CHAPTER 2

EARTHQUAKE CHARACTERESTICS AND EFFECTS ON STRUCTURES

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EARTHQUAKE GROUND MOTION

Generated seismic waves produce complex earthquake ground motions that are combination of slow and long, or short and abrupt waves.

The complexity of earthquake ground motions is due to three factors:

- The seismic waves generated at the time of earthquake fault movement are not all of a uniform character,
- As these waves pass through the earth on their way from the fault to the building site, they are modified by the soil and rock media through which they pass,
- Once the seismic waves reach the building site, they undergo further modifications that are dependent upon the characteristics of the ground and soil beneath the building.

These three factors are referred to as *source effects*, *path effects*, and *local site effects*, respectively.

Earthquake ground motions, shown in Fig. 2.1, are characterized by its:

- Duration of the shaking
- Amplitude (maximum or peak ordinate recorded)
- Frequency content

Frequency is defined as the number of complete cycles of vibration made per second, and is measured in Hertz (Hz). A complete cycle of vibration can be considered to be the same as the distance between one crest of the wave and the next (full wavelength). Although different vibration frequencies occur, some frequencies usually predominate. The distribution of frequencies in a ground motion is referred to as its *frequency content*.

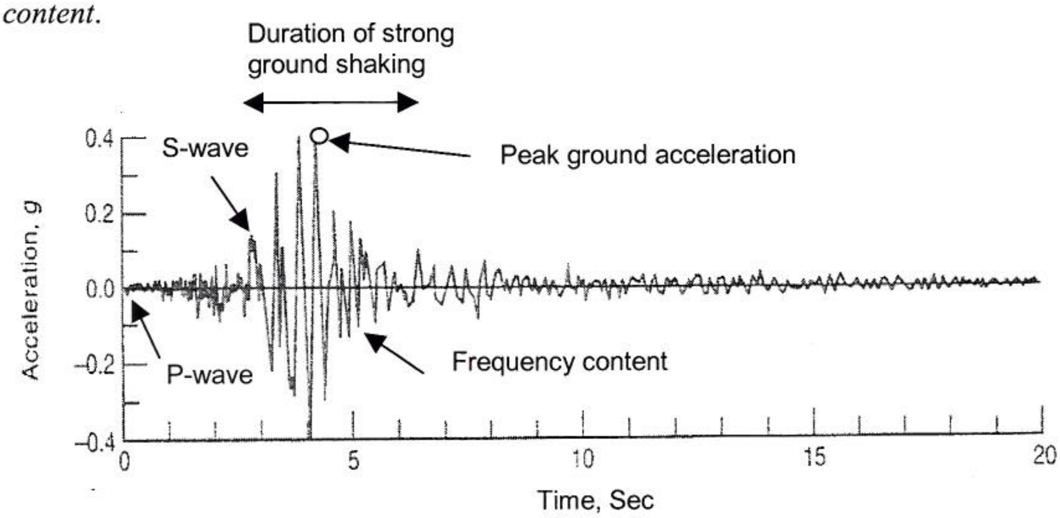

Fig. 2.1 Earthquake Ground Motion – Acceleration Versus Time Record

EARTHQUAKE RECORDS

Strong motion instruments (such as Seismometer and Accelerometer) are used to measure the ground motion amplitude during an earthquake shaking and produce earthquake records (also known as time histories).

A ***Seismometer*** (***Seismograph***) instrument is a pendulum type device that measures the displacement of the ground during an earth movement with respect to a stationary reference point. A ***Seismogram*** is the record (trace) of ground displacement during an earth movement. See Fig. 2.2.

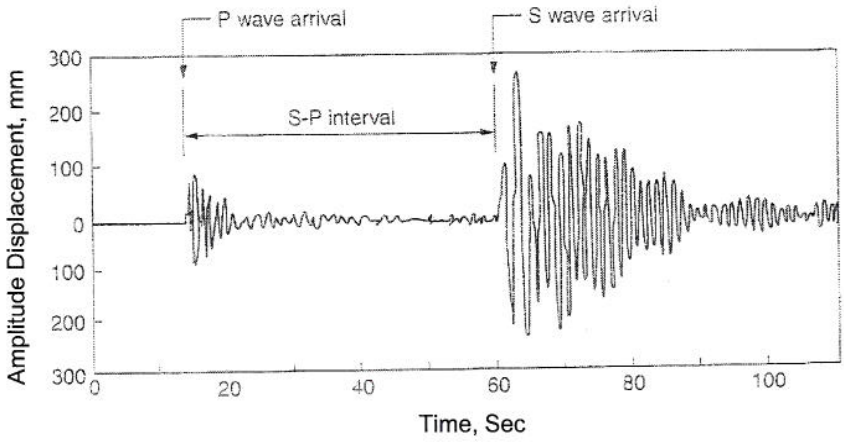

Fig. 2.2 Typical Seismometer Amplitude Trace

An ***accelerometer*** (***accelerographs***) is a seismometer that records acceleration in two horizontal directions and in the vertical plane. Typical example is shown in Fig. 2.3. By integrating the acceleration record (***accelerogram***), time histories of velocity and displacement at the site are obtained

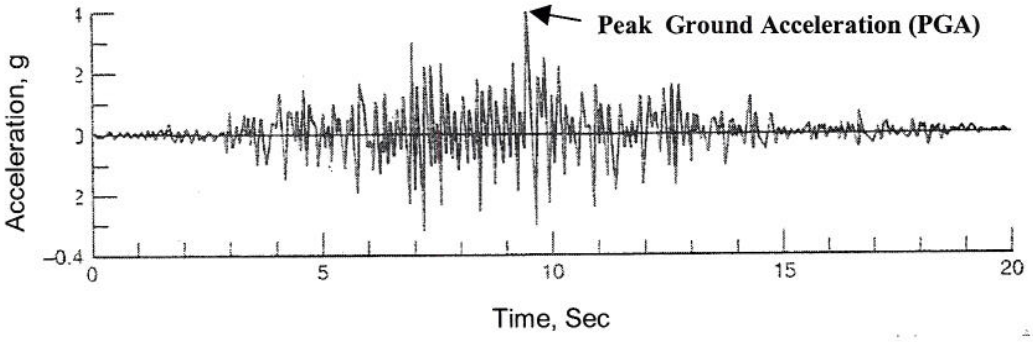

Fig.2.3 Accelerograms of Motion Recorded During Earthquake Shaking at a Site

PEAK GROUND ACCLERATION (PGA)

The maximum recorded ground acceleration of an earthquake event at a particular site is often referred to as peak ground acceleration (PGA) and measured on accelerometer in ft/sec^2, or in/sec^2. However, it is most commonly defined as a percentage of gravitational acceleration, g (32.2 ft/sec^2, 386 in/sec^2).

- For example: 0.4 g = 0.4*32.2 = 12.88 ft/ sec^2.

EFFECTIVE PEAK GROND ACCELERATION (EPGA)

The effective peak ground acceleration is the maximum ground acceleration that is used by codes or seismic provisions for the design of structures. Thus, it is a parameter set by the code rather than a quantity of an actual earthquake. Determination of the effective peak ground acceleration used for the design of California buildings will be explained in Chapter 4.

MEASUREMENTS OF EARTHQUAKE

Earthquakes are measured in terms of **Magnitude** and **Intensity**. Magnitude measures the absolute "size" or "strength" of the earthquake, irrespective of viewpoint, whereas Intensity measures the severity of an earthquake at a certain location.

EARTHQUAKE MAGNITUDE

The magnitude of an earthquake depends on the length and breadth of the fault slip, as well as the amount of slip. The Richter magnitude scale is used to determine the strength of an earthquake.

- A seismometer recording station located 100 kilometers (62 Mile) from an earthquake epicenter, and measuring a vibration amplitude of 0.001 millimeters defines a ***standard Richter earthquake***.

The Richter magnitude of an earthquake, ***M***, is given by:

$$M = \log\left(\frac{A}{Ao}\right)$$

Where A = maximum amplitude recorded by the seismometer (seismograph) located 100 km from the epicenter of the earthquake

Ao = reference vibration amplitude of 0.001 mm.

Richter magnitude is represented in whole numbers and decimals (e.g: M = 6.3). Since the Richter magnitude is a logarithmic scale, a unit increase on the scale (a whole number) represents a 10 fold increase in vibration amplitude.

The Richter scale is a reliable estimate of earthquakes up to epicenteral distance of 600 km and magnitude of ***M***=7.

For larger magnitude earthquakes, The ***Moment Magnitude*** scale, ***Mw***, is used. The moment magnitude scale accounts for the area of rupture, energy released and rigidity of rocks in addition to the amount of slippage along the fault.

The Moment Magnitude is given by:

$$Mw = \frac{(\log Mo)}{1.5} - 10.7$$

The Richter scale and Moment Magnitude scale are comparable over the range of magnitude 3 to 7.

Energy released by an earthquake, in joules, is given by:

$$E = 10^{11.8+1.5M}$$

Since the energy release is function of the 1.5 power of the earthquake magnitude, an increase of Richter magnitude of 1.0 produces an increase in energy release by 32 fold. In other words, it takes 32 smaller earthquakes, of magnitude 5 for example, to release the same energy produced by an earthquake that is one magnitude larger, magnitude 6 for example.

A magnitude increase of 2 is equivalent to an energy increase of approximately a 1000 times more.

EARTHQUAKE INTENSITY

The intensity of an earthquake is based on the damage and other observed effects on people and structures, and varies from a place to another within the affected area.

- Earthquake intensity is related to distance to epicenter, duration of ground shaking, and site soil conditions.
- Generally the further the earthquake epicenter, the less damage and intensity felt at the site, unless the site soft soil conditions amplify the ground motions.

Earthquake intensity is measured based on the Modified Mercalli intensity scale, MM.

- The MM scale is an indication of the severity of the ground shaking at a specific site.
- The MM scale is based on the observed effects of an earthquake at that specific site and on the qualitative assessment of the damage caused.

The Modified Mercalli scale ranges from a value of ***I*** to a value of ***XII***.

- The lower numbers (***MM I-VI***) are based on peoples feeling of the earthquake whereas the higher numbers (***MM VII – XII***) are based on observed structural damage.

Table 2.1 shows the 12 categories (***I* – *XII***) of observed effects of earthquakes used in the Modified Mercalli scale. In addition, Table 2.1 provides approximate relationship between MM intensity scale and the peak ground acceleration (PGA) and earthquake magnitude M.

There is no exact relationship between intensity of earthquake, peak ground acceleration, and earthquake magnitude. However, usually the longer the fault rupture length, the longer the duration of ground shaking, thus larger earthquake magnitude and higher earthquake intensity.

ISOSEISMAL MAPS

A map of earthquake intensity over a region where areas of similar earthquake damages are grouped and identified. Data for this map are collected mostly by observation or questioning locals.

ATTENUATION OF GROUD MOTION

Attenuation is the decrease in ground motion (earthquake released energy) received at a site with increasing distance from the epicenter. This attenuation is caused mainly by the geological formation of the site, focal depth and fault orientation.

- The shorter period (higher frequency) P and S waves attenuate much faster than the longer period (slower frequency) Surface waves.

TABLE 2.1 Modified Mercalli Intensity Scale

MM Intensity	***PGA (g)***	***Magnitude M***	***Description of Intensity Level & Effects on Structures***
I	< 0.03	1.0 – 2.9	Not felt except by a very few under especially favorable circumstances.
II	< 0.03	3.0 – 3.9	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	< 0.03	3.0 – 3.9	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.

IV	< 0.03	4.0 – 4.9	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	0.03 – 0.08	4.0 – 4.9	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	0.08 – 0.15	5.0 – 5.9	Felt by all; many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	0.15 – 0.25	5.0 – 5.9	Damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
VIII	0.25 – 0.45	6.0 – 6.9	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	0.45 – 0.60	7.0 – 7.9	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	0.60 – 0.80	7.0 – 7.9	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	0.8 – 0.9	> 8.0	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII	> 0.9	> 8.0	Damage total. Lines of sight and level distorted. Objects thrown into the air.

HAZARD LEVEL – EARTHQUAKE PROBABILITY OF EXCEEDANCE

The fact that earthquakes are somewhat random in occurrence, one cannot predict exactly whether an earthquake of a given magnitude or a certain ground shaking will or will not occur in the next several years. Therefore, the concepts of probability of exceedance and return period are commonly used to express the level of hazard/risk associated with an earthquake event.

- The probability of exceedance (*Pe*) is defined as the probability that a specified earthquake event (level of ground motion or earthquake magnitude) will be exceeded in a specified time (*n*).
- The probability that an earthquake event (level of ground motion or earthquake magnitude) will be exceeded during a one-year interval is termed the annual rate of exceedance (*Pa*)
- The return period, *Tr*, of an earthquake event is computed as the inverse of annual rate of exceedance (1/*Pa*). For example, an annual exceedance probability, *Pa*, of 0.1 (10%) implies a return period, *Tr*, of ten years.
- The probability that an earthquake event with a return period, *Tr*, will be exceeded during a period of, *n*, years (*Pe*) is 1.0 minus the probability that it will not be exceeded during that *n* years period.

Probability that an earthquake event **will not** be exceeded during the n-years period is:

$$(1 - Pa)^n$$

Thus, the probability that the earthquake event will be exceeded during the n-years period, *Pe*, is:

$$Pe = 1 - (1 - Pa)^n = 1 - (1 - 1/Tr)^n$$

- The *n* years period is typically set to 50 years (expected life of a project), whereas acceptable level of hazard/risks (probability of exceedance) are typically set to 2%, 5% or 10%.

Example: for a 10% probability of exceedance (*Pe*) over a 50-year (*n*) period,

$$0.1 = 1 - (1 - Pa)^{50}$$

The annual rate of exceedance (*Pa*) equals 0.0021, corresponding to a return period, *Tr*, of 475 years.

$$Pa = 0.0021 \;\; \text{->} \;\; Tr = 1/\,Pa = 475 \text{ years}$$

Keep in mind that a 10% chance of exceedance means there is a 90% chance that the earthquake event will NOT exceed the value.

Building codes for long times used to consider the risk of the earthquake ground motion level (aka, earthquake hazard map) with a 10% probability of exceedance during a 50-

year period. More recently, codes have moved to a 2% probability of exceedance during a 50-year return period. This corresponds roughly to a 2,500 year return period.

MAXIMUM PROBABLE AND CONSIDERED EARTHQUAKE

The maximum probable earthquake ground motion is the largest earthquake shaking with a significant probability of occurrence within the lifetime of structure. However, building codes use the Maximum Considered Earthquake (***MCE***) as the maximum possible earthquake ground motion for consideration in the design of structures. The Maximum Considered Earthquake (MCE) is based on code predetermined maps reflecting maximum acceleration and soil profiles.

EARTHQUAKE PREDOMINATE PERIOD

Earthquake ground motion at the building site has a compound superposition of different vibration frequencies (frequency content) with some frequencies usually predominate.

- The inverse of the frequency, f, is the period of the wave, T, and is defined as the length in seconds of a full cycle (from crest to adjacent crest).
- $T\,(\text{sec}) = 1 / f\,(\text{Hz})$
- Earthquake ground motion predominate vibration period is also called natural period or fundamental period of the wave.

BUILDING PERIOD

When a structure/building is subjected to earthquake ground motion, it begins to vibrate possessing its own frequency contents. However, the building's vibrations tend to center around one particular frequency that is known as its natural or fundamental frequency.

- The natural or fundamental frequency is the ***smaller*** of all of the frequency contents.
- The inverse of the frequency is the period of vibration of the building.
- Similarly, the building's vibrations have several periods. The ***largest*** of all periods is known as the natural period or fundamental period of the building vibration.

Generally: the shorter a building is,

- the lower its natural period and/ the higher its natural frequency,

and the taller the building is,

- the higher its natural period and/ the lower its natural frequency.

SITE PERIOD

Soil conditions at the building have itself a period on its own. This is referred to as ***Site Period***. Determining actual site period, however, is a complex case and can have a wide range depending on soil density, bearing strength, moisture content, compressibility, and sensitivity to liquefaction. Typical values of site (soil) period vary between 0.4 and 1.5 sec., with very soft soil having a period approaching 2.0 sec.

- Soft soils generally have a tendency to increase ground motion (shaking) as much as 2 to 6 times as compared to rock.

ROSONNENCE

Resonance is defined as the amplification of the response (amplitude) of a vibrating system when the frequencies (or periods) of two or more type of waves coincide with each other.

- When the frequency content (or predominate period) of the earthquake ground motion are centered around the building's natural frequency (or natural period), the building's response is greatly amplified, i.e., building resonates.

Resonance can also occur when the building's natural frequency (or natural period) coincides with the site's (soil) natural frequency (or natural period).

Also, earthquake ground motions can be greatly amplified when its natural frequency (or natural predominate period) coincide with the site (soil) natural frequency (or natural period). This typically occurs for earthquake surface waves passing through soft soil (soft clay deposit or bay mud).

Resonance also occurs when buildings natural frequency (or natural period), site (soil) frequency (or period), and earthquake frequency content (or predominate period) all coincide with each others.

As an example, during the Mexico City earthquake of 1985 (M = 8.1), a majority of the many buildings which collapsed during this earthquake were around 15 - 25 stories tall (i.e., they had a natural period of around 2.0 seconds).

- Earthquake long period surface waves resonated with the long period soft soil underlain the city, resulting in recorded motions that are 15-20 times larger than those corresponding motions recorded on rock soil at comparable distance from the earthquake epicenter.
- The amplified earthquake ground motions with approximately 2 sec predominate period resonated with These 15 - 25 story tall buildings.

Other buildings, of different heights and with different vibration characteristics, were often found undamaged even though they were located right next to the damaged 20 story buildings.

SOIL LIQUIFACTION

A saturated fine grained sand or silt when subjected to continued cycles of vibration, experiences an increase in pore water pressure and a decrease in soil shear strength (i.e., soil bearing capacity). When the shear strength drops to zero, the soil liquefies.

In effect, the soil turns into liquid, sinking any structure that it is supporting (soil settlement). In addition, lateral spreading and slope instability may result.

Mitigation of soil liquefaction includes:

- soil compaction through heavy vibration or dynamic compaction
- lowering groundwater table to reduce pore water pressure effects
- introducing cement grouting to densefy the soil.

SESIMIC DAMAGES TO STRUCTURES

Extent of damages to a structure due to earthquake event depends on:

➢ Peak ground acceleration ➢ Duration of strong shaking ➢ Length of fault rupture	Earthquake Characteristics
➢ Distance and geology between epicenter and structure ➢ Soil conditions at the structure site ➢ Natural period of the site	Site Characteristics
➢ Natural period of the structure ➢ Materials and damping of the structure ➢ Age and construction method ➢ Seismic details of the structure	Structural Characteristics

FAMOUS EARTHQUAKES IN CALIFORNIA

Table 2.2 lists a brief (select) history of famous California earthquakes in the last century along with their lessons learned/effects. California earthquake are relatively shallow, many have produced surface rupture, and typically of short duration (Loma Prieta Earthquake lasted 8 seconds).

Table 2.2: Famous Earthquakes in California

Date	*Designation*	*Effects/Lessons Learned*
1906	San Francisco	wide spread damage
1925	Santa Barbara	CA legislature expended on study of California seismology
1933	Long Beach	Resulted in: ➢ Field Act (Division of State Architecture, responsible for approving school design) ➢ Riley Act (set minimum standard for lateral force resistance in building)
1940	El Centro	7.1 Magnitude, provided valuable accelerometer data from instrumented buildings
1966	Parkfield	5.5 magnitude, 0.5g, magnitude and acceleration are not correlated
1971	San Fernando	6.6 magnitude, 1.24g, failure of new building designed with new code.
1979	Imperial Valley	6.6 magnitude, provided accelerometer data from extensively damaged building
1989	Loma Prieta	7.1 magnitude, soft soil amplified the seismic energy at large distance from the epicenter.
1994	Northridge	6.7 magnitude, peak ground acceleration exceeded code specific, ➢ produced significant vertical acceleration, ➢ fault involved was considered inactive, ➢ widespread damage to welded moment resisting steel frames.

MULITPLE CHOICE QUESTIONS

2.1 Earthquake hazard level is quantified using …….

A probability of exceedance

B Richter scale

C Modified Mercalli scale

D length of fault rupture

2.2 Which of the following statement are correct for earthquake magnitude?

A the magnitude of an earthquake is derived from the peak ground acceleration

B the magnitude of an earthquake is determined from the logarithm of the recorded amplitude

C the magnitude of an earthquake does not depend on the length of the fault slip

D the magnitude of an earthquake is expressed in Roman numeral ($I - XII$)

2.3 The Modified Mercalli scale/index is used for assessing ……….

A earthquake magnitude

B earthquake attenuation

C earthquake intensity

D earthquake hazard

2.4 The Modified Mercalli scale/index categorizes earthquake intensities into how many levels?

A 9

B 10

C 11

D 12

2.5 Earthquake attenuation of ground motions indicates ……

A an increase in Surface waves amplitude near epicenter

B a decrease in seismic energy far from epicenter

C a geologic formation to amplify seismic waves

D an earthquake fault that is oriented parallel to the site

2.6 A seismometer is used to measure ………

A earthquake magnitude

B focal depth

C earthquake attenuation

D earthquake displacement amplitude

2.7 Earthquake attenuation of ground motions is not influenced by ……..

A earthquake magnitude

B soil conditions

C path line and length

D focal depth

2.8 An increase in earthquake magnitude by two whole numbers represents ……

A 10 fold increase in vibration amplitude

B 20 fold increase in vibration amplitude

C 100 fold increase in vibration amplitude

D 1000 fold increase in vibration amplitude

2.9 An increase in earthquake magnitude by two whole numbers represents ……

A 10 fold increase in earthquake energy release

B 20 fold increase in earthquake energy release

C 100 fold increase in earthquake energy release

D 1000 fold increase in earthquake energy release

2.10 Soil liquefaction can be best described as:

A an increase in pore water pressure causing severe drop in shear strength of the soil

B a decrease in pore water pressure causing severe drop in shear strength of the soil

C a decrease in pore water pressure causing lateral spreading of loose sandy soil

D an increase in pore water pressure causing an increase in the effective stress of soil

2.11 Soil liquefaction occurs at a saturated geologic formation that are mostly composed of

A stiff clay

B loose sand

C soft clay

D soft rock

2.12 One of the most notable lessons learned from Northridge earthquake (1994)

A vulnerability of welded steel frames buildings

B soft soil amplification of building's vibration

C wide variety of accelerometer data from instrumented buildings

D building tilt and settlement due to liquefaction

2.13 Ground motions are greatly amplified when passing through geologic formation mostly composed of ......

A stiff clay

B loose sand

C soft clay

D soft rock

2.14 As a result of Long Beach earthquake in 1933, California Legislature assigned responsibility for approving design of public schools to Division of State Architecture. This is known as ….

A Riley Act

B Field Act

C Saving Our School Act

D Thomas Act

2.15 A well designed and constructed buildings that experienced considerable damage during an earthquake event, shall be assigned Modified Mercalli Intensity scale of ….

A VIII

B IX

C X

D XI

2.16 Resonance amplifies the vibration amplitude when ……

A earthquake period coincides with the site period

B building period coincides with the earthquake period

C site period coincides with the building period

D all of the above

2.17 Determine the design earthquake return period for a hazard level of 3% in 75 years life of the structure?

A 500 year event

B 1000 year event

C 2000 year event

D 2500 year event

2.18 Which of the following is likely to cause more damage to structures during an earthquake event?

A larger duration of the ground shaking

B larger distance to epicenter

C larger primary seismic waves

D larger attenuation of the ground shaking

2.19 A 20 story building with relatively large natural period is likely to have resonance with which of the following?

A soft rock soil conditions

B Shear waves

C Raleigh waves

D loose sand soil conditions

2.20 Which of the following conditions are likely to cause more damages to a structure?

A large PGA, large distance to epicenter, old age structure

B Small PGA, small distance to epicenter, new construction

C large duration of ground shaking, soft rock, new construction

D large duration of ground shaking, liquefaction potential, poor seismic detailing