Name______________________________

89.325 – Geology for Engineers
Earthquakes

I. Introduction

The crust of the earth behaves in a brittle manner. Stress is the force applied to a brittle substance and strain represents the build-up of energy in the brittle substance. As we apply stress to the crust strain increases in the rocks, and at some point the strain exceeds the strength of the rocks. When this occurs a fracture develops and the rocks move releasing some of the strain (stored energy). This released energy forms what we call an earthquake.

A simple analogy may help you understand the above relationships. Take a wooded yard stick and bend it. The force you are exerting is the stress and the bending of the yard stick represents the build-up in strain (energy). If you bend the yard stick far enough it will break (i.e. it shows brittle behavior) releasing the built-up strain. We can sense this energy release since we will hear a snapping sound. The sound waves representing this snap were generated by the energy release.

When an earthquake occurs waves propagate away from the source (hypocenter or focus) of the break. Waves which travel through the earth are called body waves and consist of two types: P waves which are longitudinal and S waves which are transverse. When the waves reach the surface another set of waves (L waves) develop which move along the earth's surface. The L waves are also transverse waves. The point on the surface directly above the source of the earthquake is referred to as the epicenter.

Earthquake waves are sensed by a device called a seismograph. The arriving earthquake waves cause the device to vibrate and these vibrations are recorded on a moving strip chart. This record is referred to as a seismogram. The arrival times of the various waves yield information concerning the distance to the earthquake, and the amplitude of the trace on the strip chart is used to determine the magnitude of the earthquake.

II. Energy and Earthquake Intensity and Magnitude

Earthquakes are cataloged according to their magnitude or intensity. The earthquake magnitude is a measure of the energy released by an earthquake at the focus. The earthquake intensity scale is more subjective and assesses the effect of the earthquake at a particular location.

Earthquake intensity. The most widely used intensity scale is the Modified Mercalli Intensity Scale (Table 1). Intensity is determined by the observed effects of earthquakes on structures. Since these effects are a function of not only the energy released by the earthquake but also the type of construction and the material on which the structures are built, the observed intensity for a particular earthquake can vary widely from location to location. For example, some years ago a large earthquake occurred just off Alcapulco. The observed damage in Alcapulco was minor, but Mexico City some 100's of kms away suffered significant damage. In part the much greater damage in Mexico City was due to the material on which the structures were built - old lake bed deposits. These materials are not well consolidated and tend to behave like a fluid during an earthquake. Thus there was differential movement of the subsurface which imputed stresses to buildings that exceeded the buildings' strength. Thus the design of earthquake resistant buildings requires knowledge not only of the absolute energy that may be released by an earthquake but also knowledge of differential movements that might occur. Destruction of presumably earthquake proof structures during recent earthquakes is a sobering reminder of the limitations of engineered solutions to natural hazards.

Table 1. Modified Mercalli Intensity scale

Intensity	Observed Effects
I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like a passing truck.
IV	During the day, felt indoors by many, outdoors by few. At night, some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably.
V	Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instance of fallen plaster or damaged chimneys. Damage slight/
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-build ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Notice by persons driving automobiles.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture over-turned. Sand and mud ejected in small amounts. Changes in well water. Persons driving automobiles disturbed (road rage become rampant).
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great damage in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslide considerable from riverbanks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into air.

Earthquake magnitude. Earthquake magnitude is determined from the size of the trace on a standard seismograph. The standard earthquake is defined as one which will cause a 1 millimeter trace on a standard seismograph at a distance of 100 kilometers from the epicenter. The standard earthquake is assigned an arbitrary magnitude of 3. The magnitude is based on a logarithmic scale; that is, the number which indicates the magnitude is an exponent of 10. In order to calculate the magnitude of any earthquake based on the standard earthquake, whose magnitude is 3, it is necessary to know the distance between the recording station and the epicenter. The relationship between earthquake magnitude, distance and size of the seismograph trace is given by the nomogram (Figure 1).

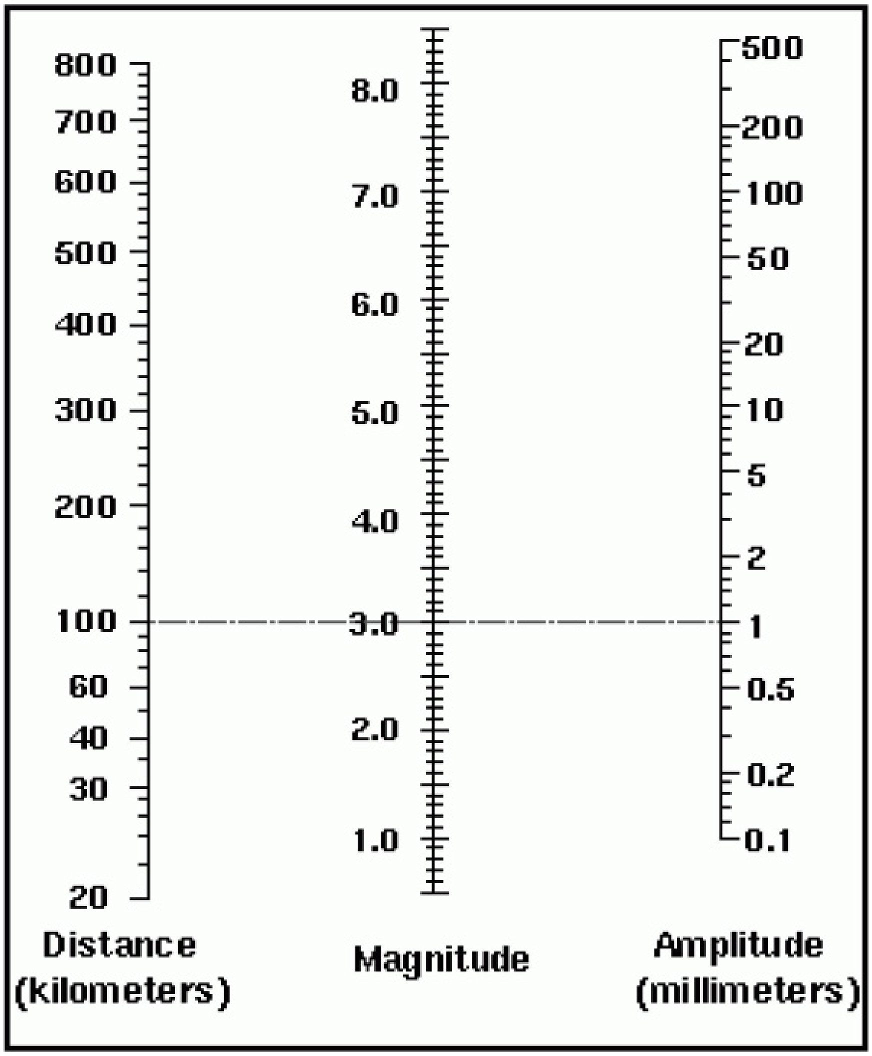

Figure 1. Nomogram for determining earthquake magnitudes from trace amplitudes in millimeters for a standard seismogram, based on a standard earthquake of magnitude 3 which causes a 1 mm trace on a standard seismograph 100 km distant from the epicenter. Corresponding values of Distance, Magnitude, and Amplitude lie on a straight line.

Earthquake energy. An earthquake occurs when there is a sudden release of energy. That portion of the energy that is recorded on a seismograph is due to wave motion. One obvious mechanism for the release of energy is faulting. In this case the total amount of released energy does mechanical work in moving masses of rock, generates heat as the result of friction and radiates various kinds of seismic waves. This last part of the energy released is that quantity of energy upon which the Richter magnitude scale is based. Once the magnitude of an earthquake is determined the amount of energy released as waves can be approximately computed from the following formula

$$\text{Log } E = 11.4 + 1.5M \qquad (1)$$

where E is the energy released and M is the Richter magnitude of the earthquake. This is an experimental formula, that is, it was derived from many observations and experiments and related theoretical calculations. Notice that the logarithm of the energy is used. This formula expresses the amount of energy released in the form of waves. In order to calculate the total energy released by an earthquake it is necessary to know the percent of the total energy that is released as waves. At the present time only crude estimates can be made for this factor. So besides the magnitude scale being somewhat approximate, the estimate of the total energy released is even more uncertain!

The total amount of energy stored as strain in a given volume of rock is computed from the following formula

$$E_{total} = 0.5Ge^2V \qquad (2)$$

where G is the elastic modulus, e is the strain and V is the volume of rock in which the strain (energy) is stored. Energy (E_{total}) is expressed in ergs. One erg = one dyne-centimeter. Most calculations concerned with the study of the earth employ the cgs (centimeter-gram-second) or mks (meter-kilogram-second) metric systems of measure. The erg is the standard energy unit for the cgs system and the joule is the standard energy unit for the mks system. 1 joule = 1×10^7 ergs.

The energy released by an earthquake is often compared to that released by a thermonuclear device ("the bomb"). By way of comparison, a 20 kiloton atom bomb releases approximately 8×10^{20} ergs of energy.

1. The Loma Pietra earthquake occurred at 5:04 PM on October 17, 1989, just before the start of the World Series game between the San Francisco Giants and the Oakland Athletics. The San Francisco – Oakland Bay Bridge suffered severe damage and the Interstate 880/Cypress Viaduct collapsed. There was significant damage in San Francisco's marina district. A standard seismograph at Los Angeles, California recorded an amplitude trace of 140 millimeters. The distance to the epicenter, from Berkeley, was calculated as 500 kilometers. The average strain released in the region was 1.1×10^{-4} and the elastic modulus, G, is equal to 3×10^{11} dynes cm^{-2}.

a. Determine the Richter magnitude of the earthquake. Use the nomogram (Figure 1) to do this.

b. If the distance between Reno, Nevada and the epicenter is 400 kilometers, what should be the trace in millimeters at Reno?

c. Using the formula (1) relating energy to magnitude, find the amount of energy (in ergs) released as waves by the earthquake.

d. Assuming that only 50% of the total energy released was used in producing the waves, what would be the minimum total accumulated strain energy (= the total energy released) in the area just before the earthquake?

e. The total energy released by the earthquake would be equivalent to how many 2O kiloton atomic bombs?

f. Using the formula (2) for stored strain energy, compute the volume affected by the strain release in cubic kilometers ($1\ km^3 = 10^{15}\ cm^3$).

g. Assuming that the strain release extended to a depth of 15 kilometers, compute the area that was affected by the release of the strain energy. The volume is rectangular in shape and has a square cross-sectional area.

III. Earthquake Waves That Travel Through the Earth

With reference to Figure 2, let us assume that an earthquake occurs at #1. Seismograph stations A, B, C, D and E lie along a great circle route that will receive vibrations from the earthquake in sequence. From the nature of the motion, the seismologist knows that the waves have passed through the earth and not along its surface. As a first approximation let us assume that the waves have taken the paths shown in Figure 2.

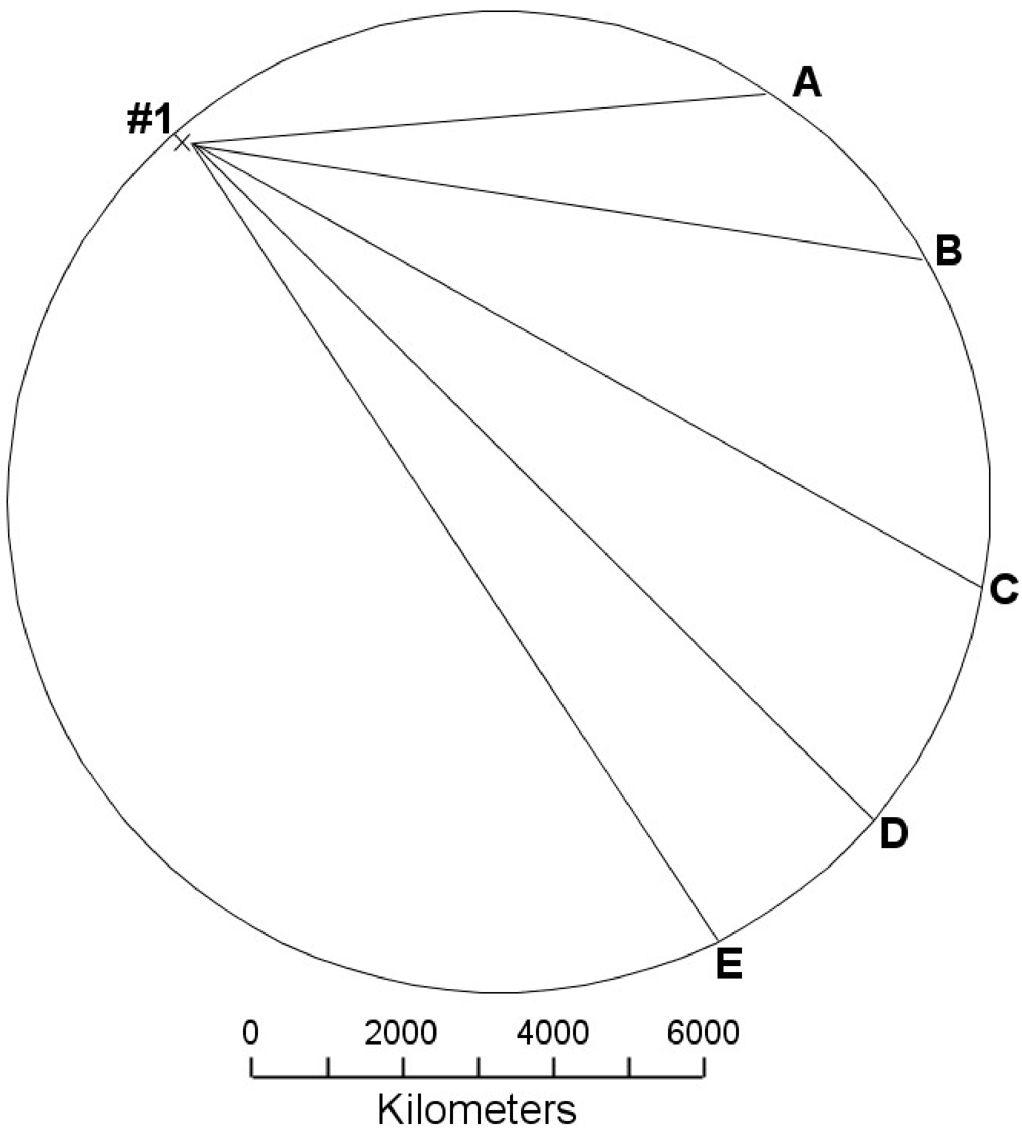

Figure 2. Travel paths for earthquake waves. The hypocenter (focus) is indicated by the "x" labeled #1.

The velocity of the P-wave is 8 km s^{-1} and the velocity of the S-wave is 4.8 km s^{-1}. *Using the paths shown on Figure 2, compute the expected travel times for the P and S waves and enter these values in the appropriate place in Table 2.*

Station	Straight line distance from earthquake (km)	Expected travel time (min)			Observed travel time (min)	
		P	S		P	S
A					16.5	27.5
B					24	40
C					ND	ND
D					30.5	ND
E					30.3	ND

ND = earthquake wave not detected.

2. How do your calculated values compare with the observed values? Can you explain this?

The speed at which waves travel through materials is related in the following ways:

P-waves:

(1) As the density of the medium increases the velocity increases.
(2) As the incompressibility or resistance to change in volume increases the velocity increases.
(3) As rigidity (a measure of resistance to change in shape) increases the velocity increases.

S-waves:

(1) As the density of the medium increases the velocity decreases.
(2) As the rigidity increases the velocity increases.
(3) The waves do not pass through material that behaves as a fluid.

3. What does the absence of the P and S waves at station C and the absence of the S waves at station D and E tell you about the structure of the earth.

IV. Location of an earthquake epicenter

The record of an earthquake as recorded at four stations is shown in Figure 3. The first set of deflections marks the arrival of the P-waves. The second set of deflections marks the arrival of the S-waves.

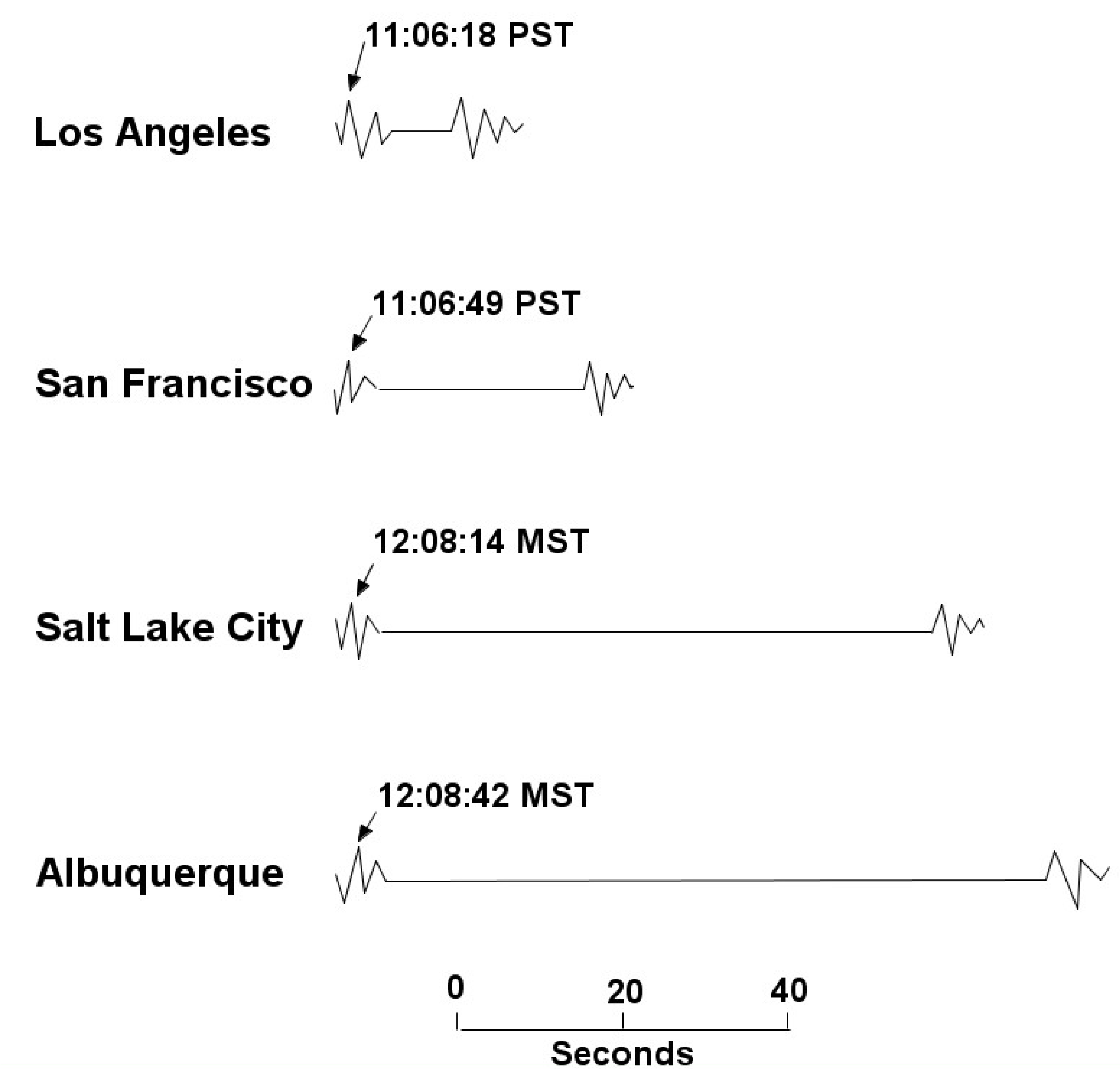

Figure 3. Arrival times for P- and S-waves from an earthquake. Indicated times are for the first arrival of the P-wave. Arrival time for the S-wave can be determined by measuring the distance between the first P-wave arrival and the first S-wave arrival and converting to time using the scale at the bottom of the figure.

4. Determine the lag in arrival time at each station. Enter the time lags in Table 3.

5. Assuming an average velocity of 6 km s^{-1} for the P-waves and 4 km s^{-1} for the S-waves how long does it take for each type of wave to travel 100 km?

6. What is the time lag at a distance of 100 km?

7. Determine the distance from reach of the four seismograph stations to the epicenter of the earthquake. Distance may be computed by proportion using the time-lag value for 100 kms determined above. Record the distances in Table 3.

Table 3. Time-lags and distances between earthquake epicenter and seismograph stations.

Station	Distance between P – S first arrivals (mm). Fig. 3	Time-lag (s)	Distance from earthquake (km)
Los Angeles			
San Francisco			
Salt Lake City			
Albuquerque			

8. On the map (Figure 4) of the western United States draw arcs with centers at the four stations and with radii corresponding to the computed distances. Where is the epicenter located?

9. At what time did the earthquake actually occur? Refer back to the seismic records (Figure 3).

Figure 4. Map of the western United States showing the location of the seismograph stations.