Evaluating Liquefaction Triggering Potential at Sites Impacted by the 2016 Mw 5.8 Pawnee, Oklahoma, Induced Earthquake

Tyler Quick[1]; Russell A. Green[2]; Ellen Rathje[3]; and James K. Mitchell[4]

[1]Graduate Student, Dept. of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA. E-mail: tylerjaq@vt.edu
[2]Professor, Dept. of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA. E-mail: rugreen@vt.edu
[3]Professor, Dept. of Civil, Architectural, and Environmental Engineering, Univ. of Texas at Austin, Austin, TX. E-mail: e.rathje@mail.utexas.edu
[4]Univ. Distinguished Professor Emeritus, Dept. of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA. E-mail: jkm@vt.edu

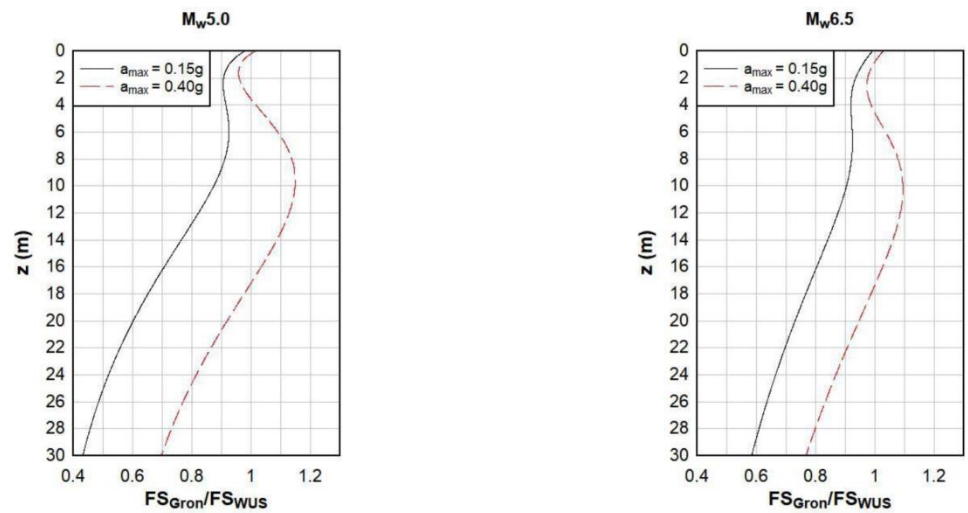
ABSTRACT

Deep wastewater injection-induced seismicity has led to over a thousand $M_w>3$ earthquakes and four $M_w>5$ earthquakes in Oklahoma over the last ten years. The 3 September 2016, $M_w5.8$ Pawnee, Oklahoma, earthquake was the first induced seismic event worldwide, that the authors are aware of, where liquefaction was observed and documented, raising concerns regarding the liquefaction risk posed by future induced earthquakes. Determining the suitability of current variants of the simplified procedure for evaluating the regional liquefaction hazard caused by induced earthquakes is part of an ongoing study. A detailed site characterization campaign examining profiles where liquefaction was and was not observed following the 2016 $M_w5.8$ Pawnee, Oklahoma, earthquake is part of this study. The purpose of this paper is to present an overview of the sites targeted as part of this testing, a summary of preliminary results from the site characterization campaign, and a description of planned future testing.

INTRODUCTION

The stress-based "simplified" liquefaction evaluation procedure (Whitman 1971; Seed and Idriss 1971) is the most widely used approach to evaluate liquefaction potential worldwide. However, the procedure is semi-empirical, with the empirical aspects of it derived from data from moderate-sized tectonic earthquakes in active shallow-crustal tectonic regimes (e.g., California, Japan, and New Zealand). As a result, the suitability of the procedure for evaluating the liquefaction hazard due to induced seismicity in stable continental tectonic regimes is questionable. Although the ability of soil to resist liquefaction triggering (i.e., $CRR_{M7.5}$) is assumed to be an inherent property of the in situ soil conditions, the ground motions from induced earthquakes may have different characteristics than those from natural tectonic earthquakes (e.g., Bommer et al. 2016; Zalachoris and Rathje 2019). Also, the geologic profiles/soil deposits in areas in the US experiencing the highest rate of induced seismicity (e.g., Oklahoma) differ from those used to develop the empirical aspects of the simplified procedure. Accordingly, and in combination with the smaller magnitudes of induced earthquakes, it is uncertain whether the depth-stress reduction factor (r_d) and Magnitude Scaling Factor (MSF) relationships inherent to existing simplified liquefaction evaluation procedures for estimating normalized Cyclic Stress Ratio (CSR*) are suitable for use with induced earthquakes because both r_d, which accounts for the non-rigid response of the soil profiles to shaking, and MSF, which accounts for durational effects of shaking on liquefaction triggering, are affected by ground motion and soil profile characteristics.

This is illustrated in Figure 1, which shows, as a function of depth (z), the ratio of FS_{WUS}, the factor of safety against liquefaction triggering (FS) for shallow crustal tectonic events in active tectonic regions (e.g., western US), to FS_{Gron}, the FS for induced earthquakes due to natural gas production in the Groningen region of the Netherlands, both computed using the simplified procedures developed by Green et al. (2019a; b). As shown in this figure, for a peak ground acceleration (a_{max}) of 0.15g occurring during events having moment magnitudes (M_w) of 5 and 6.5, the predicted FS for the induced earthquakes in Groningen is lower, and considerably so at some depths, than it is for tectonic events. However, as a_{max} increases to 0.4 g (again for M_w = 5 and 6.5 events) this trend is less pronounced and the predicted FS for induced earthquakes is actually greater than that for tectonic events for a depth range of ~5 to 17 m.



(a) (b)

Figure 1. Ratio of the predicted FS for induced earthquakes in the Groningen region of the Netherlands and shallow crustal tectonic events (Green et al. 2019a; b): (a) M_w5.0, a_{max} = 0.15g & 0.4g; and (b) M_w6.5, a_{max} = 0.15g & 0.4g.

Although most earthquakes induced by wastewater injection in Oklahoma have been small, there have been four M_w5+ events, with the largest being the 2016 M_w5.8 Pawnee earthquake. These events have resulted in some structural damage (Clayton et al. 2016), but overall economic consequences have been limited because the earthquake epicenters were located in rural areas. However, significant damages potentially could occur if additional M_w5+ earthquakes were to occur in more populated or more vulnerable areas. The dramatic increase in the number of seismic events due to induced seismicity, even when the events are limited in size, increases the overall seismic risk in the affected areas. This includes the risk due to liquefaction, with the Pawnee earthquake being the first induced seismic event worldwide, that the authors are aware of, where liquefaction has been observed and documented. As a result, a procedure is needed to be able to accurately evaluate liquefaction triggering potential due to induced seismicity in Oklahoma due to deep wastewater injection. Note that although the Green et al. (2019b) variant of the simplified liquefaction evaluation procedure was specifically developed for induced earthquakes, the predominant source mechanism of Groningen earthquakes is normal faulting having focal depths of ~3 km; in contrast, the fault mechanism for the larger induced events in Oklahoma have been predominately strike-slip and have focal depths of ~5 km. Accordingly, and due to differences in the geologic profiles/soil deposits in Oklahoma versus Groningen, the procedure developed to evaluate liquefaction triggering due to induced earthquakes in Groningen cannot necessarily be used to evaluate liquefaction triggering due to induced earthquakes in Oklahoma.

Determining the suitability of current variants of the simplified procedure for evaluating the regional liquefaction hazard caused by induced earthquakes in Oklahoma, Texas, and Kansas is part of an ongoing study. A detailed site characterization campaign to examine profiles where effects of liquefaction were and were not observed following the Pawnee earthquake is part of this study. The purpose of this paper is to present an overview of the sites targeted for testing, a summary of the preliminary results from the site characterization campaign, and a description of planned future testing.

BACKGROUND

Anthropogenic sources of seismicity include activities such as fracking, oil and gas extraction, wastewater injection, carbon capture and storage, and reservoir filling. These activities induce changes in pore pressures and stresses in fault zones, which can lead to fault rupture (Ellsworth 2013; Foulger et al. 2018). These ruptures can lead to the release of both induced stresses and pre-existing tectonic stresses. Thus, the seismic energy released during induced events can be significantly larger than that due to the induced stress changes themselves (McGarr et al. 2002). This led Mitchell and Green (2017) to distinguish between “triggered” anthropogenic earthquakes, which primarily release pre-existing tectonic stresses, and “induced” anthropogenic earthquakes, which release primarily induced stresses. In practice, it is difficult to distinguish between the two, and both are generally referred to as “induced” earthquakes (Foulger et al. 2018), which is the convention used herein. Several studies have indicated that most faults in the crust are nearly critically stressed, which suggests that even minor changes to pore pressure, confining stress, or shear stress induced by human activity can lead to fault rupture (Foulger et al. 2018). Induced earthquakes often have shallow focal depths (~5 km in Oklahoma), which can lead to larger near-source ground motion intensity than would be estimated for similarly-sized tectonic events (Zalachoris and Rathje 2019).

Deep wastewater injection has led to a significant increase in seismicity in areas where oil and gas production and wastewater injection are prevalent such as Oklahoma, Kansas, and Texas. Although recent regulation enacted to limit wastewater injection volumes in Oklahoma has led to reductions in regional seismicity, over 300 M3+ earthquakes occurred in 2017, which is still 300 times the natural tectonic rate of about one M3+ earthquakes per year in the state (Oklahoma Office of the Secretary of Energy & Environment 2019; Langenbruch and Zoback 2016). This dramatic increase in seismicity is of particular concern because it is occurring primarily in historically aseismic areas where building codes and construction methods have not traditionally accounted for higher levels of seismicity. This means that infrastructure in these areas may be more susceptible to damage caused by ground shaking. Additionally, although the number of M3+ earthquakes has been decreasing since 2015, some of the largest events, including the 2016 M_w5.8 Pawnee, OK earthquake, have occurred since that time.

LIQUEFACTION DURING THE PAWNEE OKLAHOMA EARTHQUAKE

The epicenter of the 3 September 2016, M_w5.8 Pawnee, Oklahoma, earthquake, was located about 15 km northwest of Pawnee, OK. The event was the strongest recorded earthquake in Oklahoma history and is one of the largest recorded earthquakes in the CEUS in the last 70 years

(Tiwari and Rathje 2018). The U.S. Geological Survey (USGS) ShakeMap of a_{max} for the Pawnee event is shown in Figure 2 (USGS 2016a). Inferred a_{max} values were as high as 0.36g within 5 km of the earthquake epicenter, decreasing to less than 0.06g at a distance of approximately 40 km.

Post-earthquake reconnaissance conducted by Clayton et al. (2016) and Kolawole et al. (2017) identified four sites where liquefaction manifestations were observed, shown in Figure 2 as Sites 1 through 4. Site 1 lies along Black Bear Creek, a tributary of The Arkansas River, while Sites 2 through 4 are located within the floodway of the Arkansas River. Liquefaction manifestations observed included sand boils, cracking with sand ejecta, and possible lateral spreading. Examples of the liquefaction manifestations at each site are shown in Figure 3. Conversations with landowners in the affected areas indicated that there were additional sites where liquefaction was observed but not documented. While these additional sites are not included in the present study, they are evidence that liquefaction was more widespread than suggested by initial post-earthquake reconnaissance.

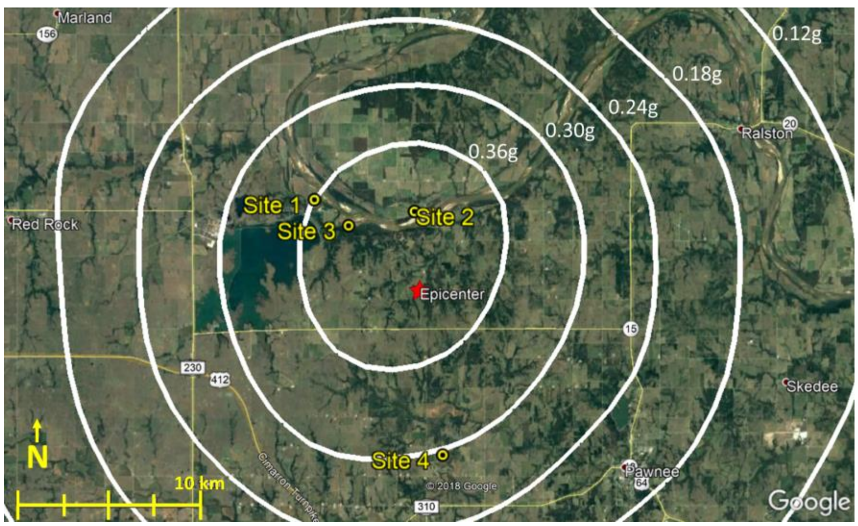


Figure 2. USGS ShakeMap for 2016 M_w5.8 Pawnee, OK earthquake showing contours of inferred peak ground acceleration. Liquefaction Sites 1,2, 3, and 4, identified by Clayton et al. (2016) and Kolawole et al. (2017), are also indicated.

SITE INVESTIGATION

The Pawnee earthquake provides an opportunity to determine the suitability of current variants of the simplified procedure for evaluating the regional liquefaction hazard caused by induced earthquakes in Oklahoma, Texas, and Kansas. To this end, a detailed site characterization campaign is being conducted to examine soil profiles at sites where liquefaction was and was not observed following the Pawnee earthquake. A preliminary site investigation was conducted in January 2019. The primary purpose of the preliminary investigation was to gather existing information on the liquefaction sites and accurately determine areas where liquefaction features were and were not observed at these sites in order to select locations for full site characterization.

USGS geologic maps for the four Pawnee liquefaction sites are shown in Figure 4 (Stanley and Chang 2016). All four sites are located in alluvial zones, which the USGS describes as consisting of sand, silt, clay, and gravel with maximum thicknesses along major streams ranging from 9 to 24 m and along minor streams ranging from 0 to 18 m (USGS 2019). Groundwater depth during the January 2019 site investigation was estimated at 1 m at Site 1, 2 m at Sites 2 and 4, and 1 to 2 m at Site 3 based on river/stream levels adjacent to the sites. Groundwater depths during the 2016 Pawnee event were estimated by comparing river gage heights during the earthquake with those during the January 2019 site investigation (USGS 2016b; c). Based on these comparisons, groundwater depth during the Pawnee earthquake was estimated at 2 m for Site 1, 2.5 m for Sites 2 and 4, and 1.5 to 2.5 m for Site 3. Shear wave velocity information was not available for any of the sites, but values of the time-weighted shear wave velocities of the upper 30 m of the profiles (V_{S30}) reported by Zalachoris et al. (2017) for alluvial sites within 35 km of the liquefaction sites ranged from 362 m/s to 580 m/s. For each of the Pawnee test sites, areas where liquefaction features were and were not observed were confirmed during the preliminary investigation using photos and anecdotal evidence provided during interviews with the property owners, as well as information from the Clayton et al. (2016) and Kolawole et al. (2017) reports.

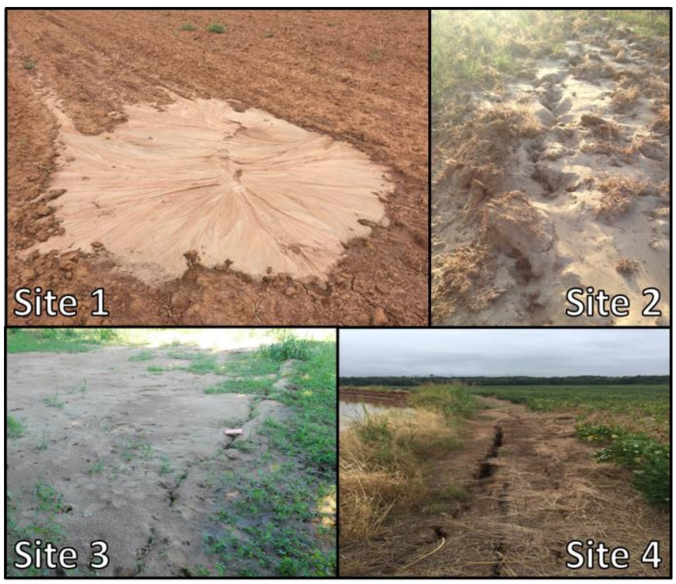


Figure 3. Photos of liquefaction taken following the 2016 Pawnee, OK earthquake (photos from Site 1, 2, and 4 courtesy Dan Ripley, Rick Rice, and Martin Williams, respectively; photo from Site 3 is from Kolawole et al. 2017).

A preliminary estimate of the liquefaction hazard at the test sites due to the Pawnee earthquake was made using the method presented by Baise and Rashidian (2018). This method estimates probability of liquefaction and liquefaction spatial extent (LSE), the percent of a given area covered by surface manifestations of liquefaction, based on peak ground velocity (PGV), V_{S30}, mean annual precipitation, closest distance to water, and water table depth. PGV was estimated based on the USGS ShakeMap (USGS 2016a), and precipitation data were taken from National Oceanic and Atmospheric Administration (NOAA) Station USC00346940 (NOAA 2019). Inputs and results for each site are shown in Table 1. As shown in the table, the predicted probability of liquefaction at the four sites based on geologic proxies is ~26%, corresponding to an LSE of ~2%. For Sites 2 and 4, 2% is generally a reasonable estimate based on the estimated extent of liquefaction observations at these sites; however, it may be low for Sites 1 and 3 where liquefaction was more extensive. Similar estimates of probability of liquefaction and LSE would be expected for similar, nearby sites along the Arkansas River and Black Bear Creek depending on site-specific soil conditions. This agrees with observations made by local landowners that liquefaction occurred at other sites in the area, aside from those formally documented in Clayton et al. (2016) and Kolawole et al. (2017). Additionally, Clayton et al. (2016) noted that thick vegetation and low population density, made it difficult to determine the full extent of damages due to the Pawnee event. As a result, liquefaction may have occurred at nearby sites and gone unnoticed or unreported.

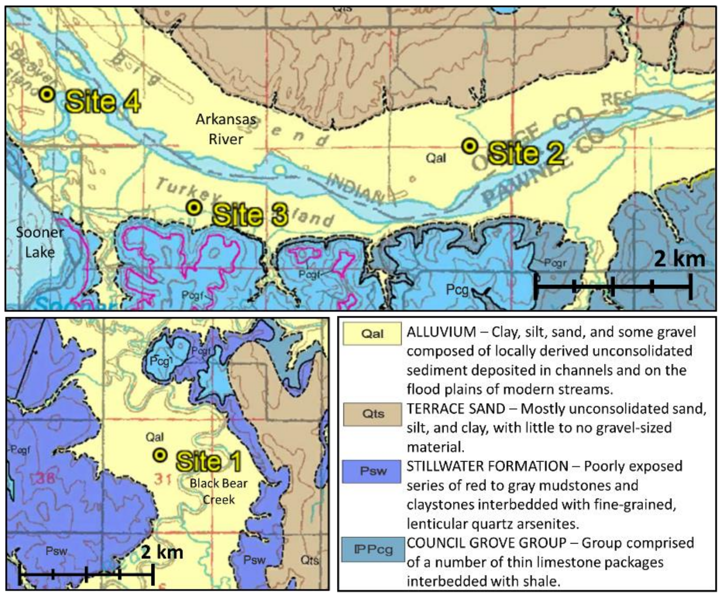


Figure 4. Geologic maps of Pawnee earthquake liquefaction sites (Stanley and Chang 2016).

Table 1. Liquefaction Hazard Estimates based on Baise and Rashidian (2018)

Site	Peak Ground Velocity (cm/s)	V_{s30} (m/s)	Mean Annual Precipitation (mm)	Closest Distance to Water (km)	Water Table Depth (m)	Probability of Liquefaction	Liquefaction Spatial Extent (%)
1	20	360	1021	0.15	2	0.262	2.11
2	25	360	1021	0.3	2.5	0.268	2.28
3	20	360	1021	0.11	1.5	0.267	2.26
4	20	360	1021	0	2.5	0.265	2.20

In addition to general site reconnaissance, Horizontal to Vertical Spectral Ratio (HVSR) tests were conducted at each site as part of the preliminary site investigation. HVSR test results will be used to constrain the small-strain shear wave velocity (V_S) models determined from subsequent Multichannel Analysis of Shear Wave (MASW) data inversions (Yust et al. 2018). The MASW and HVSR data will provide insights into the site response characteristics of the soil profiles, which in turn will provide insights into the appropriateness of existing r_d and MSF relationships for evaluating liquefaction triggering. HVSR tests were conducted following the guidelines provided by the SESAME project (Bard 2004) using ambient vibrations recorded at each site using a three-component broadband seismometer.

HVSR analysis was performed using the Geopsy software package. An example plot showing the results for Site 2 is shown in Figure 5 with the peak frequency of the average H/V curve plus or minus one standard deviation highlighted. The peak frequency corresponds to the fundamental frequency of the site. The fundamental frequency at the three sites (Sites 2, 3, and

4) along the Arkansas River was approximately 3 Hz, while it was 0.86 Hz at Site 1, located along Black Bear Creek. This may be an indication of differences in alluvium thickness along the Arkansas River versus along Black Bear Creek, where a shallower depth to bedrock would lead to a stiffer site and higher fundamental frequency and vice-versa.

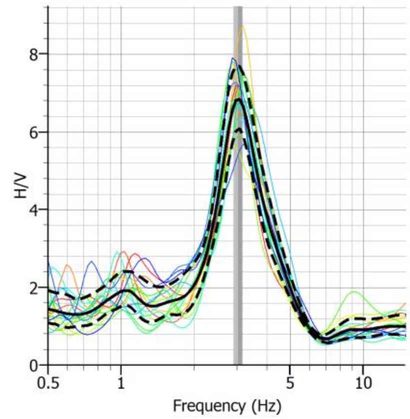


Figure 5. HVSR results for the Site 2. Peak frequency +/- one standard deviation is shown.

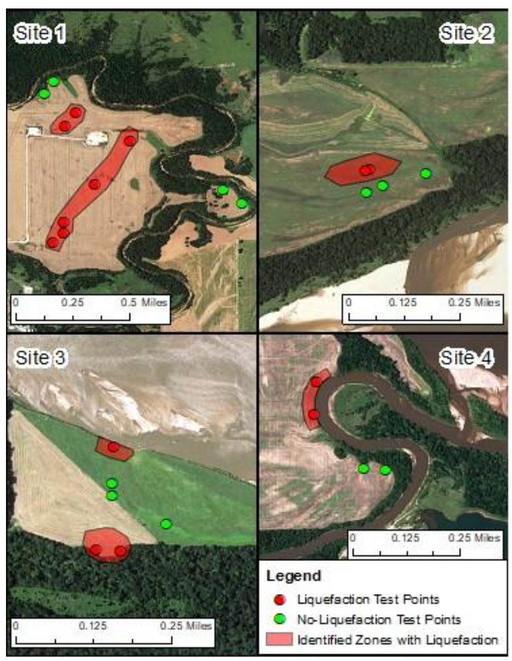


Figure 6. Identified liquefaction areas and proposed test locations for future testing.

PLANNED FUTURE TESTING

Future testing planned for Fall 2019 will involve detailed characterization of sites identified during the preliminary investigation. Testing will include Cone Penetration Tests (CPT), MASW tests, and hand auger sampling. CPT test results will be used to characterize the soil profile and evaluate the liquefaction potential of each test location using current CPT-based variants of the simplified liquefaction evaluation procedure (e.g., Green et al. 2019a; b). MASW tests, as well as seismic soundings performed with the CPT, will be used to develop shear wave velocity profiles for each site for use in numerical site response models. Both liquefaction and no-liquefaction test locations have been selected for testing. Liquefaction test locations were selected based on the liquefaction areas identified during the preliminary site investigation. No-liquefaction test locations were selected at the same sites, so as to be near the liquefaction test locations and in areas where conditions were likely favorable for liquefaction (e.g., low elevation areas, inside river bends) but where liquefaction manifestations were not observed during the Pawnee event. The selected test locations are shown in Figure 6. Predictions of liquefaction potential made for each test location using current variants of the simplified liquefaction evaluation procedure will be compared to actual observations of liquefaction to evaluate the effectiveness of these methods for predicting liquefaction potential due to induced earthquakes.

CONCLUSION

Induced seismicity resulting from oil and gas production wastewater injection has led to over a thousand M_w>3 earthquakes in Oklahoma over the last ten years, including four M_w>5 earthquakes (Oklahoma Office of the Secretary of Energy & Environment 2019). The M_w5.8 2016 Pawnee, OK earthquake was the first induced seismic event worldwide, that the authors are aware of, where liquefaction has been observed and documented. The liquefaction observed during the Pawnee earthquake occurred in a rural area and did not significantly impact infrastructure; however, it raises concerns regarding damages that may occur if future induced events led to liquefaction in more vulnerable areas.

Given the potential differences in the characteristics of shaking of induced versus tectonic earthquakes (e.g., Bommer et al. 2016; Zalachoris and Rathje 2019) and potential regional differences in soil profiles, it is uncertain whether existing variants of the semi-empirical simplified liquefaction evaluation procedure for tectonic earthquakes can be used to accurately assess the liquefaction hazard of the region. Determining the suitability of current variants of the simplified procedure for evaluating the regional liquefaction hazard caused by induced earthquakes is part of an ongoing study, which includes a detailed site characterization campaign to examine profiles where effects of liquefaction were and were not observed following the Pawnee event.

Preliminary investigations have been conducted at four sites where liquefaction was observed during the Pawnee earthquake to gather existing information on the sites and accurately determine areas where liquefaction features were and were not observed. Geologic and hydrologic data were used to estimate probability of liquefaction and the spatial extent of liquefaction at each site during the Pawnee event based on Baise and Rashidian (2018). Estimates of liquefaction spatial extent appear reasonable for Sites 2 and 4 but may be low for Sites 1 and 3 where liquefaction was more extensive. HVSR tests were also conducted using ambient vibrations recorded at each site.

Further testing at the identified sites, including CPT and MASW tests, is planned for later this year (2019). Data from the full site investigation will be used to determine liquefaction potential of the selected sites based on current variants of the simplified procedure. Results will be compared with field observations of liquefaction to evaluate the effectiveness of these methods for determining liquefaction potential of induced earthquakes.

ACKNOWLEDGEMENTS

This study is based on work supported in part by the USGS grant G18AP00094 and U.S. National Science Foundation (NSF) grants CMMI-1030564, CMMI-1435494, CMMI-1724575, and CMMI-1825189. The authors gratefully acknowledge this support. However, any opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the USGS or NSF. The authors also acknowledge and thank Dr. Clint Wood from the University of Arkansas for the use of his HVSR equipment and Dr. Brett Maurer from the University of Washington for his review of this paper.

REFERENCES

Baise, L.G., and Rashidian, V. (2018). "A Geospatial Approach to Liquefaction Assessment for Rapid Response and Loss Estimation." *Geotechnical Earthquake Engineering and Soil Dynamics V*, GSP 291, ASCE, VA, 1–10.

Bard, P. (2004). "Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: Measurements, processing and interpretation." SESAME European Research Project, WP12—Deliverable D23.12, 1–62.

Bommer, J. J., Dost, B., Edwards, B., Stafford, P. J., van Elk, J., Doornhof, D., and Ntinalexis, M. (2016). "Developing an application-specific ground-motion model for induced seismicity." *Bulletin of the Seismological Society of America*, 106(1), 158–173.

Clayton, P., Zalachoris, G., Rathje, E., Bheemasetti, T., Caballero, S., Yu, X., and Bennett, S. (2016). "The geotechnical aspects of the September 3, 2016 M5.8 Pawnee, Oklahoma earthquake." Geotechnical Extreme Events Reconnaissance Association, <http://www.geerassociation.org/> (Sep. 15, 2019).

Ellsworth, W. L. (2013). "Injection-induced earthquakes." *Science*, 341(6142), 1–8.

Foulger, G. R., Wilson, M. P., Gluyas, J. G., Julian, B. R., and Davies, R. J. (2018). "Global review of human-induced earthquakes." *Earth-Science Reviews*, 178, 438–514.

Green, R.A., Bommer, J.J., Rodriguez-Marek, A., Maurer, B., Stafford, P., Edwards, B., Kruiver, P.P., de Lange, G., and van Elk, J. (2019a). "Addressing Limitations in Existing 'Simplified' Liquefaction Triggering Evaluation Procedures: Application to Induced Seismicity in the Groningen Gas Field." *Bulletin of Earthquake Engineering*, 17, 4539–4557.

Green, R.A., Bommer, J.J., Stafford, P.J., Maurer, B.W., Kruiver, P.P., Edwards, B., Rodriguez-Marek, A., de Lange, G., Oates, S.J., Storck, T., Omidi, P., Bourne, S.J., and van Elk, J. (2019b). "Liquefaction Hazard of the Groningen Region of the Netherlands due to Induced Seismicity." *Journal of Geotechnical and Geoenvironmental Engineering*, (*in review*).

Kolawole, F., Atekwana, E. A., and Ismail, A. (2017). "Near-surface electrical resistivity investigation of coseismic liquefaction-induced ground deformation associated with the 2016 M_w 5.8 Pawnee, Oklahoma, earthquake." *Seismological Research Letters*, 88(4), 1017–1023.

McGarr, A., Simpson, D., and Seeber, L. (2002). "Case histories of induced and triggered seismicity." *International Geophysics*, 81(A), 647–661.

Mitchell, J. K., and Green, R. A. (2017). "Some induced seismicity considerations in geo-energy resource development." *Geomechanics for Energy and the Environment*, 10, 3–11.

NOAA (2019). "Normals Annual/Seasonal Station Details: PAWNEE, OK US, GHCND:USC00346940." <https://www.ncdc.noaa.gov/cdo-web/datasets/normal_ann/stations/GHCND:USC00346940/detail> (Sep. 10, 2019).

Oklahoma Office of the Secretary of Energy & Environment. (2019). "Earthquakes in Oklahoma: What We Know." <https://earthquakes.ok.gov/what-we-know/> (Jun. 20, 2019).

Seed, H. B., and Idriss, I. M. (1971). "Simplified procedure for evaluating soil liquefaction potential." *Journal of the Soil Mechanics and Foundations Division*, 97(9), 1249–1273.

Stanley, T. M., and Chang, J. M. (2016). Geologic Map of the Keystone Lake 30x60-Minute Quadrangle, Creek, Noble, Osage, Pawnee, Payne, Osage, Tulsa, and Washington Counties, Oklahoma: Oklahoma Geologic Survey OGQ-92, Oklahoma Geol. Surv., Norman, OK

Tiwari, A., and Rathje, E. M. (2018). "Engineering characteristics of earthquake motions from the Pawnee and Cushing Earthquakes in Oklahoma." *Geotechnical Earthquake Engineering and Soil Dynamics V*, GSP 291, ASCE, Reston, VA, 378–386.

USGS (2016a). "ShakeMap for M 5.8 – 14 km NW of Pawnee, Oklahoma." <https://earthquake.usgs.gov/earthquakes/eventpage/us10006jxs/executive> (Jun. 19, 2019).

USGS (2016b). "National Water Information System data available on the World Wide Web (USGS Water Data for the Nation): USGS 07153000 Black Bear Creek at Pawnee, OK." <https://waterdata.usgs.gov/nwis/uv?site_no=07153000> (Jul. 4, 2019).

USGS (2016c). "National Water Information System data available on the World Wide Web (USGS Water Data for the Nation): USGS 07152500 Arkansas River at Ralston, OK." <https://waterdata.usgs.gov/ok/nwis/uv/?site_no=07152500&PARAmeter_cd=00065,00060> (Jul. 4, 2019).

USGS (2019). "Oklahoma Alluvium." <https://mrdata.usgs.gov/geology/state/sgmc-unit.php?unit=OKQal%3B0> (Jul. 2, 2019).

Whitman, R. V. (1971). "Resistance of Soil to Liquefaction and Settlement." *Soils and Foundations*, 11(4), 59–68.

Yust, M. B. S., Cox, B. R., and Cheng, T. (2018). "Epistemic Uncertainty in Vs Profiles and Vs30 Values Derived from Joint Consideration of Surface Wave and H/V Data at the FW07 TexNet Station." *Geotechnical Earthquake Engineering and Soil Dynamics V*, GSP 291, ASCE, Reston, VA, 387–399.

Zalachoris, G., Rathje, E. M., and Paine, J. G. (2017). "V_{S30} characterization of Texas, Oklahoma, and Kansas using the p-wave seismogram method." *Earthquake Spectra*, 33(3), 943–961.

Zalachoris, G., and Rathje, E. M. (2019). "Ground Motion Model for Small-to-Moderate Earthquakes in Texas, Oklahoma, and Kansas." *Earthquake Spectra*, 35(1), 1–20.