Production-Induced Earthquakes in Southern California During the Early 20th Century

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Collaborators

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Outline

• Introduction
• Pre-instrumental earthquakes (1900-1932)  
  Hough and Page, BSSA, 2016
• Early instrumental era: 1933-1952  
  Hough and Bilham, TLE, 2016, and in review
• Modeling  
  Hough and Bilham, TLE, 2016, and in review
• Kern County (1952)  
  Hough et al., JOSE, 2017
• Santa Barbara (1925)  
  Hough and Martin, in review
USGS Forecast for Damage from Natural and Induced Earthquakes in 2016

Based on the presumption earthquakes occur naturally

Based on natural and induced earthquakes

Chance of damage

- Highest chance: 10% – 12%
- 5% – 10%
- 2% – 5%
- 1% – 2%
- Lowest chance: < 1%
Identification of Induced Earthquakes

• Spatial and temporal association between individual events and industry activities (production or injection)
• Increased seismicity rates
• Shallow hypocentral depth
• Plausible mechanism
Outline

• Introduction
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Los Angeles Basin Oil Fields

- 1892: Los Angeles City oil field
- 1890s: Salt Lake oil field, West Coyote Hills
- 1917: Montebello
- 1920: Huntington Beach
- 1921: Santa Fe Springs
- 1923: Dominguez
- 1924: Inglewood oil field
- 1937*: Wilmington
Overall Activity:
Los Angeles Basin, 1900-1933

Cum. Prod. (bbl)

Year

Hough and Page, BSSA, 2016
Outline

• Introduction
• Pre-instrumental earthquakes (1900-1932)
• Early instrumental era: 1933-1952
“Geologists think that the narrow ribbon on which these wells stand probably wouldn’t be productive for a width of more than 500 feet. The ocean stops it on one side and on the land side it is broken by a distinct fault which is supposed to separate it from the main Huntington Beach field.”
• Huntington Beach field discovered 1920
• 1930: initial production horizons depleted
• 6/1932: No. Jones 1 well, between 3,695-4,185’
• Offshore reserves tapped → start of directional drilling
• 11 March 1933 earthquake
Southwest Los Angeles Basin:
1935-1944
1. Spatial Association: Earthquakes and SW LA Basin Oil Fields

1935-1944: 8
1945-2016: 14

M>4 Events
1935-1944: 8
1945-2016: 14
Oil Production, 1938 - 1945

“The present war, referred to by many authorities as an Oil War, makes [the Wilmington] filed doubly important with its monthly production in excess of two and one-half million barrels.”
Physical Mechanism(s): Production-Induced Earthquakes

- Pore-pressure effects (inhibit rupture)
- Isostatic adjustment (long wavelength?)
- Poroelastic effects
Poro-elastic Stress
(Segall, 1985)

Hough and Bilham, in review
Stacked Reservoirs

• Lateral and vertical “reach”: 2-3 km
• Depths ~ 3 km → stress changes at 5-6 km
3. Physical modeling

- Pore pressures reduced $\rightarrow$ frictional failure inhibited
- By 1941, stress changes $\rightarrow$ 0.5 MPa, 2-3 km depth
  $\rightarrow$ 0.1 MPa, 5 km depth
4. Seismicity decrease after early 1940s:
Initially -- Pore-pressure effects + ?
Later – Water-flooding

Subsurface pressures balanced
1952 Kern County Earthquake
April 14, 1952: Eocene strike (9700’)
July 21, 1952: Kern County mainshock
Modeling: Direct Pore Pressure Effect

To estimate the direct pore pressure effect, which for production tends to increase the effective normal stress and hence bring the fault farther from failure, we use the analytic solution for pore pressure change in a homogeneous halfspace

\[ p' = C \cdot \text{erfc}\left[\frac{z_0}{2\sqrt{T_d}}\right] \]  \hspace{1cm} (A4)

To approximately account for the boundary condition being one of constant flux, we estimate \( C \) such that the pressure perturbation at distance \( 2\sqrt{T_d} \) is equal to the characteristic pressure given by Eq A2. With this estimate, then

\[ p' = \Delta p \cdot \text{erfc}\left[\frac{z_0}{2\sqrt{T_d}}\right] / \text{erfc}(1) \] \hspace{1cm} (A5)

where \( \Delta p \) is as above.
Modeling: Geomechanical Effect

Figure S3. Schematic of model. Variables are described in text.

For a single line source with force per unit distance \( F \) acting in the \( x \) direction, and in the absence of an ambient (tectonic) stress, the normal stress \( \sigma_{nn} \) due to reservoir pressure is given by

\[
\sigma_{nn} = 2F \left( \pi L \right) \cos^2(\theta)
\]  
(A1)

where \( L \) is distance from the force and \( \theta \) is the angle from perpendicular. Integrating over vertical thickness \( H \) yields

\[
\sigma_{nn} = 2\Delta p \left( \pi L \right) \left[ 2L^2 H (4L^2 + H^2) + \cot^{-1}(2L/H) \right]
\]

(A2)

where \( \Delta p \) is pressure and \( \sigma_{nn} \) is evaluated at \( x=L, y=0 \), along the midpoint of the pressure source.

This expression thus provides an estimate of the magnitude of the normal stress change due to a given pressure source of height \( H \).

To estimate the appropriate value of \( L \) and \( \Delta p \), we use a characteristic length scale and timescale for diffusion of pore pressure from a source of constant production rate \( Q \).

\[
\Delta p = Q \left( \frac{4pDHc}{9} \right)
\]

(A3)

where \( D \) is diffusivity and \( c \) is matrix compressibility, and \( L(t) = L_0 - 2\sqrt{t} \)
• Permeability, $k, = 10^{-13}$ m$^2$ ("good perm.")
• Dyn. visc., $\mu, = 2 \times 10^{-3}$ Pa-s (Glaso, 1980)
• Matrix comp., $c_t, = 5 \times 10^{-9}$ Pa$^{-1}$

$\Rightarrow D = 0.04$ m$^2$/s
• Shallow fault splay blocks pore pressure effects on fault
• Normal stress change (unloading) → 0.1 MPa, t = 80 days

Hough et al., JOSE, 2016
Weak Motion Data: Initial Sub-event

Chen Ji, personal communication
1925 M6.6 Santa Barbara Earthquake
Rupture Scenario

- Mw6.6
- L=25-30 km
- Nucleation: east of Miramar Hotel
- Unilateral propagation
  (Mesa-Rincon Creek-More Ranch fault)

Hough and Martin, in review
Summerland Oil Field

Deep Test Well at Summerland Holds Interest

SUMMERLAND, May 24.

Oil development in this vicinity has taken on fresh impetus with the spudding in of the first deep test well in the Summerland field and the spudding up of the drill in the Channel Oil Company’s well in the city limits of La Mesa.

The Summerland venture is being financed by George Y. Becker, veteran operator of the field where shallow wells in and near the ocean have been producing since 1892. Mr. Becker purchased the site abandoned by the La Mesa Oil Company a year ago and intends to run the hole to a depth of 3000 feet if necessary to get deep production. He has obtained deeds and leases to a vast amount of surrounding territory and will strongly control the field if deep oil is found.
Induced, or Induced + Triggered?

- Mw6.6
- L=25-30 km
- Nucleation: east of Miramar Hotel
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  (Mesa-Rincon Creek-More Ranch fault)

Hough and Martin, in review
Conclusion 1: Depth Matters

- Santa Barbara (Mw6.6, June, 1925)
  - Summerland: deepened to 1.5 km (May, 1925)
- Whittier, 1929 (M5.1, July, 1929)
  - Santa Fe Springs: deepened to 1.9 km (Feb., 1929)
- Long Beach, (Mw6.4, March, 1933)
  - Huntington Beach: deepened to 1.3 km (June, 1932)
- Dominguez Hills (M4.7, October, 1941)
  - Dominguez Hills: test well to 3.8 km (Feb, 1941)
- Kern County (M7.2, July, 1952)
  - Wheeler Ridge: deepened to 3.0 km (April, 1952)
Conclusions (2)

- Evidence for production-induced earthquakes in California:
  - Los Angeles basin (1920s – 1945)
  - Santa Barbara, 1925
  - Kern County (1952)
- Poroelastic stress changes → significant @ distances of 2-3 km;
- Wells at 2-4 km → significant stress change @ top of seismogenic zone;
- Waterflooding → mitigation of risk in Los Angeles Basin
- Poroelastic changes potentially dominate if
  - Pore pressure effects blocked, and/or
  - Production is rapid, and/or
  - Production horizons deep and close to fault
- Kern County:
  - Induced, or “induced and triggered”
- Santa Barbara (1925)
  - Induced, or “induced and triggered”
- Primary deep production near active faults → induced earthquakes?
- Background seismicity rate in Los Angeles Basin???