The Geotechnical Aspects of the September 3, 2016 M5.8 Pawnee, Oklahoma Earthquake

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Introduction

The Pawnee, Oklahoma earthquake occurred on 3rd of September 2016 at 12:02 PM UTC time. The epicenter, as reported by the USGS, was located 15 km northwest (Latitude: 36.4298°, Longitude: -96.9317°) of the town of Pawnee, Oklahoma. The reported magnitude is M5.8, and the focal depth is listed as 5.6 km (USGS), which is typical of stable continental earthquakes. The earthquake occurred along shallow strike-slip faulting within the interior of the North America plate, far from any plate boundaries. Figure 1 illustrates the shake map for Peak Ground Acceleration (PGA), produced by USGS for this event. The inferred PGA values range from 36 % of gravity within a radius of few kilometers from the earthquake epicenter, to less than 6 % of gravity at distances greater than 40 km.

Prior to this earthquake, two events larger than M5 had occurred in Oklahoma within the last 5 years: the November 5, 2011 M5.7 earthquake in Prague, Oklahoma, and the February 13, 2016 M5.1 earthquake in Fairview, Oklahoma. Both earthquakes caused very light to light damage. Similarly, the M5.8 Pawnee, Oklahoma earthquake, generally, resulted in light damage, primarily to non-structural elements of structures in the town of Pawnee and the area surrounding the earthquake epicenter. Only one injury from a collapsing chimney was reported.

Within the framework of the NSF-funded Geotechnical Extreme Events Reconnaissance (GEER) association, a five-membered team was mobilized to the area on 7th and 8th of September 2016. The objective of this reconnaissance effort was to collect and document information regarding earthquake effects from small-to-moderate magnitude events in regions that have recently been experiencing an increase in seismicity rates, such as North Texas, Oklahoma, and Kansas (Petersen et al., 2016). Better documentation of the earthquake effects from such events can lead to improved procedures for evaluation and mitigation of seismic risk in affected areas. The dispatched team was comprised of experts both in geotechnical and structural engineering and was primarily focused on identifying damage patterns in dams/levees, embankments, and along the river banks, as well as evaluating the performance of key bridges in the region.

The aforementioned GEER team visited a large area (highlighted in red in Figure 1) within a radius of 15-40 km from the earthquake epicenter, with a particular focus given on the areas in the vicinity of the epicenter and along the river banks (Figure 2). A Google Earth KMZ file with a summary of sites visited and geotagged, captioned photos is provided on the GEER website alongside this report. The geology of the area is generally characterized by Permian sedimentary rocks (primarily shale, but also sandstone and limestone). Substantial alluvial and terrace deposits along the Arkansas River banks are present (Figure 2). With the exception of the river banks, most of the area is covered by residual clay soil of varying thickness. Sporadic bedrock outcrops were observed in various locations, which possibly indicates that the depth to bedrock, despite varying, is generally small. Such observations may be the explanation for the absence of substantial site amplification effects, as will be described later in this report. Figure 3 shows photographs of rock outcrops (shale in Figure 3a, sandstone in Figure 3b), as well as photographs of residual clayey

soil (Figure 3c) and alluvial sand deposits (Figure 3d), typically encountered throughout the area, and along the river banks, respectively. At this point, it should be stated that, during the time of the GEER team visit, the vegetation throughout the area was particularly thick; this fact, along with the light damage caused by the September 3rd earthquake and the low population density, made identification of damage patterns along the river banks and on earth dam/levee slopes particularly difficult.

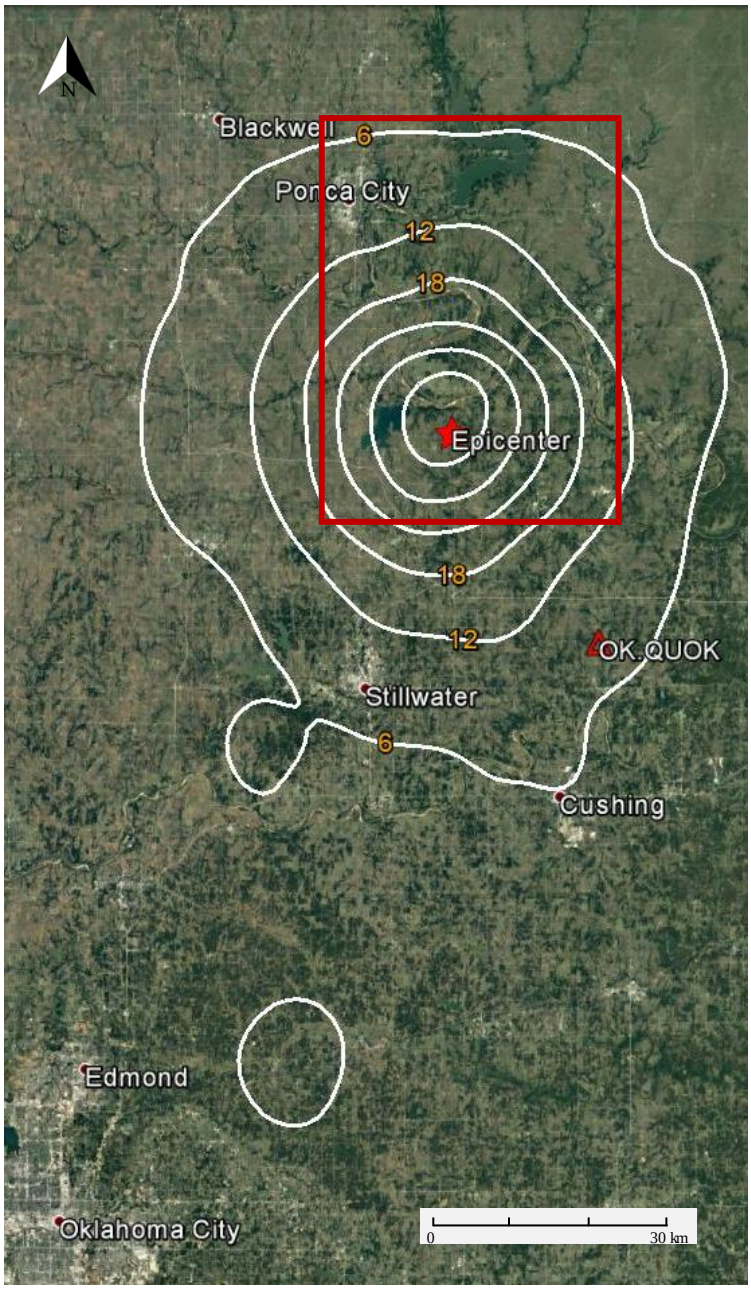

Figure 1: Shake map produced by the United States Geological Survey (USGS), for the M5.8 September 3, 2016 Pawnee, Oklahoma earthquake, showing contours of Peak Ground Acceleration (PGA, in %g). The red box outlines the area visited by the GEER team (shown in detail in Figure 2). Seismic recording station OK.QUOK is also shown.

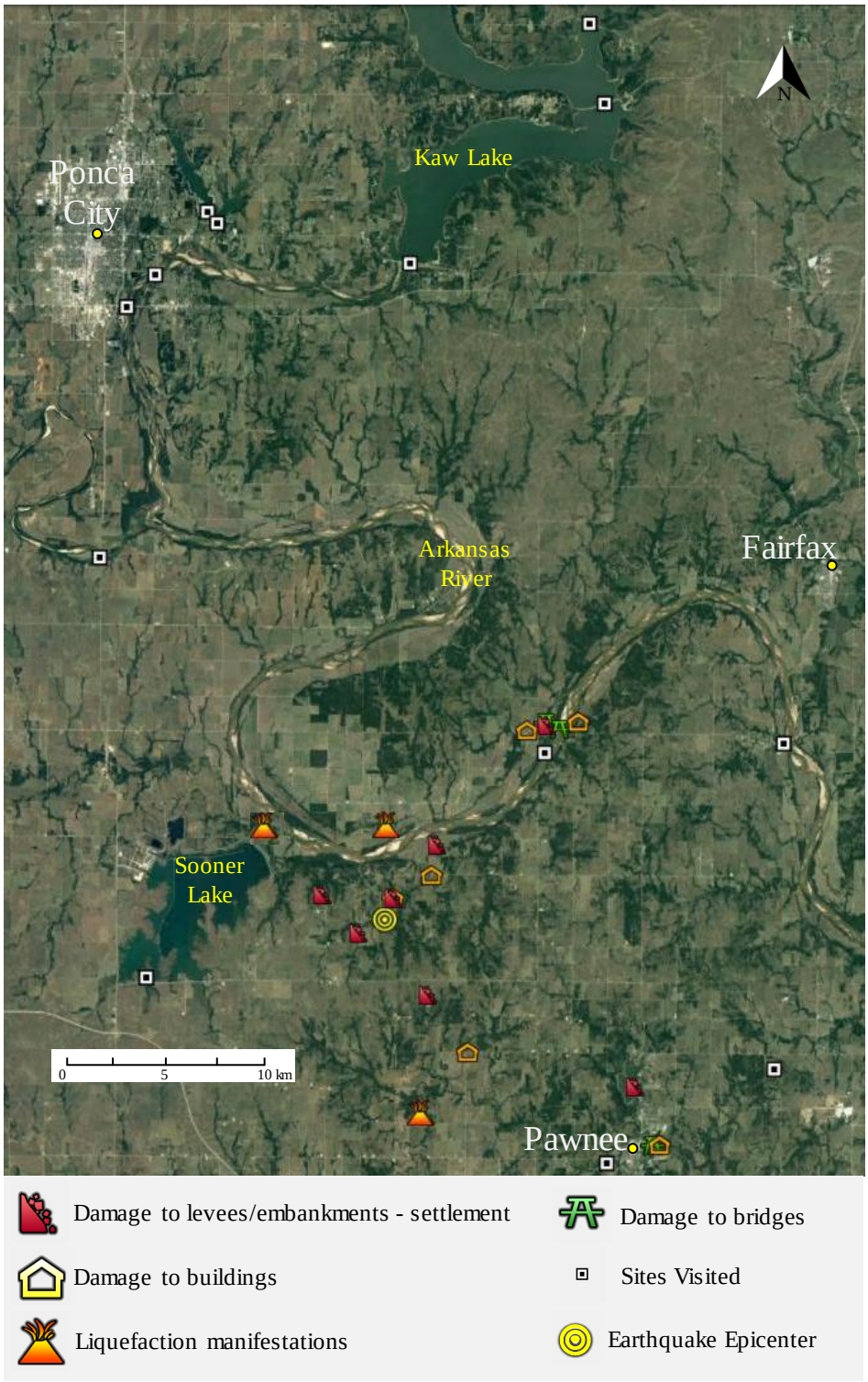

Figure 2: Regional map showing the area visited by the GEER team and locations of various earthquake effects

Figure 3: Photographs of typical geologic features across the visited area. Latitude/Longitude: a) (36.403393°, -97.050589°), b) (36.370872°, -96.728596°), c) (36.505261°, -96.723785°), d) (36.433255°, -96.926117°)

Ground Motions

Several seismic recording stations are located within a hypocentral distance (R_{hyp}) of 100 km of the earthquake epicenter. These seismic stations are part of several seismic networks, either at a state, federal, or global level (i.e., Oklahoma Seismic Network – OK; USGS Networks – GS; Central and Eastern US Networks – N4; NetQuakes network – NQ). Ground motion data recorded at these stations were retrieved using tools available on the website of the Incorporated Research Institutions for Research, IRIS (https://www.iris.edu/hq/). The retrieved recordings were processed in a unifying manner. That is, instrument correction, DC removal, linear de-trending, 1% cosine tapering, acausal Butterworth filtering, and baseline correction were applied. Finally, any records with Signal-to-Noise Ratio (SNR) greater than 5 within the examined bandwidth were rejected.

Accordingly, in total, 14 three-component recordings were obtained. V_{S30} values were assigned to 10 out of the 14 seismic stations, based on the V_{S30} proxy estimates developed by Parker et al. (2016) and Zalachoris et al. (2016), for the specific seismic station locations. Acceleration response spectra of the two horizontal components of motion (East-West and North-South) were computed for the 10 sites with assigned V_{S30} values (Figure 4). No notable differentiation in the

response of the two components of motion can be observed. Figure 5 shows the acceleration time histories of the seismic station (OK.QUOK) located closest to the epicenter of the September 3, 2016 earthquake; approximately 35.5 km in the south-east direction (Latitude/Longitude: (36.1714°, -96.708°)) (Figure 1).

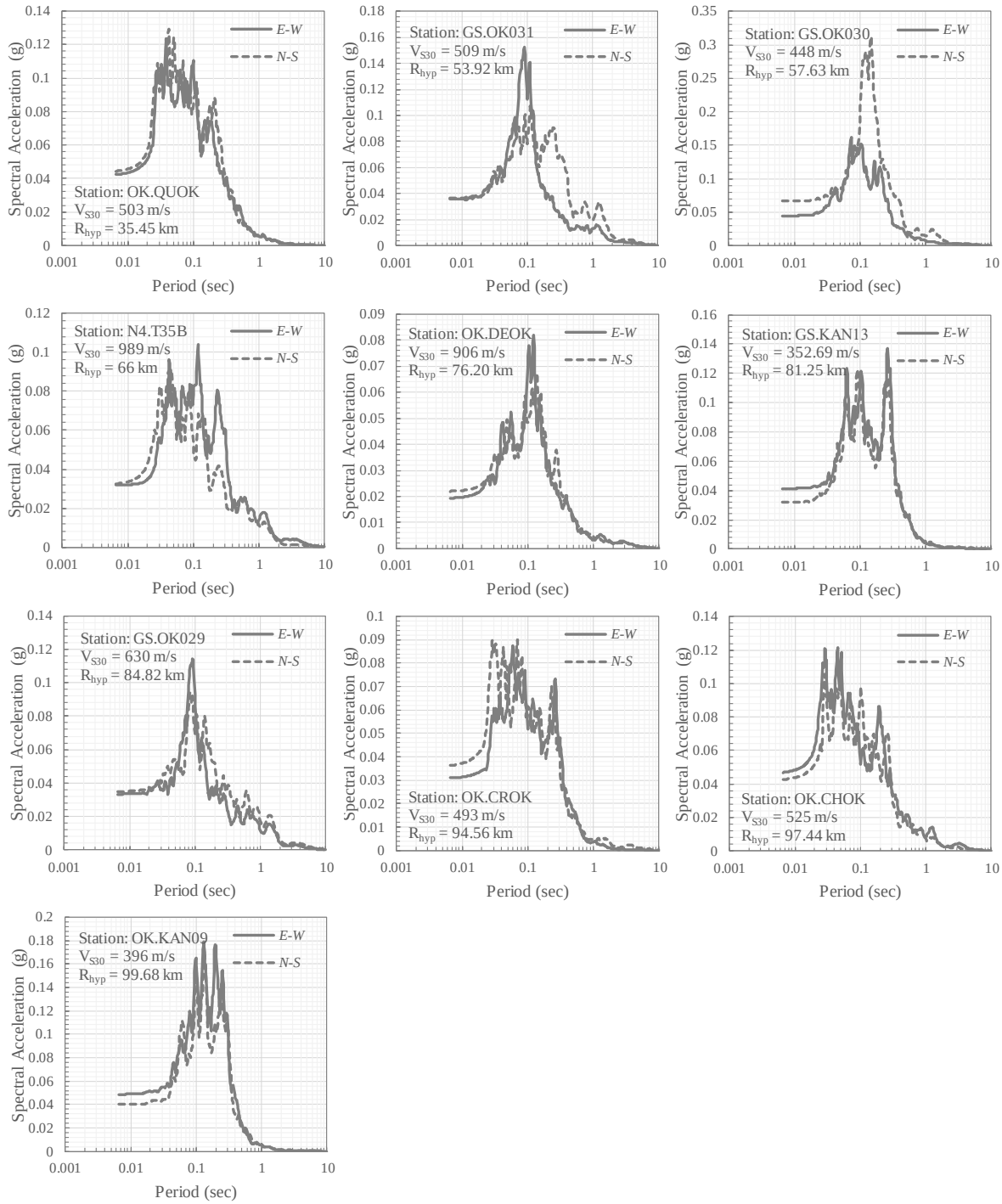

Figure 4: Acceleration response spectra for motions recorded at seismic stations within a hypocentral distance (R_{hyp}) of 100 km from the earthquake epicenter

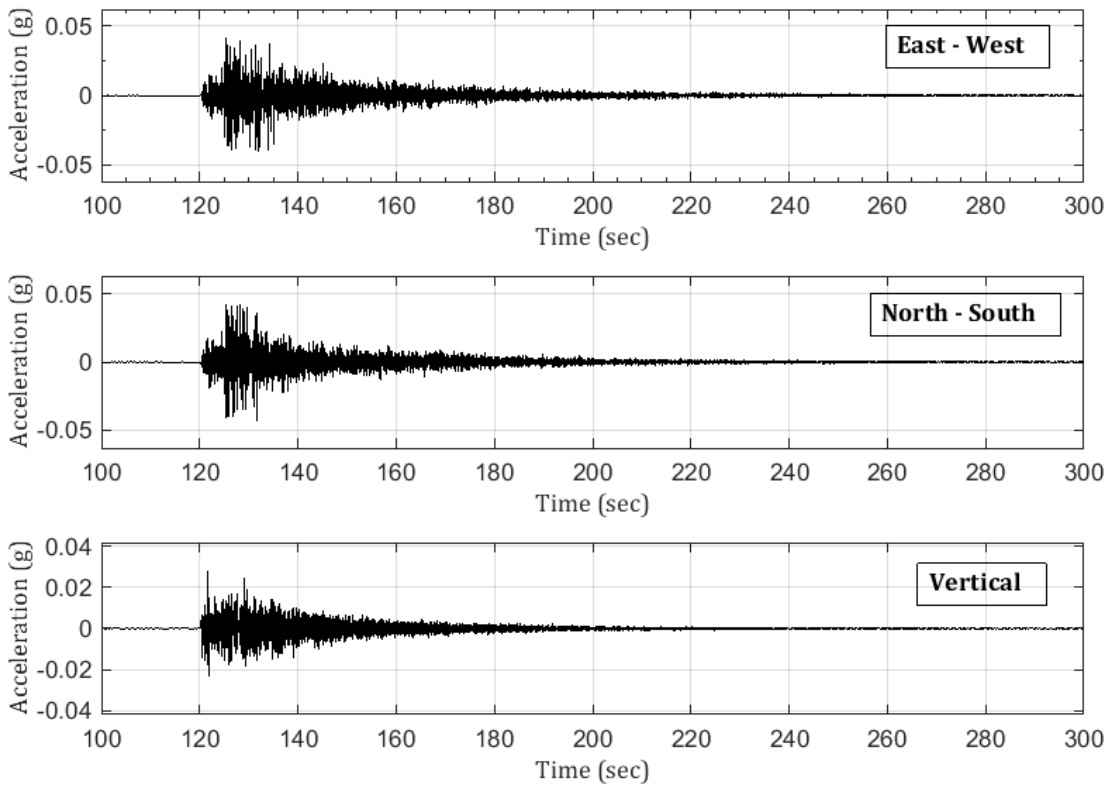

Figure 5: Acceleration time histories recorded at OK.QUOK (Latitude/Longitude: (36.1714°, -96.708°))

Earthen Dam/Levee Performance

The GEER team visited several earthen dam/levees across the area (Figure 2). In general, the performance of the dams/levees was deemed to be satisfactory. In most cases, no damage was observed. Nonetheless, in two cases (Pawnee Lake Dam and a watering pond dam north-west of the earthquake epicenter), cracks along the downstream slope of the dams were observed. These cracks seemed to have been formed recently, but they cannot be attributed to the September 3rd earthquake with absolute certainty.

Figure 6 shows photographs of the cracks observed at the Pawnee Lake dam (Figures 6a and 6b) and the watering pond dam (Figures 6c and 6d). The Pawnee Lake dam is an earthen (sand and gravel) dam along the south side of the Pawnee Lake, which is located just north of the town of Pawnee. A concrete spillway lies at the east side of the dam. Despite the abundance of vegetation along the slopes, and thus the associated difficulty to make observations, a crack on the downstream slope (south side) was visible (Figure 6a). The crack ran approximately one-third of the length of the levee (~50 m) and was roughly 10-20 cm wide. No damage to the concrete spillway was observed. A similar crack was observed at a small earthen dam (sand and gravel) for a cattle watering pond, located on a property north-west of the earthquake epicenter (Figure 6c). The crack ran longitudinally along the downstream (or “dry”) slope of the dam. The crack was approximately 15-20 m long and 1-2 cm wide.

Figure 6: Photographs of observed damage on levees/dams: a) Pawnee Lake dam (Latitude: 36.358459°, Longitude: -96.803296°), b) Pawnee Lake dam (Latitude: 36.358647°, Longitude: -96.803036°), c) Watering pond dam (Latitude: 36.436149 °, Longitude: -96.963198 °), d) Watering pond dam (Latitude: 36.436185°, Longitude: -96.963083°)

The GEER team also visited several levees/dams in the area (Figure 2) which showed no evidence of damage due to the September 3rd earthquake. These levees/dams were the following:

- Sooner Lake southern levees (Latitude/Longitude: (36.4042°, -97.0522°), (36.4044°, -97.0395°), (36.4049, -97.0256°))
- Sooner Lake dam (Latitude/Longitude: (36.4585°, -96.9939°)). It should be noted that Sooner Lake dam is a private property of Oklahoma Gas & Electric (OG&E) company. The GEER team was not able to gain access to the Sooner Lake dam. It was communicated to our team by OG&E personnel that the dam was already inspected and no damage was observed.
- Ponca Lake levee (Latitude/Longitude: (36.7150°, -97.0187°))
- Kaw Lake dam (Latitude/Longitude: (36.6991°, -96.9199°))

Liquefaction Manifestations & Ground Settlement

As inferred by the geological setting of the area (primarily shale and residual clayey soils), liquefaction susceptibility is generally considered to be low. Nonetheless, liquefiable Quaternary alluvial sediments are present along the Arkansas River and its major streams. These sediments consist of coarse to fine sand and silty sand, loosely to medium densely deposited. Further inland, and within a short distance (500 m to 1,000 m) from the river, soil deposits primarily consist of clayey soils, often tilled, overlying sand layers previously deposited by the Arkansas River and its major streams. Despite the fact that the aforementioned sand layers are generally liquefiable, the moderate level of shaking during the September 3rd event and the limited the number of cycles of loading minimized the zones that experienced liquefaction. Furthermore, as mentioned above, at the time of the GEER team visit, the vegetation across the area was thick, making the identification of possible liquefaction and ground settlement manifestations, a non-trivial issue. While the GEER team was not able to locate any sites where soil liquefaction was observed, others provided information on soil liquefaction manifestations as described below.

The days/weeks after the September 3rd earthquake, separate teams, comprised by experts from the United States Geological Survey (USGS), the Oklahoma Geological Survey (OGS), the Oklahoma State University (OSU), and the University of Oklahoma (UO), were also dispatched in the area. Based on information acquired from the local community after the September 7th-8th GEER visit as well as based on correspondence with the aforementioned teams of experts (Robert Williams from USGS; Prof. Todd Halihan from OSU; Jefferson Chang from UO), we were able to identify two locations with liquefaction manifestations (Figures 7 and 8), and a third site with indications of either lateral spreading or slump failure (Figure 9). The first site was located 3.8 km north of the earthquake epicenter (Figure 2), on a private property just north of the Arkansas River (Figure 7). The second site was located approximately 9.4 km south-east of the earthquake epicenter (Figure 2), again on a private property (Figure 8). Both sites consisted of tilled clay layers overlying sand river deposits. The observed failure included cracking accompanied with sand boils. Based on the formation of sand blows, and the relatively close proximity to the river banks (< 300 m), the team attributed these failures to liquefaction. Liquefaction likely occurred within the loose to medium dense sands underlying the clay cover. Moreover, at a third site, approximately 7 km northwest of the earthquake epicenter, cracking subparallel to the river bank, along a branch of the Arkansas River, was observed (Figure 9). This observation could be caused by liquefaction induced lateral spreading or a simple slump failure of the river bank, something that could not be determined with certainty based on our communication with the property owner.

Finally, another ground-related failure was observed at a residential property located approximately 4 km south-east of the earthquake epicenter (Figure 10). The single family house is built on a small slope of approximately 1.5 m high with the first floor against the slope on the back. The site, which consisted primarily of a clayey soil layer of approximately 1 m underlain by lime stone bedrock on a mild slope (~5-8%), experienced ground displacement. It was communicated to us by the property owner that the site was experiencing slump failure before the earthquake,

which was exacerbated by the ground motion. Lateral cracks were identified along the slope on which a residential building is built (Figure 10b). As a result of the slump failure along the slope, the porch of the residency settled by approximately 4 cm (Figure 10a), and cracks were observed on the foundation slab of the garage.

Figure 7: Cracking and sand blow and ejecta located 3.8 km north of earthquake epicenter, just north of Arkansas River (approx. Latitude/Longitude: (36.4640°, -96.9307°)) (photo by Rick Rice – property owner)

Figure 8: Cracking and sand blow and ejecta located 9.4 km south-east of earthquake epicenter, (approx. Latitude/Longitude: (36.3466°, -96.9307°)) (photo provided by Prof. Todd Halihan – OSU)

Figure 9: Cracking and lateral spreading along river branch (approx. Latitude/Longitude: (36.4701°, -96.9926°)) (photo by Martin Williams – property owner)

Figure 10: Observations at residential building 4 km south-east of earthquake epicenter (Latitude/Longitude: (36.395482°, -96.909038°)); a) Porch settlement, and b) slope failure on the back of the property

Building Performance

The GEER team visited several building sites (Figure 2), including single-family homes in the rural area around the epicenter and low-rise, historical buildings providing governmental or community services in and around the town of Pawnee, Oklahoma. In general, the buildings in the Pawnee area performed well, typically only having nonstructural damage, if any. The most common observations of damage included façade failure (Figure 11), chimney collapse or partial collapse (Figure 12), and cracking of interior plaster and/or drywall finishes (Figure 13). There were no observations or reports of damage to suspended tile ceilings in the area. Local residents also indicated that household contents such as dishware in kitchen cupboards and picture frames hanging on the walls had fallen to the floor during the event, much of which had been cleaned up by the time the GEER team visited. In one case, homeowners living approximately 12 km north-east of the epicenter stated that during the earthquake, a leak occurred in the pipe fittings on their hot water heater, causing localized flooding in their house.

It is worth noting that stone façades are common for residential buildings in the area. Several examples of stone façade collapse or partial collapse were observed. The façade in Figure 11a did have some metal strap anchors sporadically spaced at 1 to 3 m intervals; however, these anchors did not provide adequate bracing and remained attached to the structure after failure of the façade. In other observed instances of façade failure (e.g., Figure 11b), the stone façade was constructed as a free standing wall adjacent to the house, with no mechanical anchorage to the structure. Local residents indicated that this is a common construction practice in the area. One residence located approximately 2.5 km north-east of the epicenter had, according to the owner, a foundation built on clay and experienced widespread damage to the unanchored rock façade. The owner indicated that the neighboring home to the north, which is located on top of a hill and had a foundation on rock (according to the homeowner's observations during construction), had no observable damage to its brick façade. Despite the difference in façade construction between the two homes, this anecdotal observation may provide evidence of site effects, with more severe damage being observed to the house on the clay site.

Figure 11: Observations of rock façade failure: a) Latitude/Longitude: (36.5038°, -96. 8592°); b) Latitude/Longitude: (36. 3723°, -96. 883°)

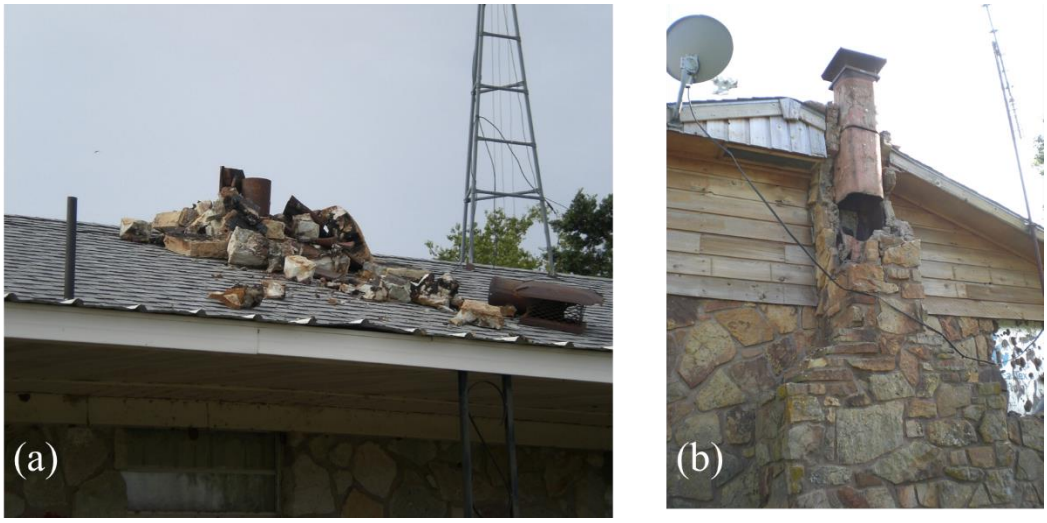

Figure 12: Observations of chimney failure: a) Latitude/Longitude: (36. 4350°, -96. 9269°); b) Latitude/Longitude: (36. 3723°, -96. 883°)

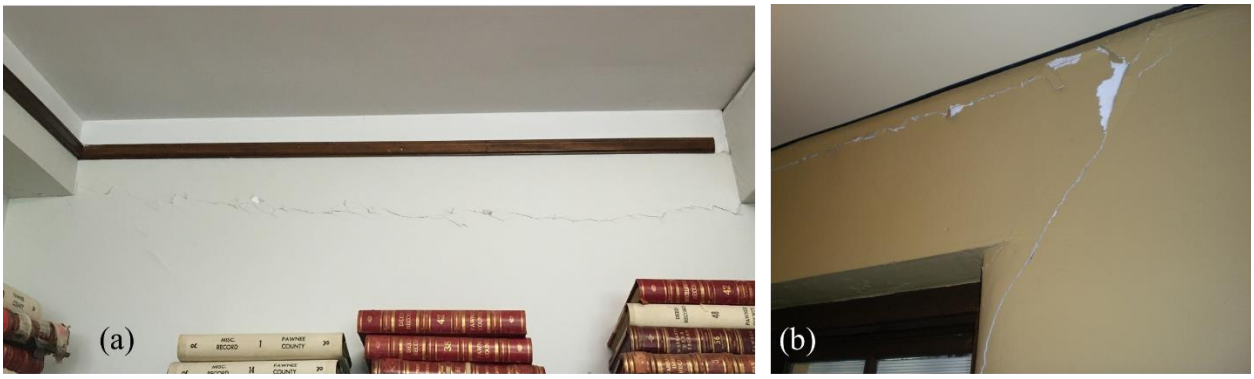

Figure 13: Observations of cracking of interior plaster finishes: a) in the historic Pawnee County Courthouse (Latitude/Longitude: (36. 3385°, -96. 8028°)) b) in a historic Pawnee Nation building (Latitude/Longitude: (36. 3347°, -96. 7904°))

Bridge Performance

The bridges in the area performed quite well during the earthquake, as reported by the Oklahoma DOT and as observed by the GEER team. Most of the bridges that the GEER team visited had no visible indications of damage from the September 3rd event. These bridges include:

- Ferguson Road on Kaw Lake (Latitude/Longitude: (36.7974°, -96.8291°))
- Oklahoma Hwy 11 on Kaw Lake (Latitude/Longitude: (36.7688°, -96.8207°))
- Bridge on Lake Ponca (Latitude/Longitude: (36.7197°, -97.0237°))
- Kelley Ave over Arkansas River (Latitude/Longitude: (36.6938°, -97.0502°))
- U.S. 60 over Arkansas River (Latitude/Longitude: (36.6805°, -97.0645°))
- U.S. 177 over Salt Fork Arkansas River (Latitude/Longitude: (36.5791°, -97.0774°))

- Oklahoma Hwy 18 over Arkansas River (Latitude/Longitude: (36.5050°, -96.7255°))
- Catlette Rd over Black Bear Creek, maintained by the Pawnee Nation (Latitude/Longitude: (36.3334°, -96.7937°)) Note that some minor cracking approx. 8 to 9 m long was observed in a sidewalk on the approach slab that the owner indicated had occurred during the September 3rd event. However, no damage was observed in the bridge structure.

Only one bridge that the GEER team visited was observed to have relatively minor damage. This bridge was and old (ca. 1927) steel truss bridge, locally known as the "Belford Bridge," that crossed the Arkansas River (Latitude/Longitude: (36.5039°, -96.8441°)). Some spalling of cover concrete was observed on top of the abutments (Figures 14a and b), which may be attributed to pounding between the bridge deck and abutment. There was also evidence of gapping between the backfill soil and the abutment backwall as shown in Figure 14c. Cracks of approximately 1 to 2 cm in width were also observed in the soil beneath the bridge at both abutments. The cracks were parallel to the abutments and were approximately 1.3 m from the abutment walls as shown in Figure 15.

The west abutment has steel plate bearings supporting the simply-supported steel girder approach spans, while the east abutment has steel pin bearings supporting the pony-truss approach span. The condition of the bearings at both abutments were consistent with the age of the bridge and expected weathering. In general, due to the age of the bridge, it was difficult to tell what, if any, of the bearing condition was affected by the earthquake.

Figure 14: Observations of damage at the West Abutment of Belford Bridge (Latitude/Longitude: (36.505°, -96. 8493°)): a,b) concrete spalling of abutment; c) approx. 4 cm wide gap between backfill soil and abutment

Figure 15: Observations of soil cracking at the East Abutment of Belford Bridge (Latitude/Longitude: (36.5032°, -96. 8424°))

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