EXERCISE 11

SEISMIC SHAKING AND EARTHQUAKE ENGINEERING

Supplies Needed

- calculator
- metric ruler
- colored pencils (at least three colors)

PURPOSE

The purpose of the exercise is to familiarize you with the effects of earthquakes on Earth materials and on buildings. The strength of shaking during an earthquake depends on the amplitude of seismic waves that reach the site, the earth materials at and near the surface, and the design of buildings and other structures. The purpose of this exercise is to outline the methods for describing and measuring seismic shaking, and for predicting its effects on human structures.

SEISMIC SHAKING

It's simple to measure the magnitude of an earthquake, but the pattern of shaking that results from a single earthquake (called *seismic shaking,* or *seismic ground motion)* is much more complex. At the same time, predicting ground motion is crucial for designing structures that will withstand the earthquakes likely to occur in an area. Several factors have to be taken into account to be able to predict ground shaking:

- tectonic framework:
  - number of faults in area, and their distance to the site
  - types of faults
  - earthquake recurrence intervals
  - predicted earthquake magnitudes
- near-surface geology
  - type of material
  - thickness of unconsolidated material
- construction materials and techniques.

Seismic Shaking and Earthquake Engineering

Earthquake intensity, introduced in Exercise 2, is an after-the-fact assessment of the strength and pattern of seismic shaking. The magnitude of earthquakes before the existence of seismometers can only be estimated indirectly. Earthquake intensities, however, can be estimated from historical records. The following relationship between magnitude and maximum intensity has been proposed (Howell, 1973) for shallow-focus earthquakes:

$$I_{max}. = (2 * M) - 4.6 \tag{11.1}$$

where I_{max} is the maximum intensity, and M is the magnitude of the earthquake.

One problem with intensity measurements is that they are essentially qualitative, whereas engineers and architects require more quantitative values. Ground motion is most commonly calculated as *acceleration,* expressed as a fraction of the acceleration of gravity (g, where $g=9.8\ m/sec^2$). In addition, seismic acceleration can be broken down into its three perpendicular components: a vertical component (up-down shaking), and two horizontal components (typically east-west shaking, and north-south shaking). The horizontal components of shaking commonly are the most damaging to buildings because structures are already designed to withstand the vertical force of gravity.

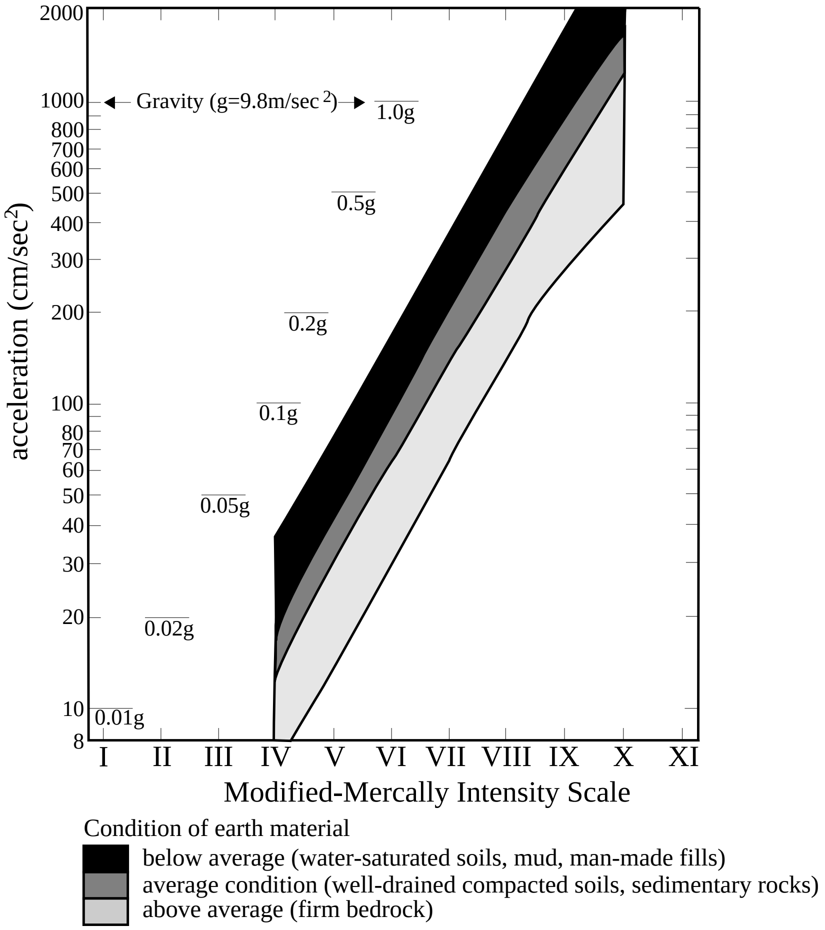

Figure 11.1. Seismic acceleration vs. ground shaking intensity for different earth materials. (After Leed, 1973)

2) Using Figure 11.1 and Equation 11.1, find the peak ground acceleration (in g) on bedrock in San Francisco during an magnitude 7.0 earthquake.

3) How much greater is the acceleration for man-made fills during a magnitude 7.0 earthquake in this area?

Acceleration at a particular site is related to the distance from the site to the epicenter. In addition, acceleration is related to earthquake magnitude – the greater the earthquake, the bigger the acceleration at all locations. An empirical equation (i.e., based on observation and measurement) relates peak ground acceleration (A, in m/sec^2) to earthquake Magnitude (M) and distance to the hypocenter (R, in km):

$$A = 1080\, e^{0.5\, M} / (R+25)^{1.32} \qquad (11.2)$$

Remember that e is the natural exponent function (see Exercise 4 for examples of the function). This equation was created for California, although it may be applicable in other plate-boundary settings. As discussed in Regional Focus B, however, intraplate earthquakes are transmitted farther.

MATERIAL AMPLIFICATION

After tectonic framework, the second major factor that determines the seismic hazard at a specific location is the type of material under foot. On a local scale, the intensity of seismic ground motion is mainly a function of surficial geology. The earthquake in 1985 that killed 5600 people in Mexico City was actually centered several hundred kilometers away in the Pacific Ocean. Many coastal areas much closer to the epicenter than Mexico City, including the city of Acapulco, sustained far less damage. Destruction in Mexico City was so severe because the city is built upon a thick pile of loose lake sediments which *amplify* seismic shaking.

Material amplification is defined as increased seismic shaking as a result of surficial and near-surface deposits. Amplification is a function of the composition and thickness of loose material that underlies an area In particular, sediments and thick soils tend to amplify seismic waves.

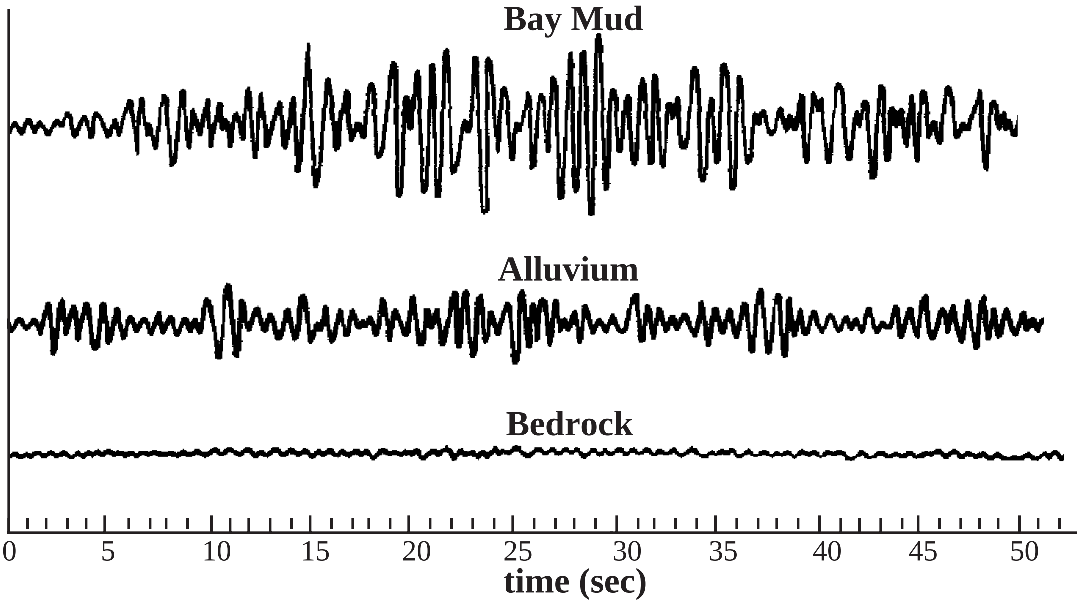

Figure 11.2. Horizontal ground motions of an underground nuclear explosion were recorded by accelographs in San Francisco. All materials were subjected to the same seismic waves. (After Borcherdt, 1975)

4) The vertical axis in Figure 11.2 uses the same scale for all three plots. Calculate how many times more violent the ground shaking was on A) bay mud and B) alluvium compared to bedrock.

A)

B)

In the terminology of seismic waves, material amplification increases the *amplitude* of ground motion, but the *period* of these waves is also important. Like the amplitude, the period of ground motion is a function of both the seismic source and the local geologic conditions. Different types of Earth materials each tend to vibrate at a characteristic period, known as the *fundamental period* of that material. Buildings also have a fundamental period, and the fundamental periods of different buildings vary depending on the height of the structure and other factors (Figure 11.4).

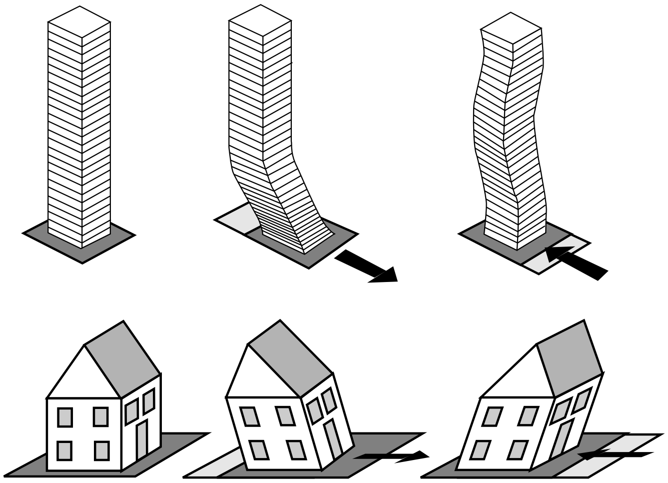

Figure 11.3. The response of a tall building to horizontal ground shaking compared with the response of a short building. (After Lagorio, 1990)

An important factor in predicting earthquake damage is the relationship between the fundamental period of a building and the period of the material on which the building is constructed. If the building's period equals the fundamental period of the material on which it is built, or if it equals some whole-number multiple of the material's fundamental period, then seismic shaking will create a *resonance* with the building that can greatly increase the stresses on the structure. Tall buildings tend to be damaged more on deep, soft soils because of their similar vibrational period. Small, rigid buildings perform poorly on short-period materials such as bedrock (Figure 11.4).

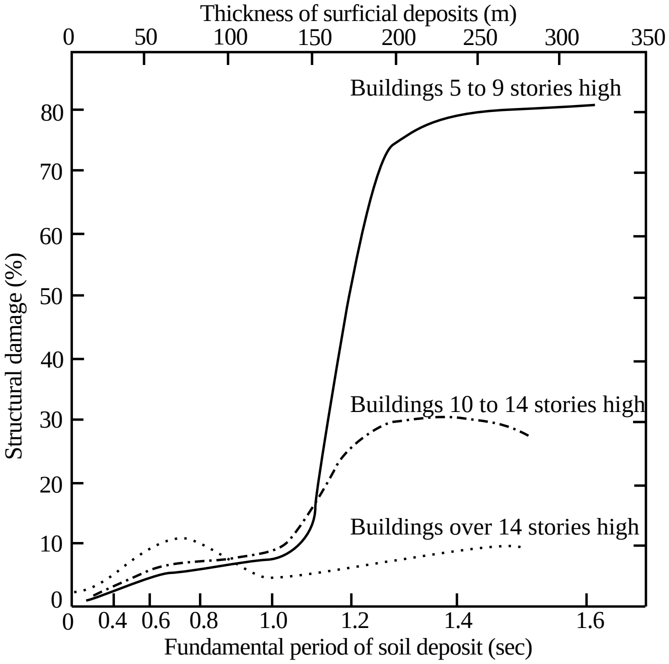

Figure 11.4. Relationship between building height, thickness of sediments, and earthquake damage. (After Seed, 1972)

5) At what fundamental period (in seconds) is the damage greatest for buildings of:

a) 5-9 stories?

b) 10-14 stories?

c) over 14 stories?

SECONDARY EFFECTS OF EARTHQUAKES

Seismic shaking is considered the *primary effect* of earthquakes, but the majority of damage and casualties often result from the indirect, *secondary effects.* The earthquake that struck San Francisco is 1906 is often called the "Great Fire" of 1906 because it was the three days of fire that followed the earthquake that did the great majority of damage, not the seismic shaking itself. Major secondary effects of earthquakes include:

- fire
- landslides
- tsunami
- liquefaction

All of the effects listed above can cause major damage during or shortly after an earthquake. The best guide to where this type of damage will occur in the future is where it has occurred in the past. Landslide-hazard, tsunami-hazard, and liquefaction-hazard maps have been compiled in many of the areas that face the greatest likelihood of these threats in the future.

We will focus on one of these secondary hazards because it is closely linked to seismic ground motion. *Liquefaction* occurs in fine, water-saturated sands during strong seismic shaking. Water-saturated sediments lose their strength as the grains are rearranged during shaking and fluid pressure increases. A sixteenth-century earthquake that struck Port Royal, Jamaica caused much of the town and its inhabitants simply to dissappear into the ground.

BUILDING CODES

In designing earthquake-safe structures, the most important criteria is to make sure that no one critical element of the building is overstressed (the "weakest link" philosophy). In other words, the building is only as strong as its weakest link. The standard in designing a safe building is the capacity or strength of the material to resist seismic stresses, in particular horizontal acceleration, without failure. It's important to understand that seismic provisions in most building codes are intended to protect life and reduce property damage but not completely eliminate losses. The Structural Engineers Association of California Structures recommend that structures be able to (a) resist minor earthquakes without damage, and (b) resist moderate earthquakes without structural damage but with some non-structural damage.

Buildings that are most vulnerable to lateral forces induced by seismic waves are unreinforced masonry, brick and mortar, and adobe constructions. Small wood frame structures are usually the safest as long as they are securely anchored to their foundations. Houses that are not anchored or are improperly anchored can shear off their foundations during lateral ground motion. Steel frame or reinforced-concrete construction methods are least hazardous for multi-story buildings or other tall structures.

The horizontal components of seismic shaking can be converted into a parameter called *base shear*. As mentioned earlier, it is the horizontal components of acceleration that are potentially the most damaging to buildings. Base shear is the maximum lateral force imposed on a structure during seismic ground motion. Newton's second law states that force and acceleration are related as follows:

$$F = m * a \qquad (11.3)$$

where F is the force in Newtons (1 Newton = 1 N = 1 kg*m/sec^2), m is the mass (in kg) and a is acceleration in g (1 g = the acceleration of gravity = 9.8 m/sec^2). In this case, F is the base shear, m is the mass of the structure, and a is the maximum horizontal component of seismic acceleration.

The actual base shear that a building experiences during an earthquake can be calculated using Equation 11.3. A much more applied equation is used by architects and engineers to calculate the base shear that a structure at a specific site *should* withstand:

$$BS = Z * I * (C/R_w) * m * g \qquad (11.4)$$

where BS is the base shear, Z is the seismic zone factor (a unitless value that incorporates the maximum seismic shaking at different locations), I is the importance factor for a structure (high for a school, for example, and low for a warehouse), C is a numerical coefficient related to soil conditions, R_w is a parameter that assessed the type of construction used, m is the total mass of the structure (in kg), and g is gravity (9.8m/sec^2) (Lagorio, 1990).

A building resists base shear with the strength of its load-bearing walls *(shear walls)*. During east-west-oriented shaking, or when the east-west component of shaking is the greatest component, the north-south walls of building must withstand the majority of the stress. The number and arrangement of shear walls determines the portion of base shear that each wall must withstand. Solid, regular arrangements of walls tend to be the strongest; buildings with unsupported walls, such as ground-level carports, often are the most vulnerable.

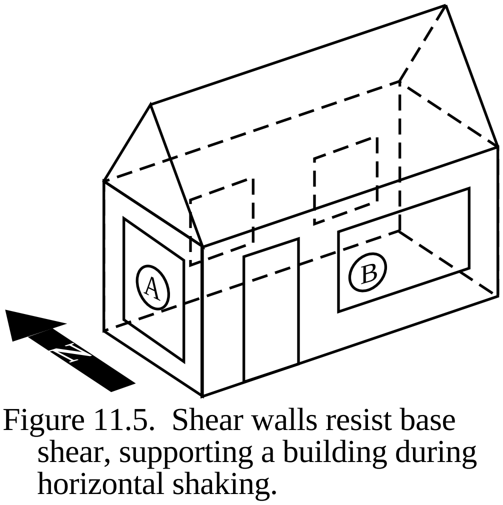

Figure 11.5. Shear walls resist base shear, supporting a building during horizontal shaking.

The building in Figure 11.5 consists of two pairs of perpendicular walls. Walls A and B each must be designed to withstand <u>one half</u> of the total base shear. If shaking is predominantly east-west, then Wall B is one of two walls resisting the seismic stress; if shaking is predominantly north-south, then Wall A is in the same situation.

6) Suggest simple modifications or additions to the

building in Figure 11.5 so that both Wall A and Wall B would only need to withstand one third of the base shear.

CASE STUDY: EARTHQUAKES IN SAN FRANCISCO

The San Francisco Peninsula lies astride the San Andreas fault where it passes northward from the land to the ocean. In 1906, the city was burgeoning as the preeminent cultural and economic center west of the Mississippi. At 5:14 a.m. on April 18, the city's fortunes suffered a severe setback:

> *"At first came a sharp but gentle swaying motion that grew less and less; then a heavy jolting sideways – then another, heaviest of all. Finally a grinding round of everything, irregularly tumultuous, spasmodic, jerky."* (Aitken and Hilton, 1906)

Damage was greatest in the Marina District of the city, where liquefaction and settling in the underlying soft sediments and artificial fill crumbled many buildings. In most of the city, however, damage was minor, and some residents simply returned to bed. Over 70% of the damage done in 1906 occurred in the fire that followed the earthquake. In the Marina district and other pockets of damage, stoves and lamps toppled, igniting scattered blazes. Firefighters rushed to contain the fires, but watched water pressure drop to a trickle and then to nothing because water mains had been cut during the shaking. For four days, fire ravaged the city, consuming 490 city blocks.

The 1906 earthquake and fire were not the first such events to strike San Francisco. The city was extensively damaged during an earthquake in 1868, in which it was again the Marina District that suffered the most. In addition, fire had swept through the city three times previously: in 1849, 1850, and 1851. The extent to which San Francisco had learned its lessons were again tested in 1989. The Loma Prieta earthquake, a magnitude 7.1 shock centered about 120 km southeast of the city, caused shaking damage similar in pattern to the damage in both 1868 and 1906. Liquefaction again caused buildings to collapse in San Francisco's Marina District, igniting scattered fires, and broke a number of water mains. Fortunately, technical improvements in the city's water-supply system avoided a repeat of the 1906 fire. Of the 65 fatalities in the 1989 earthquake, most occurred when a mile-long (1.6 km) segment of the two-tier I-880 freeway in Oakland collapsed. The freeway collapsed exactly where it passed over soft, unconsolidated sediments, which amplified the shaking and overstressed the structure.

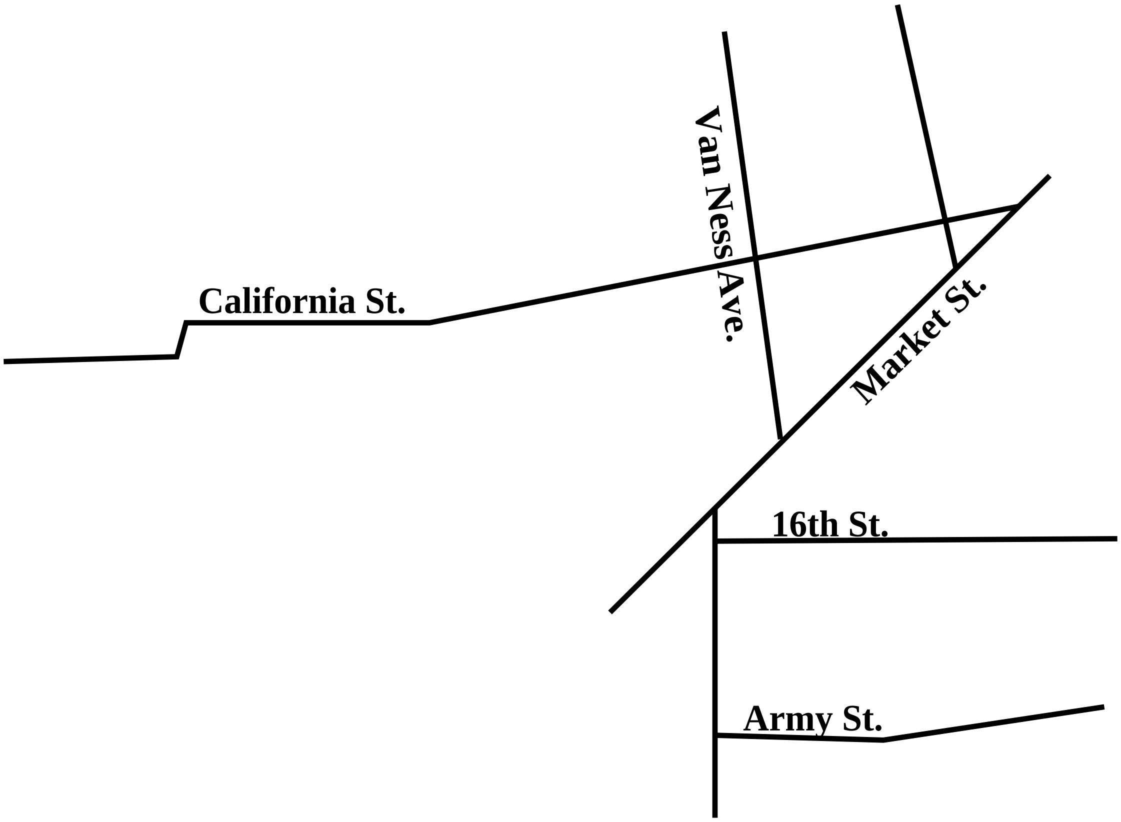

Figure 11.6. Air-photograph composite of San Francisco. (Image courtesy of the University of California, Santa Barbara Map and Image Laboratory)

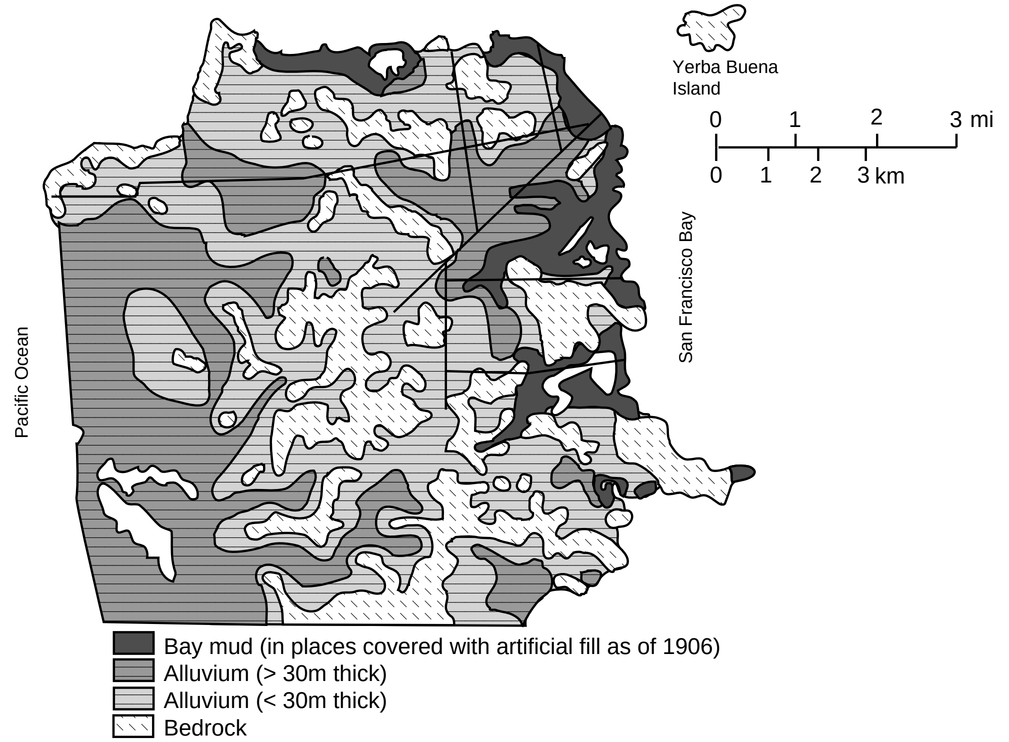

Figure 11.7. Surficial geology of San Francisco. (After Borcherdt, 1975)

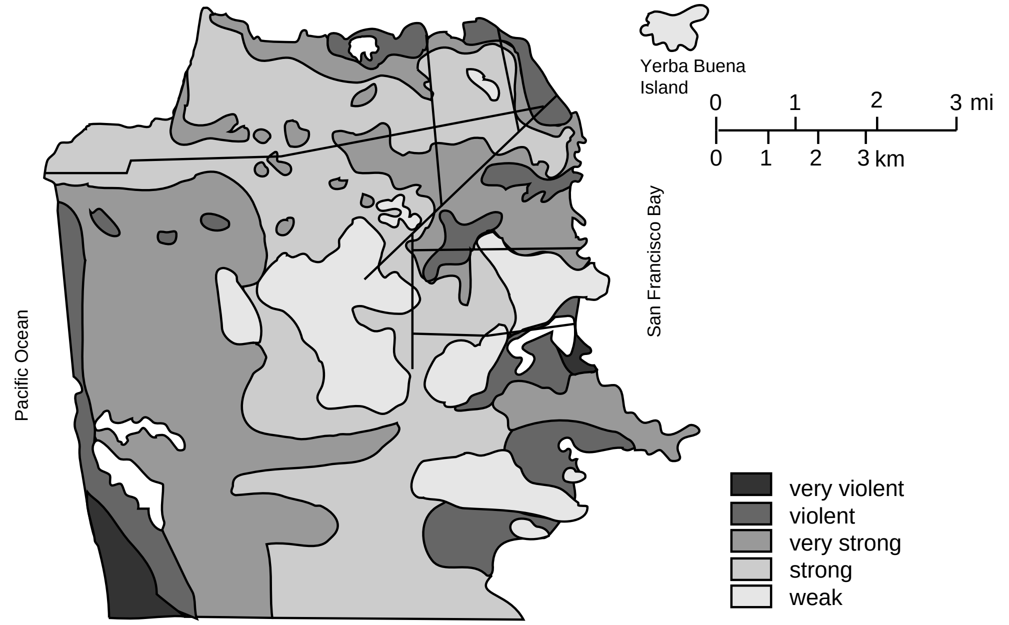

Figure 11.8. Ground-shaking intensity during the 1906 earthquake. (After Borcherdt, 1975)

Exercise 11

The questions that follow ask you to evaluate the seismic hazard in San Francisco based on the information presented in this chapter.

7) Figure 11.7 shows a generalized map of the surficial geology in the San Francisco area and Figure 11.8 shows the distribution of ground shaking intensity during the 1906 earthquake. Compare these two figures. How does the intensity of the ground shaking correspond to the different kinds of earth materials found in the San Francisco area?

8) Using Figure 11.7, color the areas of potential material amplification in red, and mark areas of liquefaction by cross-hatching.

9) Indicate in blue pencil the areas in Figure 11.7 which you would recommend as a construction site for a building over 14 stories tall.

10) Using Equation 11.2, calculate the ground acceleration (in g) for a building at the corner of California and Market streets in San Francisco (Figure 11.6) for:

a) a 6.5 magnitude earthquake at 5 km distance.

b) a 7.5 magnitude earthquake at 5 km distance.

c) a 6.5 magnitude earthquake at 2 km distance.

11) Which parameter (earthquake magnitude or distance to the epicenter) has a greater effect on ground acceleration?

Seismic Shaking and Earthquake Engineering

In the following questions, you will calculate the base shear for a small wood-frame building which houses a retail store. The store occupies a three-story building, located at the corner of California Street and Market Street in San Francisco (see Figures 11.5 and 11.6). The building's total dead weight is 33,000 kg.

12) Using Equation 11.3 and Figures 11.1 and 11.7, calculate the actual base shear (in Newtons) imposed on the building during an intensity VII earthquake.

13) Using Equation 11.4, calculate the total base shear (in Newtons) that the building is expected to resist during an earthquake. For this kind of structure in this location:

$Z = 0.40$
$I = 1.0$
$C = 2.75$
$Rw = 8$

14) Although the results for both Questions 12 and 13 represent the estimates of base shear that would be imposed on this building, the results themselves are very different. Explain why the result obtained from Equation 11.4 is higher than the number obtained from Equation 11.3?

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