Deterministic Simulation of Ground Motion from Induced Seismicity at the FORGE Site

Chandrakanth Bolisetti[a], Kristine Pankow[c], Kyung Tae Kim[b], and Robert Podgorney[a]

[a]Idaho National Laboratory
[b]California Department of Transportation
[c]University of Utah

Keywords

Source-to-site ground motion modeling; seismic hazard analysis; finite-element analysis; induced seismicity; FORGE program

ABSTRACT

Ground motions generated by induced seismicity is an important consideration and design factor for the development of enhanced geothermal systems (EGS) and operations. Typically, ground motions are estimated from empirically based ground motion prediction equations using a moment magnitude and a distance with factors to account for local site conditions and in some cases faulting style. Ground motions specific to a site, recorded or modelled, for the specific site conditions and fault geometries may better inform hazard and risk calculations. Here we demonstrate a deterministic calculation of ground motions from postulated moment magnitudes at the Utah FORGE site using source-to-site earthquake simulations using the finite-element method in the codes, FALCON and MASTODON, developed and maintained at the Idaho National Laboratory. Sample results are presented from these simulations and a plan for future work is discussed.

1. Background

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) (Figure 1) is a U. S. Department of Energy (DOE) funded project to enable research and technology testing with the goal to identify a commercial pathway for enhanced geothermal systems (EGS) (Moore et al., 2019). EGS requires the creation of a permeable reservoir, such that fluid can be circulated through the reservoir and heat can be extracted. Induced seismicity is a by-product of the creation of fractures for the EGS reservoir. Most EGS induced seismic events are too small to be felt ($M < 2.5$). However, larger seismic events that may be felt or that might result in limited damage are possible. Because of the potential for induced seismicity, Utah FORGE has developed an Induced Seismic Mitigation Plan (ISMP) following the best practices described in Majer et al. (2016). This plan includes an assessment of historical seismicity, a site specific probabilistic seismic hazard analysis (PSHA), assessment of site-specific hazard and risk, and a traffic light system for responding to seismicity that may occur at Utah FORGE.

A key element of the ISMP and PSHA is estimating the expected ground motion as a function of distance from induced seismic events occurring at Utah FORGE. Currently, ground motion prediction equations developed as part of NGA-West 2 (Abrahamson et al., 2014; Boore et al., 2014, Bozorgnia et al., 2014; Chiou and Youngs, 2014) and a relationship developed for small ($M < 4.5$) earthquakes (Chiou et al., 2010) that has been tested against data collected for earthquakes in Utah are used for assessing the potential hazard. However, ground motion is a function of the earthquake magnitude, stress drop, potentially the earthquake mechanism and fault orientation, and the local velocity structure, specifically the shallow sediments and local impedance contrasts, so site-specific ground motion predictions would be preferred. In this paper, we use the opensource finite-element modeling and simulation code, MASTODON to model ground motion in the vicinity of the Utah FORGE (see Figure 1) resulting from fractures within the reservoir.

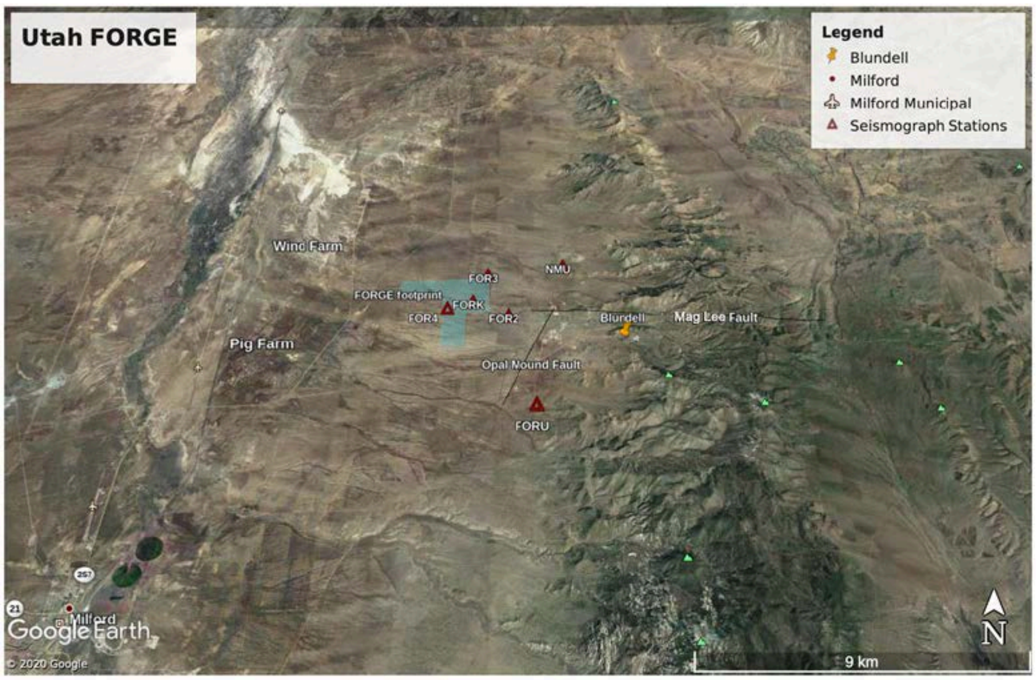

Figure 1: Map illustrating the Utah FORGE location, rural nature of the surrounding areas, and the relative distances between the FORGE site and the limited structures (University of Utah, 2021)

2. Deterministic Source-to-Site Simulations for Induced Seismicity

2.1 Introduction to MASTODON

The Idaho National Lab (INL) develops and maintains Multiphysics Object-Oriented Simulation Environment (MOOSE), which is an opensource software framework for solving differential equations using the finite-element method. MOOSE (Permann et al, 2020) currently includes various physics such as mechanics, structural dynamics, heat conduction, porous flow, and fracture mechanics. These physics modules can either be used individually, or together by combining them into multiphysics 'apps' for specific physical applications. While several apps have been developed for nuclear applications, two such apps are relevant in the context of geothermal applications: FALCON (Xia et al, 2017), which is developed for geothermal reservoir stimulation and operation simulations, and MASTODON (Veeraraghavan et al, 2020), which is developed for seismic analysis and risk assessment and can be used for deterministic ground motion estimation at geothermal sites.

MASTODON was originally developed for the seismic analysis and risk assessment of critical facilities such as safety-critical nuclear structures and dams. MASTODON is capable of fault rupture and source-to-site wave propagation using the domain reduction method, nonlinear site response and soil-structure interaction analysis, implicit and explicit time integration, automated stochastic simulations, and seismic probabilistic risk assessment. When coupled with other MOOSE applications, MASTODON can also solve strongly and weakly coupled multiphysics problems. In this paper, MASTODON is used to simulate hypothetical deterministic scenarios of induced seismicity at the FORGE site to (a) demonstrate MASTODON's capabilities, and (b) examine the earthquake shaking intensity at the FORGE site from these scenarios. MASTODON is opensource software hosted on GitHub (github.com/idaholab/mastodon). Detailed documentation and examples are provided on the documentation website (mooseframework.inl.gov/mastodon).

Earthquake source-to-site simulations involve simulation of the natural or induced fault rupture and propagation of the resulting waves from the fault throughout the domain of interest. Source-to-site simulations involve four main components: (1) fault-rupture models that, based on the geometry of the fault and the surrounding material properties, determine the magnitude, rate, location, and orientation of the energy release, (2) simulation of wave propagation from the fault throughout the domain, which is done in MASTODON using finite-element analysis, (3) material damping, which affects attenuation of the waves, and (4) energy absorption at boundaries of the domain of interest so that the outgoing waves are not transmitted back into the domain. The fault-rupture model in MASTODON is a function of the fault dimensions, fault orientation, and the slip history. The fault dimensions determine the area of fault rupture, which, in combination with the slip history provides the energy released during and earthquake. The seismic moment (equivalent of energy released during an earthquake) is given by the equation,

$$M_o(p,t) = \mu A \bar{u}(p,t) \tag{1}$$

where, M_o is the seismic moment as a function of position, p and time, t, μ is the shear modulus of the soil/rock around the fault, A is the area of fault rupture and $\bar{u}$ is the slip history as a function of position and time. The direction of the energy release from the fault rupture is a function of the orientation of the fault, defined by the strike, rake, and dip of the fault.

2.2 Source-to-Site Simulations at the FORGE site

Source-to-site simulations in MASTODON are used to simulate a few hypothetical induced seismicity scenarios at the FORGE site and the results are presented in this paper. Note that these scenarios are hypothetical, and the results are preliminary and demonstrative only. Future studies will involve more realistic scenarios. The following scenarios are presented in this paper:

1. Asynchronous rupture of the Opal Mound fault shown in Figure 1 and Figure 2
2. Asynchronous rupture of the Mag Lee fault shown in Figure 1 and Figure 2
3. Asynchronous rupture of a fracture at the end of well 16A with a circular fault geometry

Figure 2 presents a schematic that shows the location of the FORGE site in relation to the local geography, as well as the Mag Lee and Opal Mound faults. Sample simulations of these ruptures with very small slip distances corresponding to very small (< 0.0) moment magnitudes respectively are performed in MASTODON. The MASTODON finite-element mesh, along with the approximate locations of the faults are presented in Figure 3. These meshes, along with the faults are generated using MeshIt (Cacace and Blöcher, 2015), which is a meshing software specifically developed for fractured reservoirs. The results of the MASTODON simulations are presented in Figure 4 and Figure 5, which present acceleration histories and response spectra, respectively. The figures show that the peak acceleration from these scenarios is very minor (0.04 – 0.05% of g) and ground motions are unlikely to be felt. However, these scenarios simulate a very small slip history and do not reflect the maximum possible earthquake based on the fault dimensions (Wells and Coppersmith, 1994). The response spectra show that most of the energy is concentrated in 2-5Hz, which, although is not uncommon of earthquakes, but also is a result of using a coarse mesh. Future simulations with much finer meshes will provide more credible estimates of spectral accelerations at higher frequencies.

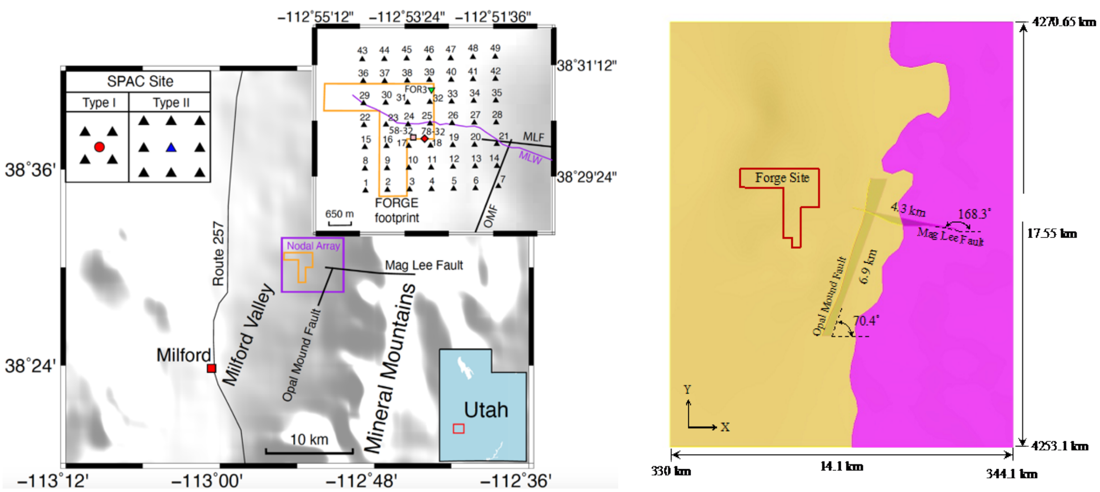

Figure 2: Schematic showing the fault locations near the FORGE site (in yellow boundaries on the left and red boundaries on the right). The domain size of the FE model in MASTODON is presented on the right. (Zhang and Pankow, 2021)

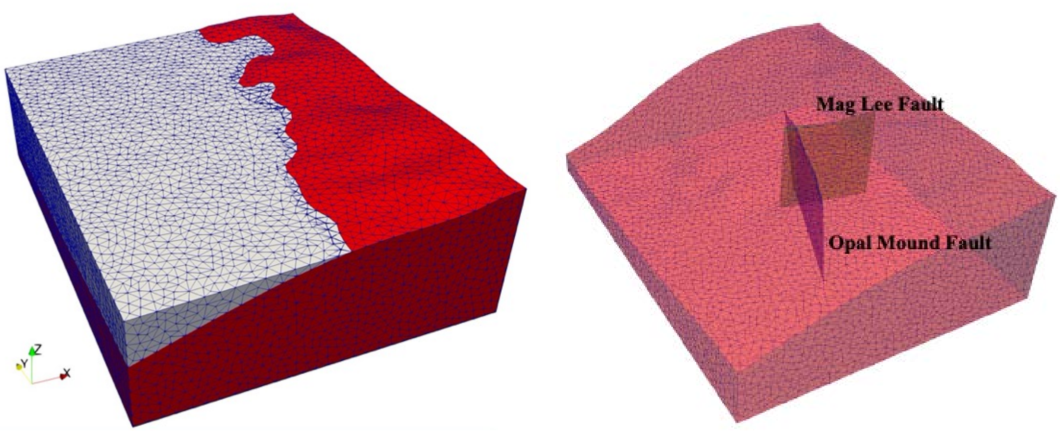

Figure 3: MASTODON finite-element models used for the source-to-site simulations. On the left is both the granitoid (red) and the sediment (gray) and the right is only the granitoid along with the fault locations marked. Both the granitoid and the sediment were modeled together in MASTODON.

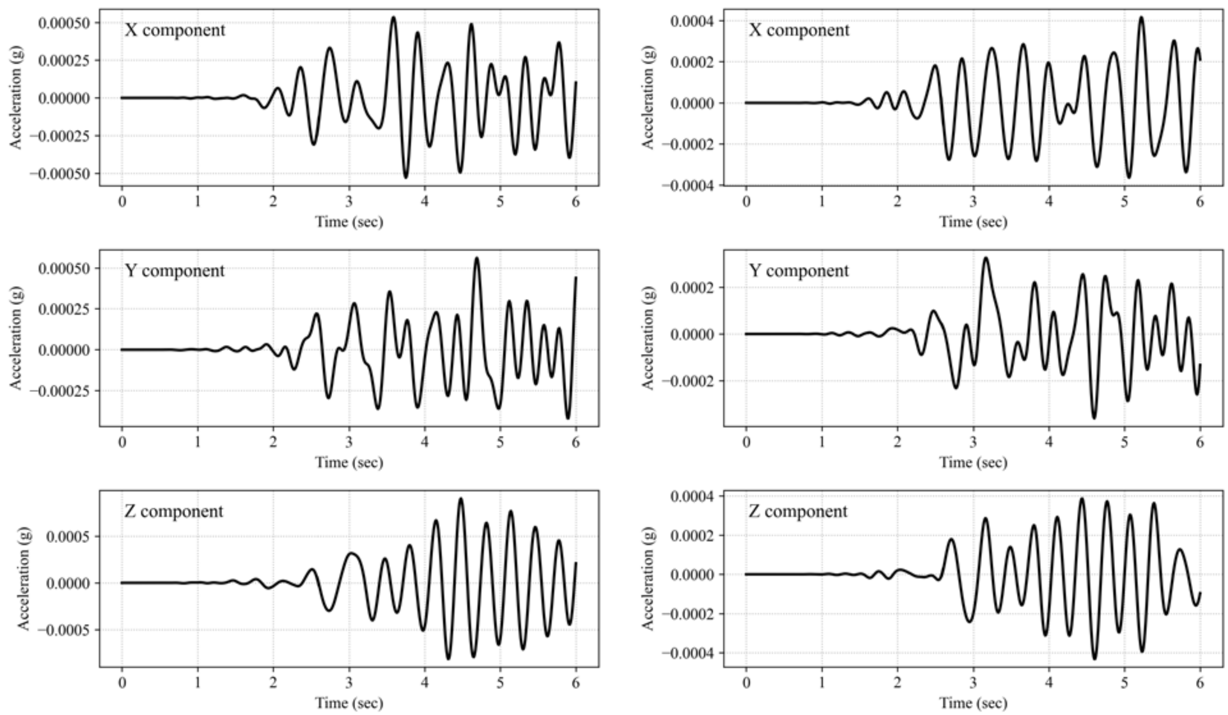

Figure 4: Accelerations at a surface point in the boundary of the FORGE site calculated using MASTODON for Opal Mound fault rupture (left column) and the Mag Lee fault rupture (right column)

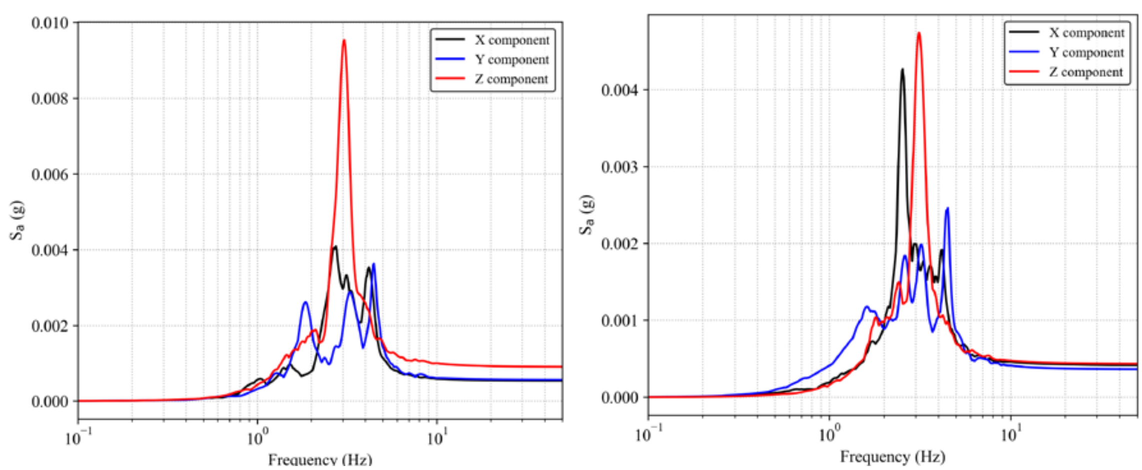

Figure 5: 5% damped spectral accelerations at a surface point in the boundary of the FORGE site calculated using MASTODON for Opal Mound fault rupture (left) and the Mag Lee fault rupture (right)

Figure 6 illustrates scenario 3 simulated in MASTODON. This scenario involves the hypothetical rupture of a fracture at the end of well 16A. For this simulation, the fracture is assumed to be a circular disc with a radius of 100m and the orientation shown in the figure. For a total slip distance of 1 m, this scenario is equivalent to an Mw -0.77, which is also very small.

Further study will simulate a larger earthquake magnitude. Figure 7 presents contours of the surface PGA calculated using MASTODON with the boundaries of the FORGE site shown in black. The contours show that the max PGA is again very small, between 0.03 and 0.04% g. However, an interesting observation here is the locations of the concentration of higher PGA (shown in red in the contours). The figures show that higher PGA is concentrated to the east on the flank of the Mineral Mountains (see Figure 1 for the local geography of the site), which is likely due to the topography of the surface and the geometry of the granitoid and the sediments. It can also be seen that the FORGE site is mostly distant from the areas of higher PGA. However, further simulations with more accurate representations of the soil/rock properties are required to make more conclusive observations.

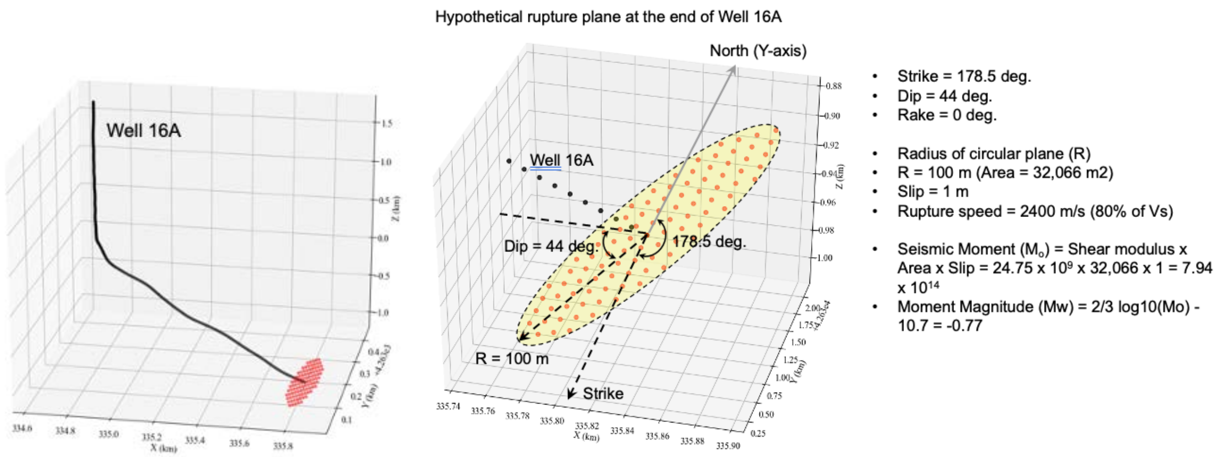

Figure 6: Description of the EGS induced hypothetical fracture and its orientation at Well 16A

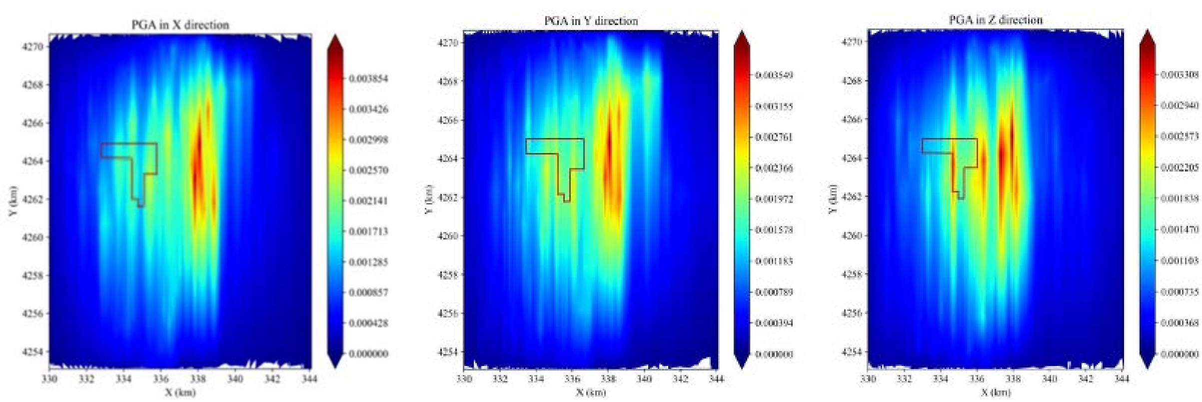

Figure 7: Surface PGA contours calculated from MASTODON simulations of a hypothetical EGS-induced fracture rupture at well 16A

3. Summary and future work

We have shown initial results for modeling ground motions that result from small magnitude events induced as part of reservoir development. While these seismic events contribute little to the overall hazard, we have developed a proof of concept that can be up scaled to model larger potential earthquakes. This modeling specific to the Utah FORGE area can be compared to ground motion prediction equations in order to identify local site effects and faulting styles that may currently not be accounted for in the hazard assessments.

Acknowledgements

This study was funded by the United States Department of Energy through the FORGE program.

REFERENCES

Moore, J. & McLennan, J., Rick Allis, R., Pankow, K., Simmons, S., Podgorney, R., Wannamaker, P., Bartley, J., and Rickard, W. (2019). The Utah Frontier Observatory for Research in Geothermal Energy (FORGE): An International Laboratory for Enhanced Geothermal System Technology Development. Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University. Published, 02/13/2019.

Majer, E., Nelson, J., Robertson-Tait, A., Savy, J., & Wong, I. (2016). Best practices for addressing induced seismicity associated with enhanced geothermal systems (EGS), Topical report, Lawrence Berkeley National Laboratory, prepared at the direction of the Dept. Of Energy Geothermal Technologies Program, April 8, 115 pp.

Abrahamson, N.A., Silva, W.J., and Kamai, R., 2014, Summary of the AKS14 Ground-Motion Relation for Active Crustal Regions, Earthquake Spectra, Vol. 30, DOI: 10.1193/070913EQS198M.

Boore, D.M., Stewart, J.P., Seyhan, E., and Atkinson, G.M., 2014, NGA-West 2 Equations for Predicting PGA, PGV, and 5%-Damped PSA for Shallow Crustal Earthquakes, Earthquake Spectra, DOI: 10.1193/070113EQS184M.

Bozorgnia, Y., Abrahamson, N.A., Al Atik, L., Ancheta, T.D, Atkinson, G.M., Baker, J.W., Baltay, A., Boore, D.M., Campbell, K.W., Chiou, B.S.-J., Darragh, R., Day, S., Donahue, J., Graves, R.W., Gregor, N., Hanks. T., Idriss, I.M., Kamai, R., Kishida, T., Kottke, A., Mahin, S.A., Rezaeian, S., Rowshandel, B., Seyhan, S., Shahi, S., Shantz, T., Silva, W., Spudich, P., Stewart, J.P., Watson-Lamprey, J., Wooddell, K, and Youngs, R.R., 2014, NGA-West2 research project, Earthquake Spectra, v, 30(3), p. 973-987.

Chiou, B. J., & Youngs, R. R. (2008). An NGA model for the average horizontal component of peak ground motion and response spectra. Earthquake Spectra, 24(1), 173-215.

University of Utah (2021). "Utah FORGE Induced Seismicity Mitigation Plan: Enhanced Geothermal System Testing and Development at the Milford, Utah Site." DE-EE0007080, United States Nuclear Regulatory Commission, Salt Lake City, Utah.

Permann, C. J., Gaston, D. R., Andrš, D., Carlsen, R. W., Kong, F., Lindsay, A. D., Miller, J. M., Peterson, J. W., Slaughter, A. E., Stogner, R. H., and Martineau, R. C. (2020). "MOOSE: Enabling massively parallel multiphysics simulation." SoftwareX, 11, 100430.

Veeraraghavan, S., Bolisetti, C., Slaughter, A., Coleman, J., Dhulipala, S., Hoffman, W., Kim, K., Kurt, E., Spears, R., and Munday, L. (2020). "MASTODON: An Open-Source Software for Seismic Analysis and Risk Assessment of Critical Infrastructure." Nuclear Technology. 10.1080/00295450.2020.1807282.

Xia, Y., Podgorney, R., and Huang, H. (2017). "Assessment of a Hybrid Continuous/Discontinuous Galerkin Finite Element Code for Geothermal Reservoir Simulations." Rock Mechanics and Rock Engineering, 50(3), 719-732. 10.1007/s00603-016-0951.

Zhang, H. and K. Pankow (2021). High-resolution Bayesian spatial autocorrelation (SPAC) pseudo-3D Vs model of Utah FORGE site with a dense geophone array, Geophysical Journal International, 225, 1605-1615.

Aki, K., and Richards, P. G. (2002). Quantitative Seismology, University Science Books.

Cacace, M., and Blöcher, G. (2015). "MeshIt—a software for three-dimensional volumetric meshing of complex faulted reservoirs." Environmental Earth Sciences, 74(6), 5191-5209. 10.1007/s12665-015-4537.

Wells, D. L., & Coppersmith, K. J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America, 84(4), 974-1002.