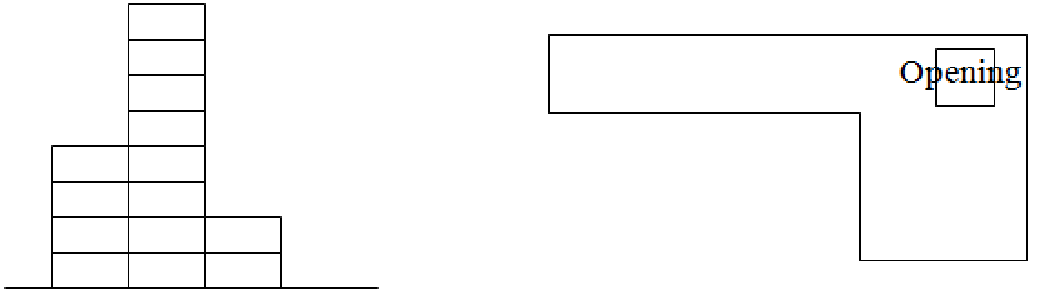


Fig. 37. Deformation of a Building Having Soft Story.

STRUCTURAL DYNAMICS- General Considerations for Seismic Design

3. Steps to strengthen a member for one type of loading may actually increase the forces in the member and change the mode of failure from ductile to brittle.
4. As the frequency of the ground motion becomes closer to one of the natural frequencies of a structure, the chances of the structure to experience resonance increases. This results in an increase in both displacements and damage to the structure. The frequency or time period of a structure basically depends on height of the structure and the earthquake response of a structure especially varies with the height. Tall buildings usually exhibit stronger response to long period ground motion and short buildings usually exhibit stronger response to short period ground motion.
5. The first mode of vibration usually provides the greatest contribution to lateral displacement.
6. The taller structures are more affected by the higher modes of vibration and their effect actually adds to the effects of lower modes.

7. The longer duration of earthquake always has a greater potential for damage to the structure.
8. Vertical geometric (Fig. 38 a) and plan irregularities (Fig. 38 b) may result in torsion induced by ground motion.



a) Vertical Geometric Irregularities   b) Plan Irregularities

Fig. 38. Geometrical Irregularities in Structures.

9. The addition of stiff members, such as shear wall, can on one side reduce the displacements of the structure and hence the damage. On the other side, stiff members pick up a greater portion of the load. When this effect is ignored in design, unexpected and often undesirable results can occur.

STRUCTURAL DYNAMICS- General Considerations for Seismic Design

10. An adequate separation must be left between structures. Large lateral displacements can cause the structures to come in contact with each other during an earthquake. This results in major damage due to hammering effect.
11. Members designed for seismic loading must behave in a ductile manner and should dissipate energy without compromising the strength.

- Confinement of concrete is to be provided to ensure ductility in members subjected to shear and bending. Due to this confinement, the beams and columns can undergo nonlinear cyclic bending.
- the flexural strength is maintained and no excessive diagonal tension cracking occurs.
- Confinement is provided by the use of closed loops or spiral reinforcement that encloses the core-concrete of beams and columns.
- Confined concrete allows the formation of ductile hinges that can dissipate energy in case of reinforced concrete frames.

12. It must be tried that the plastic hinges are developed in the beams rather than columns.

- The **weak beam – strong column approach** is always preferred for the design of reinforced concrete frames subjected to seismic loading.
- This effect is achieved by making the columns stronger than the beams at the joints, forcing the hinges to be formed in the beams.
- The advantage of this approach is that the overall vertical load carrying capacity is maintained near collapse and smaller portion of the structure is affected by the nonlinear behavior.

13. Transverse reinforcement for the columns is to be carefully designed for the shear force due to lateral loads in addition to shear force resulting from the dead and live loads.

- A smaller length column closer to high stiffness members or shear walls may attract large shear forces and may fail in shear. This type of column, called ***captive column***, is more critical for design in shear than in flexure

- Chapter 21 of the ACI code deals with special provisions for seismic design. Some of the definitions are discussed below:

Ductile Connection:

- A connection that is capable of yielding up to the level of the design earthquake displacements.

Strong Connection:

- This type of connection remains elastic even if the adjoining members yield as a result of design earthquake displacements.

Crosstie:

- This is a continuous reinforcing bar satisfying the following requirements:
  a. It should have a seismic hook at one end.
  b. It should have a hook not less than 90° at the other end.
  c. It should have a six-diameter extension at the 90° hook side.
  d. Both the hooks must go around and anchored against peripheral longitudinal bars.
  e. Two successive cross ties between the same longitudinal bars must alternate in their hooks.

Design Displacement:

- It is the code prescribed total lateral displacement in case of earthquake.
- As the codes for seismic design allow inclusion of the nonlinear response, the stability of the lateral force resisting system must be studied at displacements larger than those obtained by linear analysis.
- Further, the interaction with other structural and non-structural members must also be considered.
- If detailed nonlinear response analysis is not carried out and code specific value is also not available, an approximate method may be to consider the total displacement equal to double of the displacement obtained by linear analysis considering cracked stiffness for the members.

Hoop:

- This is a closed tie with seismic hooks at both ends, or a spiral with seismic hooks at both ends.

Lateral Force Resisting System:

- The members of the structure designed to resist the earthquake forces, collectively making the resisting frames.

Moment Frame:

- This is a lateral force-resisting frame that resists forces by flexure besides shear and axial forces.
- This may be of three types, namely, ordinary moment frame, intermediate moment frame, and special moment frame.

STRUCTURAL DYNAMICS- ACIDefinitions For Seismic Design

Ordinary Moment Frame:

- Any frame that satisfies the general ACI Code provisions but not necessarily the seismic provisions is called ordinary moment frame. It may be cast-in-place or precast frame.
- This type of frame may be used in regions of low seismic risk or where correspondingly low seismic performance is used in the calculation of seismic forces.
- This frame has performance corresponding to Seismic Design Category B.

Intermediate Moment Frame:

- This type of frame satisfies the general requirements of the ACI Code along with provisions of ACI 21 for super-structure and part of the structure between the base and the foundation.
- Base of the foundation is the level at which earthquake motions are transferred to the structure, not necessarily the ground level.
- only cast-in-place frames are included in this category.
- This type is used in regions of moderate seismic risk or for frames where intermediate seismic performance is taken in the calculation of the loads.
- Once this type of frame is considered for the seismic analysis, all requirements of this type of frame given in Chapter 21 of ACI Code must be applied.

Special Moment Frame:

- This frame may be either cast-in-place satisfying the ACI Code 21.1.3 to 21.1.7 and 21.5 to 21.7 or it may be precast additionally satisfying the Code requirement 21.8.
- The general provisions of ACI must also be satisfied.
- This type of frame must be used in regions of high seismic risk or where high seismic performance is considered in the analysis.
- In such cases special structural walls and diaphragms may also be used.
- For design and detailing, all requirements of special moment frame must be satisfied if it is used for calculation of the forces.

STRUCTURAL DYNAMICS- ACIDefinitions For Seismic Design

Plastic Hinge Region:

- The is the length over which the flexural yielding due to design displacements is extended, which is not to be taken lesser than the overall depth of the member from the critical section at which yielding starts.

Seismic Hook:

- This is a hook having a bend greater than or equal to 135° for crossties, rectangular stirrups and hoops and greater than or equal to 90° for circular hoops.
- The hooks after going around the longitudinal reinforcement must have extension of greater of six-diameters and 75mm, projecting into the interior of the stirrup or hoop.