Seismic Sources

- Seismic sources
  - Earthquakes
    - Faults;
    - Moment tensor and magnitudes
  - Sources used in seismic exploration
    - Requirements;
    - Principles;
    - Onshore, offshore.

• Reading:
  - Shearer, 9.1-9.3
  - Telford et al., Section 4.5
Sources of seismic energy

- **Natural (earthquakes)**
  - Mostly shear-wave (“double-couple”);
  - Result from sudden slipping of blocks of rock along faults (“stress release”);
- **Artificial (used in seismic exploration)**
  - Mostly $P$-wave (pressure);
  - Produced by explosives or various kinds of mechanical impact.
Some Source Theory

- Generally, a force $\mathbf{f}$ applied at point $\mathbf{x}_0$ causes displacement $\mathbf{u}$ that is proportional to the force:

$$u_i(x, t) = G_{ij}(x, t; x_0, t_0) f_j(x_0, t_0)$$

- A single point force could only be applied from the outside;

- An *internal* source would have to conserve the momentum and angular momentum, and thus it cannot exist alone;

- Seismic source forces always exist in mutually compensated *force couples*:

![Force Couples](image1.png)  ![Double Couple](image2.png)
Earthquake faults

- In terms of slip motion, faults are identified as predominantly “strike-slip” (horizontal motion) and “dip-slip” (vertical-motion) faults.

Fig. 9.4. Owing to the symmetry of the moment tensor, these right-lateral and left-lateral faults have the same moment tensor representation and the same seismic radiation pattern.
Earthquake faults

- Displacement and seismic wave fields produced by a slip on a fault are equivalent to those caused by orthogonal pressure and tension:

Fig. 9.5. The double-couple pair on the left is represented by the off-diagonal terms in the moment tensor, $M_{12}$ and $M_{21}$. By rotating the coordinate system to align with the $P$ and $T$ axes, the moment tensor in the new coordinate system is diagonal with opposing $M_{11}$ and $M_{22}$ terms.
Radiation patterns
(“earthquake beach balls”)
Moment tensor

- Nine different possible force couples form the source *moment tensor* $M_{ij}$:

In each of these plots, $f = M_{ij} \, d$
Seismic Moment

For a right-lateral movement on a vertical fault oriented along the $x$ direction, the moment tensor is:

$$
M = \begin{pmatrix}
0 & M_0 & 0 \\
M_0 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}
$$

where the *scalar seismic moment*:

$$
M_0 = \mu \cdot D \cdot A
$$

($\mu$ is the shear modulus, $D$ – fault displacement, and $A$ – slip area)

$M_0$ measures the energy release and is related to seismic magnitude.
# Earthquake classification

- Based on numeric “magnitudes”

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Type</th>
<th>Effect</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2.0</td>
<td>Micro</td>
<td>Not felt</td>
<td>~8,000/day</td>
</tr>
<tr>
<td>2.0 - 2.9</td>
<td>Minor</td>
<td>Recorded, not felt</td>
<td>~1,000/day</td>
</tr>
<tr>
<td>3.0 - 3.9</td>
<td>Felt, damage rare</td>
<td></td>
<td>50,000/year</td>
</tr>
<tr>
<td>4.0 - 4.9</td>
<td>Light</td>
<td>Noticeable shaking; no significant damage</td>
<td>6,200/year</td>
</tr>
<tr>
<td>5.0 - 5.9</td>
<td>Moderate</td>
<td>Damages poor buildings in local areas</td>
<td>800/year</td>
</tr>
<tr>
<td>6.0 - 6.9</td>
<td>Strong</td>
<td>Can be destructive over ~100 miles in populated areas</td>
<td>120/year</td>
</tr>
<tr>
<td>7.0 - 7.9</td>
<td>Major</td>
<td>Serious damage over large areas</td>
<td>18/year</td>
</tr>
<tr>
<td>8.0 - 8.9</td>
<td>Great</td>
<td>Serious damage over several hundred miles</td>
<td>1/year</td>
</tr>
<tr>
<td>9.0 - 9.9</td>
<td>Devastating in ~1000 miles across</td>
<td></td>
<td>1 per 20 years</td>
</tr>
<tr>
<td>10.0+</td>
<td>Massive</td>
<td>Planetwide (never recorded)</td>
<td>Unknown</td>
</tr>
</tbody>
</table>
Seismic Magnitude
Richter scale

- The Richter scale ("local magnitude") measures the combined horizontal displacement on "Wood-Anderson torsion" seismometer

\[ M_L = \log_{10} \frac{A_{shaking}}{A_0(\Delta)} \]

Empirical correction for distance, \( \Delta \)

- The energy release scales with the power of 3/2 of \( A_{shaking} \)

\[ \text{Thus, a difference of } 1.0 \text{ in } M_L \]
\[ \text{corresponds to a factor } 10^{3/2} \approx 31.6 \text{ in energy} \]
Seismic Magnitude
Moment Magnitude scale

- Starting from 1970's, supersedes the Richter scale
- Reflects real physical parameters of earthquake source
- Based on the seismic moment $M_0$ above in dyne·cm ($10^{-7}$ N·cm):

$$M_w = \frac{2}{3} \log_{10} M_0 - 10.7$$

- As with the Richter scale, an increase of 1.0 in $M_w$ corresponds to
$10^{3/2} \approx 31.6$ times increase in energy
- Earthquake energy in Joules:

$$E = 10^{9 + 1.5M_w}$$
Source in Seismic Exploration

- Localized region within which a sudden increase in elastic energy leads to rapid stressing of the surrounding medium.

- Most seismic sources preferentially generate $P$-waves
  - Easier to generate (pressure pulse);
  - Easier to record and process (earlier, more impulsive arrivals).

- Requirements
  - Broadest possible frequency spectrum;
  - Sufficient energy;
  - Repeatability;
  - Safety - environmental and personnel;
  - Minimal cost;
  - Minimal coherent (source-induced) noise.
Land Source

- Explosives – chemical base
  - Steep pressure pulse.
  - Shotguns, rifles, blasting caps;
  - …bombs, nuclear blasts…

- Surface (mechanical)
  - Weight drop, hammer;
  - Piezoelectric borehole sources (ultrasound );

- Continuous signal
  - Vibroseis (continuously varying frequency, 10-300 Hz)
  - Mini-Sosie (multiple impact);
    - Combination with Vibroseis (Swept Impact Seismic Technique, SIST)
  - Drill bit (‘Seismic While Drilling’);
  - sparkers, ...truck spark plugs.
Mechanism of generation of seismic waves by explosion

- **Stage 1**: Detonation.
  - Start of explosion - electric pulse ignites the blasting cap placed inside the charge. The pulse is also transmitted to recorder to set \( t = 0 \);
  - Disturbance propagates at \( \sim 6-7 \text{ km/s} \) (supersonic velocity); surrounding medium is unaffected;
  - The explosive becomes hot gas of the same density as the solid - hence its pressure is very high (several GPa)

- **Stage 2**: Pressure pulse spreads out spherically as an *inelastic shock wave*
  - Stresses \( >> \) material strength;
  - Extensive cracking in the vicinity of the charge.

- **Stage 3**: At some distance, the stress equals the elastic limit
  - Pressure pulse keeps spreading out spherically as an *elastic wave*.
Important parameters of an explosion

- **Radius of the Explosion Cavity:**
  \[ R \text{ [ft]} = BW^{\frac{1}{3}} \]  
  Weight in lbs

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Granite</th>
<th>Chalk</th>
<th>Limestone</th>
<th>Soft Sandstone</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.46</td>
<td>0.6</td>
<td>0.3-1.0</td>
<td>1.3</td>
<td>1.3</td>
</tr>
</tbody>
</table>

- **Pulse width:**
  \[ T \text{ [ms]} = 2.8 \cdot W^{\frac{1}{3}} \]
  - Frequency *decreases* for larger charges.

- **Energy:**
  - Only 4% (soft sandstone), 9% (clay) to 10-20% (granite) of chemical energy is radiated as seismic waves;
  - Absorption and scattering cause energy loss:
    - At 3 m from the source, there remains 2.5% of available energy;
    - At 30 m - 0.5%.

- **Effects of shot depth:**
  - If water table is shallow - place shots below it;
  - Seismic amplitude increases as the shot depth decreases
    - However, ground roll becomes broadband and hard to attenuate.
Criteria for selection of explosives

- **Density**
  - Higher density means the explosive column length is shortened, resulting in an energy pulse of higher frequency. Higher frequency means better data quality. Typical values are 1.2-1.8 g/cc.

- **Velocity**
  - Higher velocity means a higher frequency energy pulse will be generated because the explosive column detonates more quickly. Typical values are 6-8 km/sec.

- **Detonation pressure**
  - Detonation pressure is an indication of energy released by the detonation. High detonation pressure is beneficial in seismic blasting. Typical range - 2-4 GPa (70-250 kBar).

- **Self-disarming**
  - Unexploded charges left in the ground could be hazardous to future drilling or excavation. Seismic explosives that self-disarm are the best choice.
Standard for minimum distances

- International Association of Geophysical Contractors:
  - Pipelines - 60 m;
  - Telephone lines - 12 m;
  - Railroad tracks - 30 m;
  - Electric lines - 24 m;
  - Oil wells - 60 m;
  - Water wells, cisterns, masonry buildings - 90 m.

- Ground velocity of 5 cm/s is considered 'safe' for structures
  - For seismic explosives, achieved at distances $x = 23m^{1/3}$ m, where $m$ is the charge in kg.
Explosives

- Gelatin dynamite, ammonium nitrate, pentolite (SEIS-X).
- Packaged in tins, cardboard or plastic tubes ~5 cm in diameter (0.5-5 kg each).
- Connected to make desired charges.
Charge emplacement

- Crown block
- Mast
- Swivel (mud is injected into center of Kelley and drillstem)
- Draw-works (for pulling drillstem from the borehole)
- Rotary table (turns Kelley and hence drillstem and bit)
- Pull-down pulley (puts pressure on the drillstem and bit)
- Portable mud pit (collects mud returning up the annular space around drillstem)
- Kelley
- Kelley screwed into drill stem
- Drill stem
- Bit screwed onto drill stem (mud emerges through bit)
- Mud flows back to surface through annular space between drillstem and hole wall, carrying the cuttings with it
- Power take off
- Transfer case
- Mud-return hose
- Mud is lubricated, for moving to the surface
- Air compressor for air for moving to the surface
- Mud pump to circulate mud
- Mud pump to circulate water
- Water return to Circulate mud
- Water return to Circulate water
Surface Energy Sources  
(less powerful, easier access)

- **Thumper/weight dropper**
  - Bison Accelerated Weight Dropper

- **Dynoseis**
  - Mixture of $O_2$ and propane exploded in an expandable chamber with a metal plate as the bottom
  - Mounted on a truck or used as a buried explosive charge
  - Self-disarming (the metal plate rusts through and the gas dissolves)
Vibroseis

Used in > ½ of land seismic exploration

- Vibroseis
  - Energy introduced into the Earth in the form of a *sweep* of varying frequency for several seconds
    - Typical sweep time - 7-35 s;
    - ~45 minutes in recent mantle investigations
    - Typical frequencies - 12 -> 60 Hz (upsweep) or 60 -> 12 Hz (downsweep);
    - Low energy density - environmentally friendly;
    - Time-Distributed signal - lower noise requirements.
  - A control signal causes a vibrator to exert variable pressure on a steel plate pressed against the Earth.
    - Radio-controlled hydraulics allows *syn-phase* vibration of a *group* of vibrators;
    - Shear-wave vibrators also shake the ground in horizontal directions

![Diagram of Vibroseis setup]
Vibroseis
Mini-Vibroseis
Vibroseis Correlation

- Recorded signal is *cross-correlated* with the *sweep* sent into the ground
  - As a result, matching waveform patterns (caused by reflections) are identified;
  - The signal is compressed in time - the energy of the entire sweep is condensed into a single pulse.
Other Land Sources
(for shallow or mine investigations)

- Sosie, Mini-Sosie, SIST
  - Impactor hits ground 5-15 times per second, in ~3-min long, *pseudo-random* series.

- Sparkers
Air Gun
Primary marine source

- High pressure bubble of air is released into the water
  - Operating pressure 10-15 MPa, in 1-4 ms;
  - Size (volume of the lower chamber) 10-2000 in$^3$ (0.16-33 liters)
  - Primary pulse is followed by a surface ghost and a train of bubble pulses
Air Gun
Bubble oscillations

- Over-pressured bubble expands expelling water radially
  - ... and becomes under-pressured;
- Under-pressured bubble collapses under water pressure
  - ... and becomes over-pressured again.
- This cycle is repeated until the energy dissipates and/or bubble vents into through the surface.
Suppression of bubble pulses

Bubble pulses can be suppressed in two ways:

- Use array of air guns with different dimensions;
- Shallow firing (~2 m) - bubble vents to the surface.

During digital processing, the wavelet is further compressed by using *deconvolution*. 
Other Marine Sources

- **Water gun**
  - Compressed air drives a piston that ejects a jet into the surrounding water;
  - Vacuum cavity created behind the jet causes an implosion generating a strong pulse.
  - No bubble pulse.

- **Piezoelectric transducers**
  - *e.g.*, barium titanate - change their volume when subjected to electric field;
  - Up to 2-10 kHz frequency for shallow water work.