DEVELOPMENT OF ABC COURSE MODULE – THE RISK DUE TO INDUCED EARTHQUAKES AND ACCELERATED SOLUTIONS

Quarterly Progress Report
For the period ending August 31, 2019

Submitted by:
P. S. Harvey Jr. (PI)
K. K. Muraleetharan (Co-PI)
S. Sivakumaran (Graduate Student)

Affiliation: School of Civil Engineering and Environmental Science
University of Oklahoma
Norman, OK

ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

Submitted to:
ABC-UTC
Florida International University
Miami, FL

1 Background and Introduction

Since 2009, there has been a dramatic increase in the number of earthquakes in the central U.S. (Fig. 1) (USGS, 2017). States such as Oklahoma, Kansas, Arkansas, and Texas have not historically experienced earthquakes at the rate currently observed, nor of this magnitude (McGarr et al., 2015). Studies such as by Keranen et al. (2013) have linked the increased rate of seismic activity since 2009 to wastewater injection in disposal wells. These induced earthquakes are not limited to the U.S., but are also experienced in other countries including Canada, China, and the United Kingdom (McGarr et al., 2015). The seismicity of places such as California and the New Madrid seismic zone is well documented and generally thought of when discussing seismic hazards in the contiguous U.S. Yet the cumulative moment in Oklahoma in 2015 and 2016 (1 January 2015 to 31 December 2016) exceeded that of southern California and the New Madrid seismic zones.

The major fault in the central U.S. is the New Madrid fault (Frankel et al., 2009) located along the Mississippi River between Tennessee, Arkansas, Missouri, and Kentucky. The only other identified source of tectonic earthquakes in this region is the Meer's fault in southwest Oklahoma, as reflected in the U.S. Geological Survey (USGS) national seismic hazard maps (Petersen et al., 2014) and accordingly the mapped design ground motion data provided by design provisions, such as the *2009 AASHTO Guide Specifications for LRFD Seismic Bridge Design* (AASHTO, 2009). In 2016, the USGS made an effort to incorporate non-tectonic earthquakes (or "induced seismicity") into the national seismic hazard model (Petersen et al., 2016), but these are not reflected in seismic design provisions. Accordingly, concern has risen about how civil infrastructure in the central U.S. will handle the increased seismic demand.

A majority of the earthquakes occurring in the central U.S. are small-to-moderate in magnitude, ranging from magnitude (M) 3.0 to 5.0. Over the last decade, the central U.S. has experienced nearly 120 M4.0 and greater earthquakes, with a majority (81) occurring in Oklahoma. At 12:02:44 Coordinated Universal Time (UTC) on 3 September 2016, a M5.8 earthquake struck 15 km northwest of Pawnee, Oklahoma. The event was triggered by strike-slip faulting within the interior of the North America plate (USGS, 2016a), at a focal depth of 5.6 km and is the largest

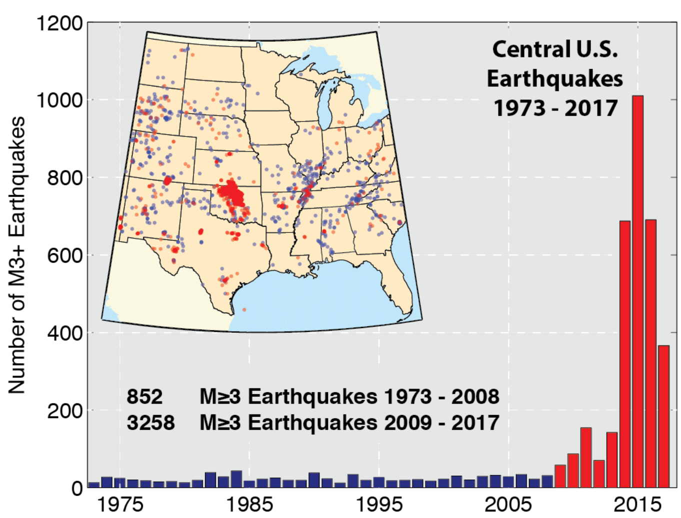

Figure 1: Cumulative number of earthquakes with a magnitude 3.0 or larger in the central United States (USGS, 2017).

recorded event in Oklahoma to date. Over the decade prior to this event, the central U.S. experienced two other events larger than M5.0: the 6 November 2011 M5.7 earthquake near Prague, Oklahoma (USGS, 2016b) and the 13 February 2016 M5.1 earthquake near Fairview, Oklahoma (USGS, 2016c). A fourth large event (M5.0) occurred on 7 November 2016 near Cushing, Oklahoma (USGS, 2016d). These M5.0 and larger events were felt in the surrounding states, caused damage to residential structures, and resulted in minor injuries (Taylor et al., 2017). Slight damage to highway bridges was also reported following the M5.8 Pawnee event, which included spalling of concrete on one bridge (GEER, 2016) and a roller bearing coming dislodged on another (W. L. Peters, *pers. comm.*, 20 October 2016).

While collapse is unlikely for the induced earthquakes currently observed, the cumulative effects of a large number of small earthquakes on bridges are not fully understood. These cumulative effects compounded with the occasional moderate earthquake (M5.0 and larger) may lead to damage requiring rapid repairs to avoid acute traffic control issues at the affected bridge sites. To reduce impacts to the driving public, *accelerated bridge construction* (ABC) techniques have been developed over recent years (Culmo, 2011), but have primarily focused on rapidly constructing new or replacement structures. Another benefit derived from these ABC methods is rapid post-earthquake repair of damaged structures, for example accelerated column repair/replacement with carbon fiber wrapping and steel casings. Post-earthquake accelerated column repair/replacement was identified as a high priority research need at a Federal Highway Administration (FHWA) workshop on seismic ABC (FHWA, 2007). While this workshop focused on moderate-to-high seismic zones, the need for additional analysis, new techniques, and associated specifications is also critical for low-to-moderate seismic zones affected by induced earthquakes.

2 Problem Statement

The recent surge in seismic activity in the central U.S. has motivated the need for rapid repair techniques that leverage ABC methods. The proposed continuing education course will provide the bridge community, especially bridge engineers in states impacted by induced seismicity, with the opportunity to learn about (a) the seismic demand due to induced earthquakes, (b) an approach to quantifying the cumulative seismic demand, (c) tools developed through this ABC-UTC project for quickly characterizing the potential impact from the determined cumulative seismic demand, and (d) a brief overview of available accelerated methods to repair/retrofit damaged bridges based on material type.

3 Research Approach and Method

The objective of the proposed web-based continuing education course is to provide the bridge community with the opportunity to learn how to estimate the cumulative seismic demand on bridges, both accelerated and conventional, due to a large number of small-to-moderate earthquakes and to educate engineers on the potential use of ABC repair/retrofit technologies. The course will provide training on the *ABC-UTC Guidelines for Assessing Effect of Frequent, Low-Level Seismic Events*. Also, a brief survey of available ABC repair techniques appropriate for cumulatively damaged bridges will be provided. The following section provides additional detail on the tasks that have been, and will be, performed to achieve the project objective.

4 Description of Research Project Tasks

The following is a description of tasks carried out to date. Note that these tasks are not consistent with those in the proposal, as FIU has dictated a different plan for developing the modules and their format since the project started.

4.1 Task 1 – Outline Course Content

Description: *Prepare an outline detailing the anticipated modules for the ABC course module.*

It is envisioned that the course will be developed in several modules of about 20 to 30 minutes presentation/lecture progressing from introduction and outline to various modules on specific topics. A tentative list of the topics/modules for this course is as follows:

- Module 1- Introduction and outline of the course
- Module 2- Induced seismicity
- Module 3- Fatigue analysis
- Module 4- Cycle counting
- Module 5- Fatigue damage index (FDI) framework w/ example
- Module 6- Accelerated repair solutions

The course will have an **accompanying report** describing in more details each module under a separate chapter. As a supplement, the audience will be referred to the *ABC-UTC Guidelines for Assessing Effect of Frequent, Low-Level Seismic Events*.

Additionally, an **appendix** with frequently asked questions (FAQs) will be provided.

4.2 Task 2 – Prepare Modules

Description: *Prepare approximately 10–20 slides for each module.*

Preliminary work on this task has begun. Modules 1 and 2 completed. Awaiting slide template to be provided by FIU.

4.3 Task 3 – Prepare Accompanying Report

Description: *Prepare accompanying report describing in more details each module under a separate chapter.*

Preliminary work on this task has begun. Materials from the *ABC-UTC Guidelines for Assessing Effect of Frequent, Low-Level Seismic Events* are being parsed out to form the individual reports.

4.4 Task 4 – Record Modules

Description: *Record continuing education course modules, including audio, picture-in-picture, and closed captioning for ADA compliance.*

Preliminary work on this task has begun. The Record Slide Show feature in PowerPoint is being used to record the modules.

4.5 Task 5 – Submit Course Module

Description: *Submit final videos and accompanying report to FIU to be uploaded to the ABC-UTC webpage.*

No work on this task to report.

5 Expected Results and Specific Deliverables

The major deliverable from this project is:

- Deliverable: Web-Based Continuing Education Course

  AASHTO and other transportation organizations and agencies are in need of rigorous methods to properly quantify the impact of large number of small earthquakes on their bridges. This continuing education course is expected to support their needs in this regard. The target groups for the course will be state DOTs (and consulting engineers) in regions facing the emerging threat from induced earthquakes (e.g., Oklahoma, Texas, Arkansas, Kansas). These groups are facing increased seismic hazards not historically experienced, so guidance as to the management and repair of their facilities will be essential.

6 Schedule

Progress on this project is shown in Table 1.

Item	% Completed
Percentage of Completion of this project to Date	43.75

Table 1: Project schedule.

Research Task	2019											
	J	F	M	A	M	J	J	A	S	O	N	D
1. Outline Course Content												
2. Prepare Modules												
3. Prepare Accompanying Report												
4. Record Modules												
5. Submit Course Module												

Work Performed Work to be Performed

7 References

USGS, Induced Earthquakes, *Earthquake Hazards Program*, U. S. Geological Survey, URL https://earthquake.usgs.gov/research/induced/overview.php, accessed February 17, 2017, 2017.

McGarr, A., Bekins, B., Burkardt, N., Dewey, J., P. Earle, W. E., Ge, S., Hickman, S., Holland, A., E. Majer, J. R., Sheehan, A., Coping with earthquakes induced by fluid injection, *Science* 347 (6224) (2015) 830–831, doi:10.1126/science.aaa0494.

Keranen, K. M., Savage, H. M., Abers, G. A., Cochran, E. S., Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake, *Geology* 41 (6) (2013) 699–702, doi:10.1130/G34045.1.

Frankel, A. D., Applegate, D., Tuttle, M. P., Williams, R. A., Earthquake hazard in the New Madrid Seismic Zone remains a concern, U.S. Geological Survey Fact Sheet: 2009-3071, 2 p, 2009.

Petersen, M., Moschetti, M., Powers, P., Mueller, C., Haller, K., Frankel, A., Zeng, Y., Rezaeian, S., Harmsen, S., Boyd, O., Field, N., Chen, R., Rukstales, K., Luco, N., Wheeler, R., Williams, R., Olsen, A., Documentation for the 2014 update of the United States national seismic hazard maps, Tech. Rep. Open-File Report 2014-1091, U. S. Geological Survey, doi:10.3133/ofr20141091, 2014.

AASHTO, Guide Specifications for LRFD Seismic Bridge Design, American Association of State Highway and Transportation Officials (AASHTO), Washington D.C., 2009.

Petersen, M. D., Mueller, C. S., Moschetti, M. P., Hoover, S. M., Llenos, A. L., Ellsworth, W. L., Michael, A. J., Rubinstein, J. L., McGarr, A. F., Rukstales, K. S., 2016 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes, Open-File Report 2016-1035, U.S. Geological Survey, Reston, Virginia, doi:10.3133/ofr20161035, 2016.

USGS, M 5.8 - 14km NW of Pawnee, Oklahoma, *Earthquake Hazards Program*, U. S. Geological Survey, available at http://earthquake.usgs.gov/earthquakes/eventpage/us10006jxs#executive, URL http://earthquake.usgs.gov/earthquakes/eventpage/us10006jxs#executive, accessed 28 November 2016, 2016a.

USGS, M 5.7 - Oklahoma, *Earthquake Hazards Program*, U. S. Geological Survey, available at http://earthquake.usgs.gov/earthquakes/eventpage/usp000jadn#executive, URL http://earthquake.usgs.gov/earthquakes/eventpage/usp000jadn#executive, accessed 28 November 2016, 2016b.

USGS, M 5.1 - 31km NW of Fairview, Oklahoma, *Earthquake Hazards Program*, U. S. Geological Survey, available at http://earthquake.usgs.gov/earthquakes/eventpage/us20004zy8#executive, URL http://earthquake.usgs.gov/earthquakes/eventpage/us20004zy8#executive, accessed 28 November 2016, 2016c.

USGS, M 5.0 - 3km W of Cushing, Oklahoma, *Earthquake Hazards Program*, U. S. Geological Survey, available at http://earthquake.usgs.gov/earthquakes/eventpage/us100075y8#executive, URL http://earthquake.usgs.gov/earthquakes/eventpage/us100075y8#executive, accessed 22 December 2016, 2016d.

Taylor, J., Celebi, M., Greer, A., Jampole, E., Masroor, A., Melton, S., Norton, D., Paul, N., Wilson, E., Xiao, Y., M5.0 Cushing, Oklahoma, USA earthquake on November 7, 2016, Tech. Rep. Oklahoma-EERI-Recon-Report-2017-02-15-Finalized, EERI, 2017.

GEER, The Geotechnical Aspects of the September 3, 2016 M5.8 Pawnee, Oklahoma Earthquake, Tech. Rep., Geotechnical Extreme Events Reconnaissance (GEER), 2016.

Culmo, M. P., Accelerated bridge construction-experience in design, fabrication and erection of prefabricated bridge elements and systems, Tech. Rep. FHWA-HIF-12-013, Federal Highway Administration, Washington, DC, 2011.

FHWA, 2007 FHWA Seismic Accelerated Bridge Construction Workshop Outcomes and Follow-up Activities, Tech. Rep., Federal Highway Administration, San Diego, CA, Final Report from the Rapid Bridge Construction: Seismic Connections Moderate-to-High Seismic Zones, 2007.