EARTHQUAKES

I. RUPTURE MECHANICS

A. Seismic Moment, $M_0 = \mu D S$

1) fault plane area S

a) we also use linear scale, $L \sim S^{1/2}$

2) displacement on fault plane D

3) time for energy release, $\tau \sim L/v$

a) rupture speed, v, is a significant fraction of the shear speed, v_s

b) $\tau \sim (L/\,\mathrm{km})(v/\,\mathrm{km\,s^{-1}})^{-1}\,\mathrm{s}$

4) far field displacement, $r \gg L \sim v_s \tau$

$$\xi \sim \frac{DL}{r} \sim \frac{M_0}{\rho v_s^3 \tau r}$$

a) factors of $v/v_s \lesssim 1$ have been discarded

b) quadrupole displacement pattern

i) seismic source can be represented by a double couple

c) underground (nuclear bomb) explosions are monopole sources

i) they create volume

d) compare monopole, dipole, and quadrupole sources

5) M_0 is observationally determined from measurements of ξ and τ

a) it has units of energy

b) it provides an accurate measure of the size of an earthquake at low frequency

B. Seismic Radiation

1) total seismic energy radiated

$$E_s \sim \rho \left(\frac{D}{\tau}\right)^2 L^3 \sim \rho v_s^2 D^2 L \sim \mu D^2 L$$

a) $E_s/M_0 \sim D/L$

b) ratio of energy in P (primary) and S (secondary) waves $\sim 0.7(v_s/v_p)^5 \approx 0.04$

i) comes from neglected factors involving v

c) stress drop $\Delta\sigma \sim \mu D/L$

$$E_s \sim \frac{(\Delta\sigma)^2}{\mu} L^3$$

2) quake may not relieve total stress σ

a) ratio of seismic energy radiated to total elastic energy released is $\Delta\sigma/\sigma$

b) aseismic energy release

i) heat source

ii) may excite tsunami or Chandler wobble

3) observations show $\Delta\sigma \sim 3 \times 10^7\,\mathrm{dyne\,cm^{-2}}$ or 30 bars

a) strain release $\Delta\epsilon \sim \Delta\sigma/\mu \sim 10^{-4}$

b) stresses below large mountains are much larger, up to 1-2 kilobars.

i) are stresses low near faults?

ii) or is $\Delta\sigma \ll \sigma$?

iii) evidence favors low stresses

4) energetics

a) parameters: take $\rho \approx 3\,\mathrm{g\,cm^{-3}}$, $\mu \approx 3 \times 10^{11}\,\mathrm{erg\,cm^{-3}}$, and $\Delta\epsilon \approx 10^{-4}$

i) $v_s \sim 3\,\mathrm{km\,s^{-1}}$

ii) $D \approx 10(L/\,\mathrm{km})\,\mathrm{cm}$

$$E_s \sim 3 \times 10^{18} \left(\frac{L}{\mathrm{km}}\right)^3 \mathrm{erg}$$

b) note for comparison, a kiloton of TNT releases $4 \times 10^{19}\,\mathrm{erg}$

5) earthquake magnitudes

a) Richter magnitude, $M_R \approx -2.4 + 0.4\log(E_s/\,\mathrm{erg})$

i) based on displacement at $P = 0.8\,\mathrm{s}$

ii) magnitude depends upon spectrum

iii) $M_R \sim 5.3 + 1.25\log(L/\,\mathrm{km})$

b) moment magnitude, $M_w \approx 0.67\log(M_0/\,\mathrm{erg}) - 10.7$

i) provides an accurate measure of low frequency size of earthquake

ii) $M_w \sim 4.3 + 2\log(L/\,\mathrm{km})$

c) $M_R - M_w \sim 1.0 - 0.75\log(L/\,\mathrm{km})$

d) examples of large earthquakes

i) San Francisco 1906, $E_s \approx 6 \times 10^{23}\,\mathrm{erg}$

ii) Chile 1960, $E_s \approx 10^{26}\,\mathrm{erg}$, largest this century

iii) Alaska 1964, $E_s \approx 4 \times 10^{25}\,\mathrm{erg}$, largest event in U.S.

II. CAUSES AND RECURRENCE RATES

A. Plate Motions

1) San Andreas Fault

a) $u \approx 5\,\mathrm{cm\,yr^{-1}}$ across fault

b) strain builds up across pinned section of length L at rate

$$\dot{\epsilon} \approx \frac{u}{L} \approx 5 \times 10^{-7} \left(\frac{u}{5\,\mathrm{cm\,s^{-1}}}\right)\left(\frac{10^2\,\mathrm{km}}{L}\right)\,\mathrm{yr^{-1}}$$

c) nominal earthquake parameters: $u = 5\,\mathrm{cm\,s^{-1}}$, $L = 10^2\,\mathrm{km}$, $\Delta\epsilon = 10^{-4}$

i) recurrence time $t \sim 2 \times 10^2\,\mathrm{yr}$

ii) $D \sim 10\,\mathrm{m}$

iii) $E_s \sim 3 \times 10^{24}\,\mathrm{erg}$

iv) $\tau \sim 50\,\mathrm{s}$

v) $M_R \sim 7.8$

vi) $M_w \sim 8.3$

III. EFFECTS ON STRUCTURES

A. Shaking

1) swaying frequency of a column

a) length l, square cross section of width d, elastic modulus μ, density ρ

$$\omega \sim \frac{1}{2}\left(\frac{\mu}{\rho}\right)^{1/2}\frac{d}{l^2}$$

b) for a steel column with parameters

i) $\mu \approx 10^{12}\,\mathrm{dyne\,cm^{-2}}$, $\rho \approx 8\,\mathrm{g\,cm^{-3}}$, $d/l \sim 0.2$

ii) $\omega \approx 40(10\,\mathrm{m}/l)\,\mathrm{s^{-1}}$

c) rule of thumb gives $\omega \sim (10^2/N)\,\mathrm{s^{-1}}$ for an N story building

d) corner frequency of a large earthquake, $\omega_0 \sim v/L \sim 2 \times 10^{-2} (10^2 \text{ km}/L)\,\text{s}^{-1}$

i) much too low to match resonant frequencies of buildings

2) resonant shaking is due to high frequency tail of seismic radiation

a) this ameliorates threat from large earthquakes

b) also, attenuation increases with frequency

i) damping length (for amplitude) $d \sim \pi Q v_s/\omega \sim 3 \times 10^3 (\text{s}^{-1}/\omega)\,\text{km}$

c) countering these, the number of cycles of flexure increases with earthquake size

2) high frequency, $\omega > \omega_0$, spectra of earthquakes

a) not the same for all quakes

i) depend on local regions of high strength, asperities

b) observational data suggest $\tilde{\xi}_\omega \propto \omega^{-2}$ as a good compromise

$$\xi_\omega \sim \left(\int_{\omega/2}^{3\omega/2} d\omega' |\tilde{\xi}_{\omega'}|^2 \right)^{1/2}$$

i) in individual cases the exponent of ω lies between -1.5 and -3.0

3) local acceleration, $\tilde{a}_\omega = \omega^2 \tilde{\xi}_\omega$

a) for $\omega > \omega_0$ and above scaling, in the far field, $r > L$

$$a_\omega \sim \omega^2 \xi_\omega \sim 3 \left(\frac{10^2 \text{ km}}{L} \frac{\omega}{\text{s}^{-1}} \right)^{1/2} \left(\frac{L}{r} \right) \text{cm}\,\text{s}^{-2}$$

i) for body waves

ii) neglecting attenuation

B. Soil Liquifaction

1) occurs when soil is saturated with water

a) shaking causes grains to be suspended in water and out of contact as they settle

i) sand boils associated with historical earthquakes on San Andreas at Pallett Creek

2) damage to buildings is due to tilting and settling, not shaking

a) responsible for destruction near SF bay seen following Loma Prieta earthquake