Geotechnical Earthquake Engineering: Homework #1

Due on October 10, 2022 at 9:00am

Professor Byungmin Kim 9:00-10:15

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Problem 1

(a) Select a fault anywhere (it could be in Korea, USA, Japan, or any other countries). Find seismicity along the fault that you selected and present it in a map.

(b) Plot annual rate of earthquakes with magnitude greater than a certain values vs. earthquake magnitude.

(c) Construct an earthquake recurrence relationship using Guternberg and Richter (1954) and Cornell and van Marke (1969). Present coefficients such as a and b.

(d) Plot annual rate of earthquakes vs. magnitude.

Solution

(a) **Seismicity Map**

The seismic records were gathered from the USGS database in https://earthquake.usgs.gov/earthquakes/search/. The options used where `Magnitude: 2.5+`, `Date&Time: Start(UTC):1930-01-01 00:00:00 End(UTC):2022-09-30 23:59:59` and `Geographic Region Custom Rectangle: [9.46,10.207] Latitude [123.687,124.571] Longitude`. The data were downloaded as `.csv` format and reflected as a map below.The geospatial information about the active faults were collected from GEM Global Active Faults Database. The data can be downloaded from https://github.com/cossatot/gem-global-active-faults. Although there are two active faults present in the island, as an illustrative example it is assumed that all these recorded earthquakes just came from a single source. A more detailed analysis is needed to segregate the recorded earthquakes into corresponding active fault.

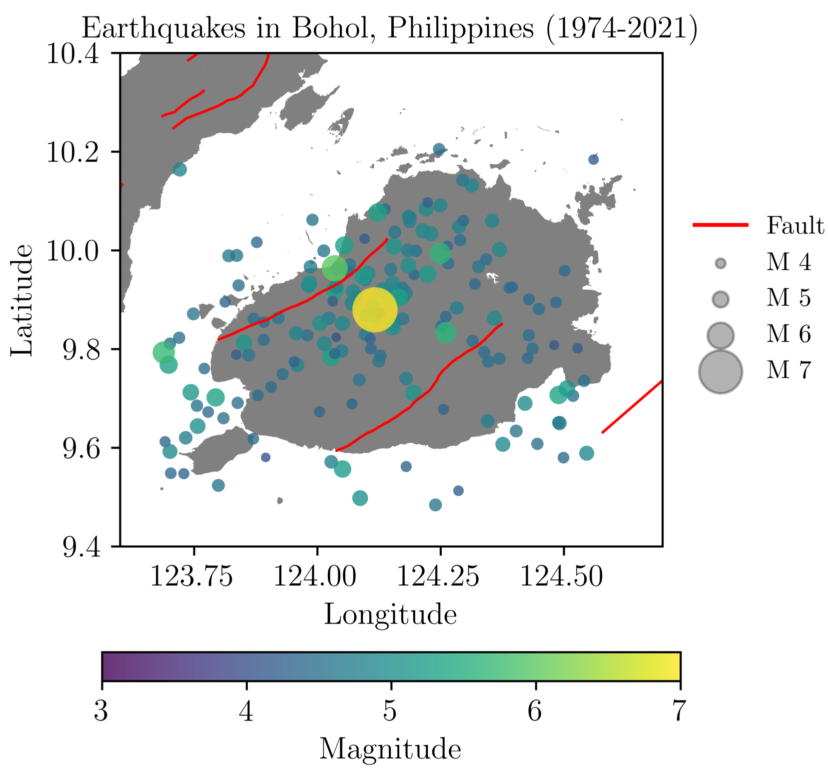

Figure 1: Seismicity Map of Bohol, Philippines

(b) **Annual rate of exceedance**

The database acquired from the USGS was further processed to determine the annual rate of exceedance,

Description	**Value**
Count	167
Mean	4.676
Min	4.0
Max	7.1
Start Year	1974
End Year	2021

λ_m. The annual rate of exceedance is calculated as number of exceedances of each magnitude divided by the length of the time period. Each exceedance for magnitudes $(4, 4.5, 5, 5.5, 6 \ldots 7)$ were counted and divided by the time period.
As an example, the annual rate of exceedance for magnitude 4.0 is calculated as

$$\lambda_{m \geq 4} = \frac{167}{2021 - 1974} = 3.553$$

There are a total of 167 earthquakes having greater than or equal to magnitude 4 in the span from 1974 to 2021. This was done for several other magnitudes. The plot is shown below.

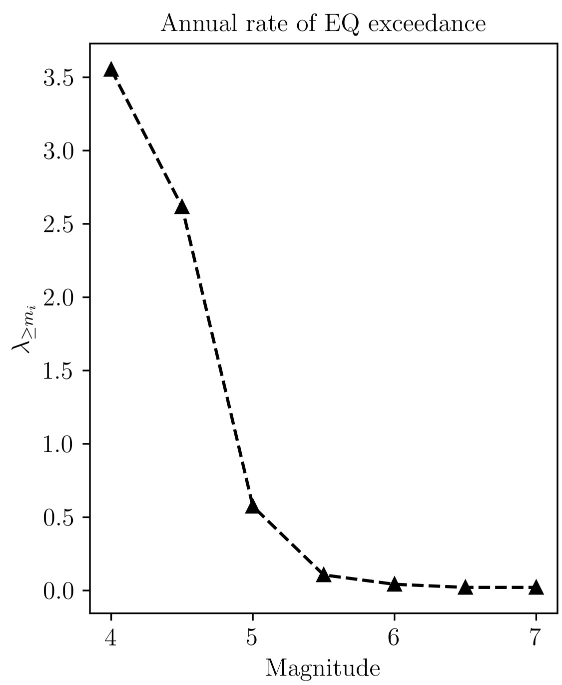

Figure 2: Annual rate of exceedance

(c) **Recurrence Law model**
The size or magnitude of earthquake from an identified source can be predicted using a *recurrence law model*. The *Gutenberg-Richter law* for earthquake recurrence is expressed as $\log \lambda_m = a - bm$. The data acquired in Part (b) was used to fit in this model. The `polyfit` in the python numpy package with linear degree was utilized to solve for the coefficients. The graph of the *Gutenberg-Richter law (G-R)* in log scale is shown below.

Problem 1 continued on next page...

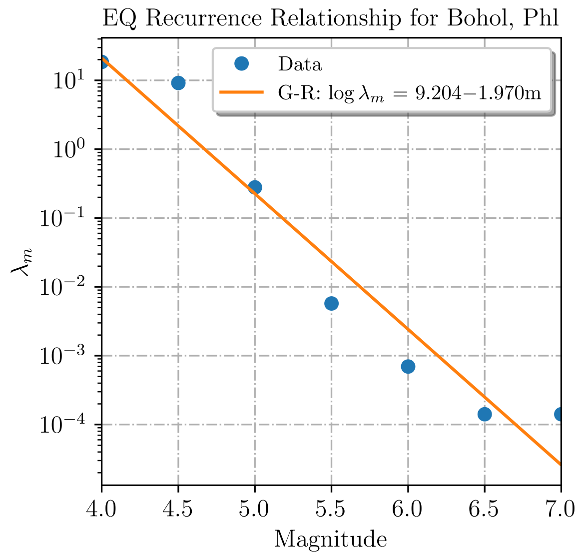

Figure 3: *Gutenberg-Richter law (G-R)*

Another recurrence law that is commonly used is the Cornell and Van Marke (1969) or also called in literature as Bounded Gutenberg-Richter recurrence law. This model includes a maximum, m_{max}, and minimum, m_0, magnitude. The mathematical expression for this model is

$$\lambda_m = \nu \frac{\exp\left[-\beta(m - m_0)\right] - \exp\left[-\beta(m_{max} - m_0)\right]}{1 - \exp\left[-\beta(m_{max} - m_0)\right]} \qquad m_0 \leq m \leq m_{max}$$

where $\nu = \exp\left[\alpha - \beta m_0\right]$, $\alpha = 2.303a$ and $\beta = 2.303b$. This model is not a polynomial model. In order to solve the parameters a and b, a curve fitting function is used from `scipy`. The minimum $m_0 = 4.0$ and $m_{max} = 7.1$ were used. The plot of the *Bounded Gutenberg-Richter recurrence law* is shown below.

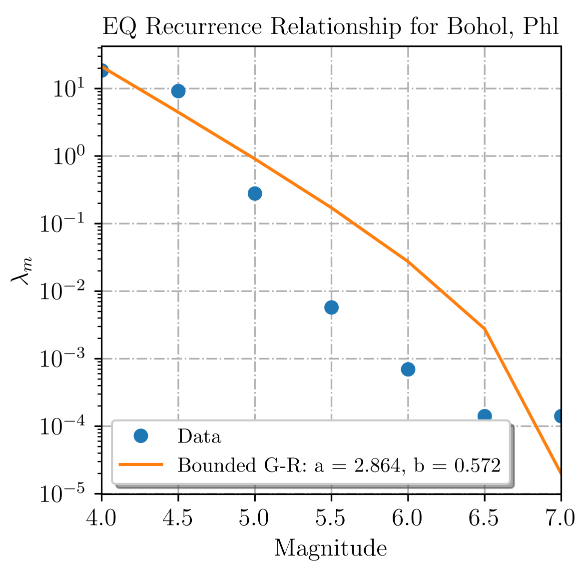

Figure 4: *Bounded-Gutenberg-Richter law*

Problem 1 continued on next page. . .

The calculated parameters are shown in the table below. The calculated parameters varies from each other

Recurrence Model	a	b
Gutenberg-Richter (1954)	9.20363	1.9700
Cornell and van Marke (1969)	2.8645	0.5723

because there is a change in the assumed model or fitting function. The Gutenberg-Richter Law assumes a linear model (in log scale) which may produce increasingly large magnitude of earthquake at smaller annual rate of exceedance. The bounded Gutenberg-Richter Law on the otherhand assumes/considers a maximum magnitude that a source can produce and include it its fitting function.

(d) **Annual rate of earthquake**

The annual rates for different values of magnitudes are calculated. Each earthquake record's magnitude is grouped to the ranges defined in the table below and counted for the given time period.

Range	**Count**
$[4.0, 5.0)$	140
$[5.0, 6.0)$	25
$[6.0, 7.0)$	1
$[7.0, 8.0)$	1

Each count for the individual ranges were divided by the time period. As an example, there were 140 recorded earthquakes having magnitude between 4.0 and 5.0 (exclduding magnitude 5.0). To calculate its annual rate,

$$\lambda_{m=[4.0,5.0)} = \frac{140}{2021 - 1974} = 2.97$$

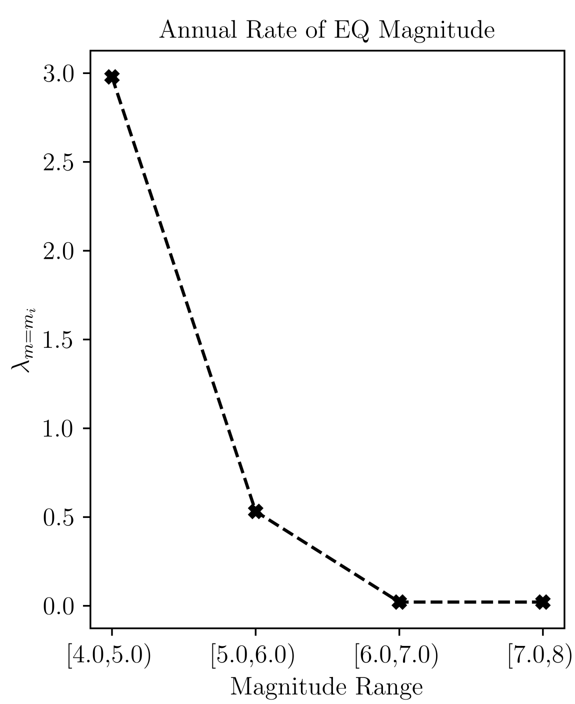

Figure 5: *Annual Rate of Earthquake Magnitudes*

Problem 1 continued on next page. . .

Appendix

A. Python script for creating map

```
import geopandas as gpd
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd
import matplotlib as mpl

# set properties first
mpl.rc('text', usetex='True')
mpl.rcParams.update({'font.size': 12})
plt.rcParams["font.family"] = "tex"

# load data into the workspace
# active fault shape files were downloaded from
# 1) https://github.com/cossatot/gem-global-active-faults/tree/master/shapefile
# 2) https://data.humdata.org/dataset/cod-ab-phl
gdf_fault= gpd.read_file('gem_active_faults.shp')
gdf_boundary = gpd.read_file('phl_admbnda_adm3_psa_namria_20200529.shp')
# EQ records acquired from USGS(https://earthquake.usgs.gov/earthquakes/search/)
eq = pd.read_csv("bohol_eq_record.csv")

# create geo data frame of EQ records
gdf_eq = gpd.GeoDataFrame(eq, geometry=gpd.points_from_xy(eq.longitude, eq.latitude))

# create maps
fig, ax = plt.subplots(1, 1)

# plot boundaries
ax2 = gdf_boundary.plot(ax=ax,color='gray')

# plot the active faults
gdf_fault.plot(ax=ax2,color='red',linewidth=1.0,legend=False)
plt.ylim([9.4,10.4])
plt.xlim([123.6,124.7])

# plot EQ
lat, lon = eq['latitude'], eq['longitude']
magn = eq['mag']
plt.plot([127,129],[11,12],c='red',label='Fault')
plt.scatter(lon, lat, label=None,
c=magn, cmap='viridis',
s=np.exp(magn)/4, linewidth=0, alpha=0.8)
plt.colorbar(label='Magnitude',orientation='horizontal')
plt.clim(3, 7)

for magn in [4, 5,6,7]:
  plt.scatter([], [], c='k', alpha=0.3, s=np.exp(magn)/4,
        label='M ' +str(magn))

plt.legend(bbox_to_anchor=(1.04, 0.5), loc="center left",
  borderaxespad=0,frameon=False,)
plt.xlabel('Longitude')
plt.ylabel('Latitude')
plt.title('Earthquakes in Bohol, Philippines (1974-2021)')
fig.savefig('seismicity_map.png', format='png', dpi=2000,
  bbox_inches = "tight")
plt.show()
fig.savefig('seismicity_map.png', format='png', dpi=2000)
```

Problem 1 continued on next page. . .

B. Python script for recurrence law models

```
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd
import matplotlib as mpl
import scipy as sci
from scipy import optimize

plt.rc('axes', titlesize=12)      # fontsize of the axes title
plt.rc('axes', labelsize=12)      # fontsize of the x and y labels
plt.rc('xtick', labelsize=12)     # fontsize of the tick labels
plt.rc('ytick', labelsize=12)     # fontsize of the tick labels
plt.rc('legend', fontsize=10)     # legend fontsize
plt.rc('font', size=14)           # controls default text sizes
plt.rcParams["font.family"] = "tex"
mpl.rc('text', usetex='True')

# EQ records acquired from USGS(https://earthquake.usgs.gov/earthquakes/search/)
eq = pd.read_csv("bohol_eq_record.csv")

# add year column in dataframe
time = eq['time'][:]
year = []
for i in range(0,len(time)):
  year.append(float(time[i][0:4]))
eq['year'] = year

# calculate annual exceedance
magni = eq['mag']
m = np.arange(4, 7.5, 0.5)
time_period = eq['year'].max() - eq['year'].min()
count_gt_mag,lambda_m = [],[]
for lim in m:
  count_m = magni[magni >= lim].count()
  count_gt_mag.append(count_m)
  lambda_m.append(count_m /time_period )

# plot annual exceedance
fig, ax = plt.subplots(1,1)
plt.plot(m,lambda_m,'k--^')
plt.xlabel('Magnitude')
plt.ylabel('$\lambda_{\geq m_i}$')
plt.title('Annual rate of EQ exceedance')
plt.show()
fig.savefig('annual_exceed.png',
  format='png', dpi=2000, bbox_inches = "tight")

# fit a linear model using G-R law
yi = np.log(lambda_m)
xi = m
model = np.polyfit(xi,yi,1)
b = -model[0]
a = model[1]
mi = np.linspace(4,7,10)
lambda_mi = model[0]*mi + model[1]

# Plot recorded data and G-R model
fig2, ax2 = plt.subplots(1,1)
fig2.set_size_inches(4,4)
plt.plot(m,10**np.log(lambda_m),'o',label='Data')
plt.plot(mi,10**lambda_mi,label=f'G-R: $\log \lambda_m$ = {a:.3f}$-${b:.3f}m')
```

Problem 1 continued on next page...

```
plt.xlim([4,7])
ax2.set_yscale('log')
ax2.legend(shadow='True')
plt.xlabel('Magnitude')
plt.ylabel('$\lambda_m$')
plt.grid(linestyle='-.')
plt.title('EQ Recurrence Relationship for Bohol, Phl')
plt.show()
fig2.savefig('GR_model.png', format='png', dpi=2000, bbox_inches = "tight")

# Define function of Bounded G-R
def func(x,a,b):
  m0,mmax = 4.0,7.1
  m_range = mmax-m0
  alpha,beta = 2.303*a,2.303*b
  nu = np.exp(alpha - beta*m0)
  lambda_m = nu * (np.exp(-beta*(x-m0))-np.exp(-beta*m_range))/(1-np.exp(-beta*m_range))
  return lambda_m

popt, pcov = sci.optimize.curve_fit(func, m, lambda_m)
## Plot recorded data and Bounded G-R model
fig3,ax3 = plt.subplots(1,1)
fig3.set_size_inches(4,4)
plt.plot(m, 10**np.log(lambda_m), 'o', label='Data')
plt.plot(m, 10**np.log(func(m, *popt)),
  label=f'Bounded G-R: a = {popt[0]:.3f}, b = {popt[1]:.3f}')
ax3.set_yscale('log')
ax3.legend(shadow='True')
plt.xlabel('Magnitude')
plt.ylabel('$\lambda_m$')
plt.grid(linestyle='-.')
plt.xlim([4,7])
plt.title('EQ Recurrence Relationship for Bohol, Phl')
plt.show()
fig.savefig('BoundedGR_model.png', format='png', dpi=2000, bbox_inches = "tight")

# determine annual rate for each range of EQ magnitude
magnitude_range = np.zeros((4,1))
for i in range(0, len(eq['mag'] )):
  if eq['mag'][i] >= 4.0 and eq['mag'][i] < 5.0:
    magnitude_range[0] = magnitude_range[0] + 1
  if eq['mag'][i] >= 5.0 and eq['mag'][i] < 6.0:
    magnitude_range[1] = magnitude_range[1] + 1
  if eq['mag'][i] >= 6.0 and eq['mag'][i] < 7.0:
    magnitude_range[2] = magnitude_range[2] + 1
  if eq['mag'][i] >= 7.0 and eq['mag'][i] < 8.0:
    magnitude_range[3] = magnitude_range[3] + 1
annual_rate = magnitude_range / (eq['year'].max() - eq['year'].min())
mag_range = [['[4.0,5.0)',float(annual_rate[0])],
  ['[5.0,6.0)',float(annual_rate[1])],
  ['[6.0,7.0)',float(annual_rate[2])],
  ['[7.0,8)',float(annual_rate[3])]]
  ann_rate = pd.DataFrame(mag_range,columns=['Magnitude Range','Annual Rate'])

# Plot annual rate of EQ magnitude
myplot=ann_rate.plot(x='Magnitude Range', y='Annual Rate',
  c='k',linestyle='--',marker='X',
  legend=False,title='Annual Rate of EQ Magnitude')
myplot.set_ylabel('$\lambda_{m=m_i}$')
fig4=myplot.get_figure()
fig4.savefig('annual_rate.png', format='png', dpi=2000, bbox_inches = "tight")
```

References

[1] Steven L. Kramer. *Geotechnical Earthquake Engineering.* Prentice-Hall, Inc., 1996.

[2] Richard Styron and Marco Pagani. The gem global active faults database. *Earthquake Spectra*, 36:160–180, 10 2020.