Geotechnical Extreme Events Reconnaissance (GEER)

Geotechnical Quick Report on the Affected Region of the 23 August 2011 M5.8 Central Virginia Earthquake near Mineral, Virginia

Photo: damage from unreinforced masonry wall collapse in the Washington DC area.
Credit: adapted from MSNBC

EDITOR: James R. Martin, II, Team Leader (Virginia Tech, Blacksburg, VA)

Contributing authors (alphabetical order):

- **Carl Benson** (Virginia Department of Transportation, Richmond, VA)
- **Martin Chapman** (Virginia Tech Seismological Observatory, Blacksburg, VA)
- **Morgan Eddy** (Steele Foundation, LLC, Washington, DC)
- **Russell Green** (Virginia Tech, Blacksburg, VA)
- **Annie Kammerer** (US Nuclear Regulatory Commission, Rockville, MD)
- **Sam Lasley** (Ph.D. Candidate, Virginia Tech, Blacksburg, VA)
- **Carlos Lazarte** (Schnabel Engineering, Inc., Gaithersburg, MD)
- **Sissy Nikolaou** (Mueser Rutledge Consulting Engineers, New York, NY)
- **Burak Tanyu** (George Mason University, Fairfax, VA)
- **Martitia Tuttle** (M. Tuttle & Associates, Georgetown, ME)

Contributors:

Mark Carter, US Geological Survey, Reston, VA
Brett Maurer, Ph.D. Candidate, Virginia Tech

INTRODUCTION

The 2011 Virginia Earthquake occurred on August 23, 2011, at 1:51 pm EDT (17:51 UTC) in the Piedmont region of central Virginia. The epicenter was in Louisa County near the small town of Mineral, about 50 km east of Charlottesville, 60 km northwest of Richmond, and 130 km southwest of Washington, DC. The event occurred as reverse faulting on a north or northeast-striking plane within the Central Virginia Seismic Zone, a region long associated with frequent felt earthquakes. The 23 August earthquake, the largest historical earthquake in the region, was magnitude 5.8 with a maximum perceived intensity of VII on the Modified Mercalli Intensity scale; see Figure 1. The hypocentral depth was about 6 km. Several aftershocks, ranging up to M 4.5 occurred after the main tremor.

The main shock was felt along most of the eastern seaboard, reaching from Georgia to Canada. The large felt area coupled with the high population density along the coast meant that this was the most felt earthquake in US history. There were no reported fatalities or serious injuries, but minor damage to buildings was widespread. Unreinforced masonry walls, gable walls, and chimney collapses were the most common failures. In the sparsely populated epicentral region, tens of private residences, especially unreinforced masonry structures, were severely damaged and several were partially collapsed. Across the state, 33 residences were destroyed and 180 suffered major damage. Two public schools were damaged seriously enough that they will be closed for the entire school year. Current damage estimates are more than $90 million in Virginia, and $200 million to $300 million overall.

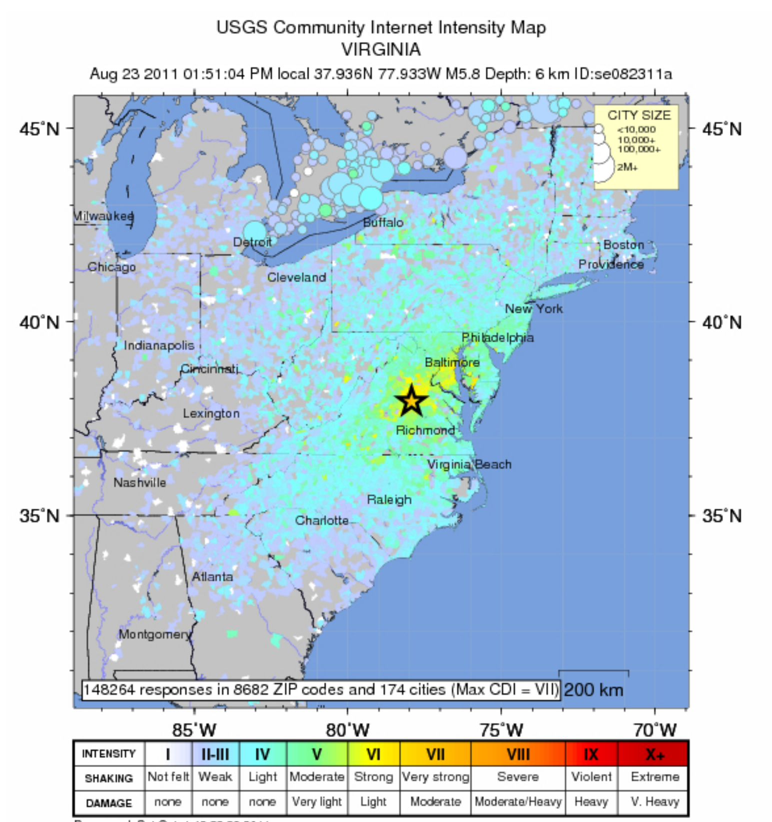

Figure 1 – Intensity map showing affected region of the 23 August M5.8 Earthquake

The earthquake resulted in the shutdown of the nuclear reactors at the North Anna Power Plant (NPP), 18 km from epicenter, which used backup generators to keep spent nuclear fuel cooled and to remove residual heat from the reactor. In-structure foundation level recordings in the reactor containment, founded on hard rock, indicated a PGA of 0.26g. The recorded response spectrum exceeded the Design Basis Ground motion of the reactor, but did not result in apparent damage to the safety related systems. The NPP record is the best and closest available strong motion recording of the M5.8 main shock.

Toward the east in the Richmond area, minor damages occurred to unreinforced masonry structures especially in the form of broken chimneys. To the northeast in Washington, DC, southern Maryland and Delaware, more than 130 km away, there was a marked uptick in damages relative to other locations closer to the epicenter. This was especially apparent for sites on Coastal Plain sediments overlying hard rock. Damages, some of which were quite significant, occurred to a variety of structures, including buildings, bridges, and monuments and institutions.

The earthquake tied up phone and internet connections, disrupted rail lines, and caused extensive traffic delays and business disruptions as far away as New York City. Minor damages were reported as far away as New Jersey and New York more than 450 km to the northeast, and as far as Charleston, SC 600 km to the southwest. The earthquake caused widespread confusion between the public and emergency personnel on how to respond.

GEER Reconnaissance

In the hours following the earthquake engineering and seismology faculty members and graduate students from Virginia Tech, along with local United States Geological Survey (USGS) and Virginia Department of Mines, Minerals, and Energy (VA DMME) personnel, mobilized to the epicentral area for field reconnaissance. Several of the early arrivers included would-be GEER team members.

The initial core GEER team was formed two days after the event and was focused on collecting geotechnical data as rapidly as possible, building on the efforts of those that mobilized to the affected area immediately after the earthquake. The most pressing issue was collecting perishable data ahead of Hurricane Irene which struck the area a few days after the earthquake.

In this effort, the GEER team successfully leveraged the assistance of many geotechnical engineering firms and relevant contacts throughout the region. We coordinated with key agencies and organizations such as EERI, USGS, the VA DMME, Departments of Transportation in Virginia, Maryland, and Washington, among other groups.

Current GEER team members and their primary areas of responsibility are:

- Professor James Martin, Civil and Environmental Engineering, Virginia Tech – team leader

- Mr. Carl Benson, P.E., P.G. VDOT Geotechnical Engineering Program Manager – geotechnical findings in Richmond and eastern VA, and performance of VA bridges

-Mark W. Carter, Research Geologist, U.S. Geological Survey– geology of the epicentral region

-Dr. Martin Chapman, Director, Virginia Tech Seismological Observatory- seismology issues and recorded ground motions, NPP seismic instrumentation

-Mr. Morgan Eddy, P.E., Geotechnical Engineering Contractor, Steele Foundation, and PhD Candidate, Virginia Tech – epicentral region and Washington, DC area geotechnical issues

- Assoc. Professor Russell Green, P.E., Civil Engineering, Virginia Tech - epicentral area geotechnical issues and structural failures; NPP facility and Lake Anna Dam

-Dr. Anne Kammerer, P.E, US Nuclear Regulatory Commission, Rockville, MD - geotechnical observations in National Capital Region; regulatory issues associated with NPP

-Mr. Sam Lasley, Geotechnical Engineering Ph.D. candidate, Virginia Tech - epicentral area geotechnical issues and structural failures

-Dr. Carlos Lazarte, P.E., Senior Associate, Schnabel Engineering –Washington, DC and Maryland area geological and geotechnical issues

-Dr. Sissy Nikolaou, P.E., Head Geo-Seismic Department, Mueser Rutledge Consulting- Geo-seismic issues, geological and geotechnical information for distant damages in DC and NY

- Asst. Professor Burak Tanyu, P.E., Civil Engineering, George Mason University - geologic and geotechnical issues in northern VA and DC area

-Dr. Martitia Tuttle, Director and Principal Investigator, M. Tuttle & Associates - liquefaction evidence along streams in the epicentral region, National Capital Region, and Eastern VA

As expected, given the proximity of this moderate earthquake, the team is dominated by participants based in the region. Most team members have a strong regional network of contacts at private engineering firms companies and state and federal agencies. Since costs are relatively low for reconnaissance in the affected area for participants based close by, there was little downside to adding as many willing contributors who wanted to take part.

Geotechnical reconnaissance was organized into four regions, including the epicentral area, Richmond and Eastern Virginia, the National Capital region, and distant sites. Findings are grouped and presented in this manner. We focused on documenting ground failure, such as liquefaction, along with the performance of bridges and other lifelines, dams and embankments, building foundations, landfills, and critical facilities within each region. Although few ground failures were suspected, our philosophy is that it is of equal significance to study sites where failure did not occur, especially in the epicentral region where PGAs were relatively high. Careful documentation of this earthquake is of added importance due to the sparseness of recorded motions and modern documentation of seismic performance in the eastern US.

In the epicentral region careful searches were conducted along rivers, creeks, and Lake Anna where we focused on vulnerable soils areas such as boat ramps, small marinas, creeks and inlets, retaining structures, man-made beaches, railroad and highway embankments, and slopes and dams. We were especially interested in the performance of the North Anna Nuclear Power Plant and the 30-m high embankment dam on Lake Anna. In Richmond and eastern Virginia, we focused mainly on soft Coastal Plain deposits and major waterways such as the James River. In the Washington, DC area careful searches were made along major waterways, at waterfront structures, at critical facilities such as dams and airports, and at sites where damage occurred to monuments and institutions. At distant sites, such as New York, we focused mainly on documenting isolated sites of minor damage.

There were few instances of ground failure produced by this earthquake. We found minor liquefaction and slumping along some streams, minor separation of approach abutments from bridge bents, rockfalls, and slope movements in marginally stable slopes. Most of these observations were in the epicentral region. Although there were few sites of ground failure, there were observations important to the geotechnical engineering community. Of particular significance, we saw a clear correlation between geotechnical conditions and damages from this event, especially in the National Capital Region. It was clear that soil amplification in soft sediments overlying hard rock influenced damage and shaking intensity patterns, as did the underlying geologic structure associated with the Appalachian Mountains and the strike of regional geologic faulting. There will also be instructive findings related to regional ground motion attenuation, topographical effects, unique site conditions not fully captured by current IBC/ASCE7 soil amplification factors, and seismic hazard assessment.

From a seismological standpoint, it was unfortunate that the M5.8 event was not well recorded, although several of the larger aftershocks were very well recorded. Only a few strong motion instruments were located within 200 km of the epicenter at the time of the main shock. This will limit the ultimate amount of seismological and engineering knowledge that can be gained; nevertheless, there will be valuable lessons. Among these include a complex fault rupture process, which may be found to be characteristic of central and eastern North American (CENA) earthquakes, and a pronounced directivity of maximum radiated shaking. Both issues increase uncertainties associated with ground motion prediction and seismic hazard for CENA. The event has important implications for current efforts such as the New Generation Attenuation (NGA) East program charged with developing a new set of comprehensive and broadly accepted attenuation models for CENA. Finally, beyond engineering and seismological findings, the event can teach us much about the need for improved preparedness for and better awareness of eastern US earthquake hazards.

This report presents findings from the reconnaissance efforts to date. It is preliminary in scope and inevitably incomplete, and presented mainly for timely dissemination of observations to the engineering community and relevant stakeholders. Analyses are being conducted that will allow refined assessments. A subsequent report, more comprehensive in scope, will be issued in the next few months.

In addition to Section 1, presented here, Sections 2 and 3 present a summary of Central Virginia Zone seismicity and regional geological structure. Seismological findings are presented in Section 4. Sections 5, 6, and 7 present findings from the epicentral region, Richmond and eastern Virginia, and the National Capital region, respectively. Section 8 presents possible research topics associated with this event.

Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the associated organizations and funding agencies.

Acknowledgements

Team members gratefully acknowledge generous support from numerous individuals, firms, organizations, agencies and institutions: **DC Department of Transportation (DDOT), Earthquake Engineering Research Institute (EERI), Fugro Consultants, Maryland Department of Transportation (MDOT), Mueser Rutledge Consulting Engineers, PSI, Schnabel Engineering, Smithsonian Institution, Steele Foundations, Virginia Department of Mines, Minerals, and Energy (DMME), United States Geological Survey (USGS), Virginia Department of Transportation (VDOT), the Virginia Tech Seismological Observatory (VTSO), Dr. Deborah Pettit, Superintendent of Louisa County Schools, and residents of the affected area.**

Support for the GEER participants in this work was provided from grants from the U.S. National Science Foundations (NSF) as part of the Geo-engineering Extreme Event Reconnaissance (GEER) Association activity through an NSF RAPID GRANT and CMMI-00323914.