Source Mechanism Inversion of Earthquake Induced by Wastewater Injection in Oklahoma, US.

Jia Yoong Chong and Qinya Liu
Department of Earth Sciences, University of Toronto *March 2019*

1 INTRODUCTION

In recent decade, swarms of earthquake activities have flooded Oklahoma in United States followed by an increase of wastewater disposal activities due to hydraulic fracturing operations in the region. This disposal practice is known to have induced a number of felt-earthquakes in Oklahoma (Rubinstein et al., 2016). The Arbuckle Group, beneath Oklahoma, is a favorable formation for wastewater disposal due to its highly porous and low pressure sediment layer overlying a crystalline basement (Chen et al., 2017). An average of 2.3 billion barrels of wastewater have been injected into the basement since 2011 (Hincks T et al., 2018). Previously recorded seismicities found within Pre-Cambrian crystalline basement suggests faults could have been reactivated by wastewater injection into Arbuckle Group (Keranen et al., 2013, 2014).

Pawnee M5.8 earthquake is the largest instrumentally recorded event in Oklahoma, United States. Although the foreshocks and aftershocks of Pawnee sequence were sparse with magnitudes smaller than M4, this main shock in the unusual sequence appears to have been induced by high-volume wastewater disposal within 10km from the mainshock epicenter (McGarr et al., 2017). Foreshock activities within the conjugate fault system too have been identified with instantaneous response to fluctuation in injection rate at 95% confidence interval. (Chen et al., 2015)

An important task in seismology is to compute the moment tensor of seismic event using seismic observations. Moment tensor solution can provide fundamental information on focal mechanisms and event magnitude of earthquakes. This study aims to conduct an updated analysis of moment tensor inversions for earthquakes source mechanisms in region nearby Pawnee that occurred from June 2016 to September 2016 by using general "Cut-and-Paste" (gCAP) method. Combining the moment tensor solution catalogue with wastewater injection parameters, we will better understand the nature of earthquake sequence occurred in Pawnee, Oklahoma. This constitutes an essential step in the industrial practice of seismic monitoring.

2 DATA AND METHOD

Seismic waveforms used in this study consists three-component recordings from stations of selected telemetered networks. The distribution of seismic stations, ranging 30km-300km from epicenters, shows a good azimuthal coverage around events of interest. Events selected for inversion are based on proximity to disposal wells and Pawnee main shock epicenter.

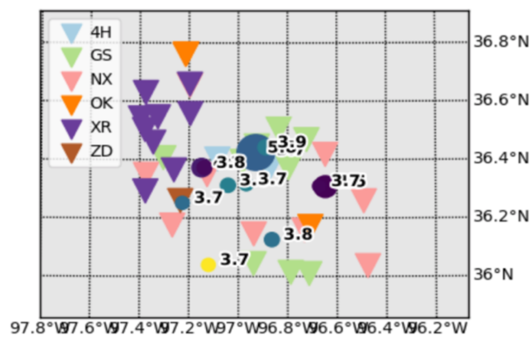

Figure 1: *Distribution of seismic stations (inverted triangles) of 4H, GS, NX, OK, XR, XR and ZD networks and events (colored circles with Mw)*

Magnitude (Mw)	Event Time (D/T)	Hypocenter depth (m)	Epicenter (lat, long)
3.6	2016-09-03 12:58:37	6.162	+36.423, -96.909
5.8	2016-09-03 12:02:44	5.557	+36.425, -96.929
3.6	2016-07-21 21:33:30	10.354	+36.355, -97.091
3.9	2016-06-08 16:50:41	6.632	+36.443, -96.888

Table 1: *Catalogue of selected events for the moment tensor inversion.*

Moment tensor solution can be computed with gCAP inversion technique, which is developed by Dr. Lupei Zhu. Seismic waveforms are cut into Pnl window (two P-wave windows on the vertical and radial components) and surface wave window (all three surface wave components). To optimize fitting for inversions, the Pnl and surface wave window are each filtered with different frequencies. For pre-processing, filters of 0.08Hz-0.5 Hz with 35s long window length and 0.05 Hz-0.12Hz with 70s long window length are each applied to Pnl and surface wave windows respectively.

Synthetic seismograms are generated by Green's functions, which are calculated by Frequency-Wavenumber (FK) method of Zhu & Rivera (2002) based on a regional 1-D velocity model in Chelsea, Oklahoma (Figure 2). Green's functions for each stations are set with initial time headers to match with the event time of observational waveform. The observational and synthetic waveforms generated from same set of parameters are fitted and cross-correlated. Due to inaccuracies in epicenter location and regional velocity model, Pnl waveforms and the surface waves are allowed to shift with respect to their synthetics for time windows of 2s and 5s, respectively. This maximizes the cross-correlation coefficients of original and synthetic waveforms.

T	Vp	Vp/Vs	rho	Qs	Qp
3.1	3.048	1.732	2.46	730	1460
23	3.677	1.732	2.81	1700	3400
20.2	4.168	1.732	3.08	1700	3400
0.0	4.723	1.732	3.39	1700	3400

Figure 2: *The 1-D velocity model of Chelsea, Oklahoma in the format of thickness(km), P-wave velocity(km/s), P-wave velocity/S-wave velocity, Density(g/cm3), Attenuation of Qs and Qp.*

Waveform data are requested from IRIS web service and formatted into Seismic Analysis Code (SAC) with header information. This allows observed waveform to match with its corresponding synthetics waveforms. For data processing, instrument responses are deconvoluted and its linear trends are removed. The three-component seismograms are also rotated to the great circle, and units are converted from m/s to cm/s. Waveform screening is also carried out to remove clipped or irregular waveforms.

A weight.dat file consists of station information and weights for each different time windows is prepared for gCAP inversion. With the pre-processed waveform data, FK computed Green's functions and weight.dat file, gCAP would perform a grid search of source mechanism parameters (strike, dip, rake and magnitude) in specified search range and step size. This grid search of strike, dip and rake allows the assessment of the whole parameter space volume. Grid search for magnitude starts from catalogue magnitude of the event until minimum misfit is obtained. The entire grid search process is looped over a range of source depths from 2km to 7km, of 1km step size, to obtain best set of parameter values.

Scalar moment is then estimated using ratio of L2 norms of observational and synthetics. Each component of waveform segments is visually screened to confirm the quality of fit, and poorly fitting phases are assigned with lower weight to reduce potential data errors.

3 RESULT

The moment tensor solution for 3rd Sept. 2016 shows an above-average fitting between observational and synthetic waveforms with a variance reduction score of 93.7%. For mainshock, the moment magnitude and centroid depth obtained from inversion is consistent with that of catalogue.

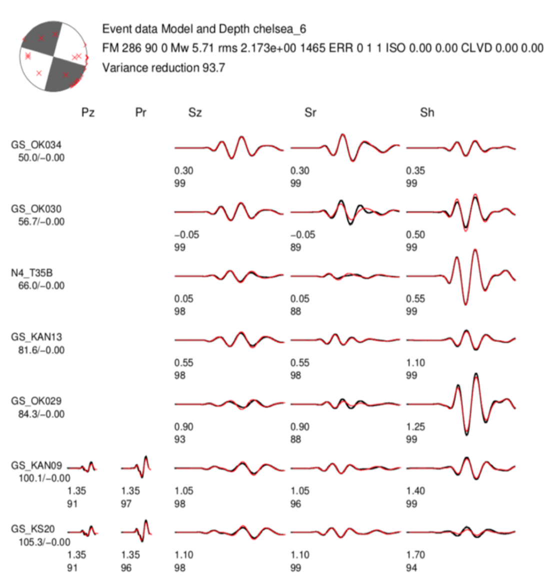

Figure 4: Sample gCAP inversion output at focal depth 6km for Pawnee M5.8 event.

Focal mechanism solution of event can be represented with beach ball plot, which is located on upper-left corner of inversion output (Figure 4). Focal mechanism and moment magnitude of inversion are resulted from best-fitting solutions of vertical Pnl waves (Pz), radial Pnl waves (Pr), vertical surface waves (Sz), radial surface waves (Sr) and transverse surface waves (Sz) of all stations, which are arranged by its epicentral distance (shown in km below the station name). Black traces are observed waveforms and red traces are predicted waveforms. The numbers below each waveform segment refers to the time shift in seconds (top), and waveform cross-correlation coefficient in percentage (bottom). Stations used in the inversion process are labelled as red dots on the beach ball on upper left corner. Focal mechanisms at different focal depths are plotted on a misfit graph to determine the best-fit focal depth (Figure 5). For mainshock, inversion result shows that best-fit fault plane solution at its best-fit focal depth, 6km, has strike 286, dip 90 and rake 0 degrees.

Focal mechanism solutions of other events analyzed in this study are similar to each other and the obtained moment magnitudes are close to that of catalogue, differ approximately by 0.1M.

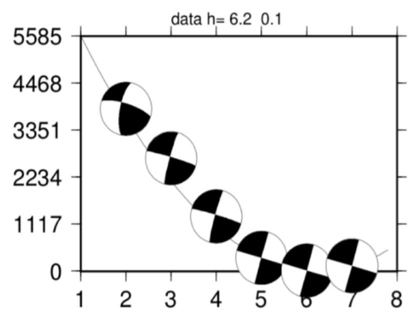

Figure 5: Waveform misfit vs centroid depth plot for Pawnee 5.8M event. Best fit-focal depth is determined at 6km.

Event (Day/Time)	Focal plane (strike/dip/rake)	Moment magnitude (M)	Best-fit focal depth (km)
2016-09-03 12:58:37	321/72/10	3.55	4
2016-09-03 12:02:44	286/90/0	5.71	6
2016-07-21 21:33:30	144/90/09	3.73	4
2016-06-08 16:50:41	141/83/-8	4.03	3

Table 3: Summary of inversion results for 4 events analyzed in this study.

4 DISCUSSION

Moment tensor solutions of all events analyzed in this study suggests a strike-slip mechanism with almost-vertical nodal planes. To distinguish the fault plane from auxiliary plane, understanding of local geological features is required. The Pawnee earthquake sequence occurred within a conjugate fault system, which has a fault plane of similar geometry to our west-northwest nodal plane in the moment tensor solutions. This fault, known as Sooner Lake fault, is a left-lateral almost-vertical fault that strikes west-northwestwardly. Active wastewater injection in close proximity to the conjugate fault system may have reduced the background stress and caused the reactivation of pre-existing faults. Most of the injection took place at depth of 1km – 2km in sediment layer, while most of the earthquakes occurred in the deeper crystalline basement. Rapid response to small fluctuations in injection rates indicates that the conjugate fault system is sensitive to small stress perturbations prior to mainshock rupture (Chen et al., 2015). Pawnee M5.8 mainshock is likely the destabilization of fault 3-4km below the depth range where injection took place. Combining fault plane solutions for analyzed events, it is very likely that the Pawnee sequence was a result of left-lateral slip across Sooner Lake Fault.

5 CONCLUSION

With observational and synthetic waveforms, we determined source mechanism solutions of Pawnee sequence induced by wastewater disposal operations. The moment tensor solutions and location of this earthquake sequence suggest activation of NW-SE striking and vertically dipping Sooner Lake Fault.

ACKNOWLEDGEMENT

Earthquake waveforms are provided by GM, GS, N4, NX, OK, TA, US, Y9 stations and downloaded from IRIS web service through Obspy. Green’s functions were computed with FK software package by Dr. Lupei Zhu and Rivera. Inversion was obtained with gCAP software package developed by Dr. Lupei Zhu and Helmberger. Disposal well data are obtained from Oklahoma Corporation Commission (OCC). We thank Yiru Zhou and Chuangxin Lin for their scientific help.

REFERENCES

Chen, X., Nakata, N., Pennington. C, Haffener. J, Chang. J.C, He. X, Zhan. Z, Ni.S & Walter. J (2017) The Pawnee Earthquake as a result of interplay among injection, faults and foreshocks, Nature,Scientific Report 7, 4945

Grandin, R., Vallee, M., Lacassin, R., (2017) Rupture Process of the Mw 5.8 Pawnee Oklahoma, Earthquake from Sentinel-1 InSAR and Seismological Data. Seismological Research Letters 88(4), 994 – 1004

McGarr, A., Barbour, A.J. (2017). Wastewater Disposal and Earthquake Sequences During 2016 near Fairview, Pawnee, and Cushing Oklahoma. Geophysical Research Letters, 10.1002 /2017GLO75258, 9330-9336

Mitchell, B.J. and M. Landisman, 1970, Interpretation of a Crustal Section across Oklahoma, Geol. Soc. Amer. Bul 81(9), p. 2647-2656.

Zhu, L., & Helmberger, D. V. (1996). Advancement in source estimation techniques using broadband regional seismograms. Bulletin of the Seismological Society of America 86(5), 1634-1641.

Zhu, L. & Rivera, L., 2002. A note on the dynamic and static displacements from a point source in multi-layered media, Geophys. J. Int. 148, 619–62