Learning from Earthquakes

The M_w 5.8 Virginia Earthquake of August 23, 2011

After the M_w 5.8 earthquake of August 23, 2011, EERI assembled a team of East Coast EERI members to document various aspects of the event. Co-leaders were James Beavers, a consulting structural engineer from Knoxville, Tennessee, and William Anderson, a sociologist and an EERI Board member from Washington, D.C. Other team members included Matthew Eatherton, Virginia Tech; Ramon Gilsanz, Gilsanz Murray Steficek Inc; Frederick Krimgold, Virginia Tech; Ying-Cheng Lin, Lehigh University; Claudia Marin, Howard University; Justin Marshall, Auburn University; Jelena Pantelic, the World Bank; and James Ricles, Lehigh University. Marshall participated remotely by mapping structural damage. Additional material was furnished by members of the Geotechnical Extreme Events Reconnaissance (GEER) Association team: Russell Green, Virginia Tech; James Martin, Virginia Tech; Sissy Nikolaou, Mueser Rutledge Consulting Engineers; and Sam Lasley, Virginia Tech. Other contributors to this report included Jeff Munsey, Tennessee Valley Authority, and a team of social scientists from the Disaster Research Center at the University of Delaware: Yvonne Rademacher, Alex Greer, Laura Keeley, James Kendra, Benigno Aguirre, and Lucia Velotti.

Unless otherwise indicated, photos in this report were taken by EERI team members.

Introduction

The M_w 5.8 earthquake that struck central Virginia at 1:51 p.m. local time on August 23, 2011, caused no deaths and few injuries, but did damage buildings and other structures within a 100-mile radius of the epicenter. Perhaps its biggest effects were the business and social disruptions up and down the East Coast that lasted from several hours to some months. The quake caused widespread interruptions to communications and transportation systems, numerous school closings in the epicentral area of Louisa County, other closures in the greater Washington, D.C., area, and an automatic shutdown of the North Anna Nuclear Power Plant. The earthquake is a noteworthy reminder that communities on the East Coast are not prepared to cope with a major earthquake, and that steps could be taken to improve their readiness and increase loss reduction efforts.

Seismology

The M_w 5.8 (USGS) earthquake resulted from reverse faulting at shallow depth (estimated at 6 km) on a north-northeast-striking plane within a previously recognized seismic zone: the Central Virginia Seismic Zone. This zone has produced small and moderate earthquakes since at least 1774, the previous most damaging shock having been in 1875. That quake predated the invention of effective seismographs, but its felt effects and area suggest that it had a magnitude of about 4.8. It shook bricks from chimneys, broke plaster and windows, and overturned furniture at several locations. An M4.5 earthquake on December 9, 2003, also caused minor damage.

The epicenter of the August 23 quake was 8 km from Mineral, Virginia, 61 km from Richmond, and 135 km from Washington, D.C. (Figure 1). A network of seismographs installed following the August 23rd main shock has enabled accurate location of many aftershocks. The aftershocks define a 10-km-long, N28°E striking, 45°ESE dipping fault at between 2.5 and 8 km depth, in good agreement with the focal mechanism of the main shock. The locations of aftershocks do not correspond to a previously identified fault; previous, smaller, instrumentally recorded earthquakes in the zone have had diverse focal mechanisms over an area with a length and width of about 120 km, rather than alignment in a pattern that might suggest a single causative fault.

Figure 1 shows the regional distribution of intensities associated

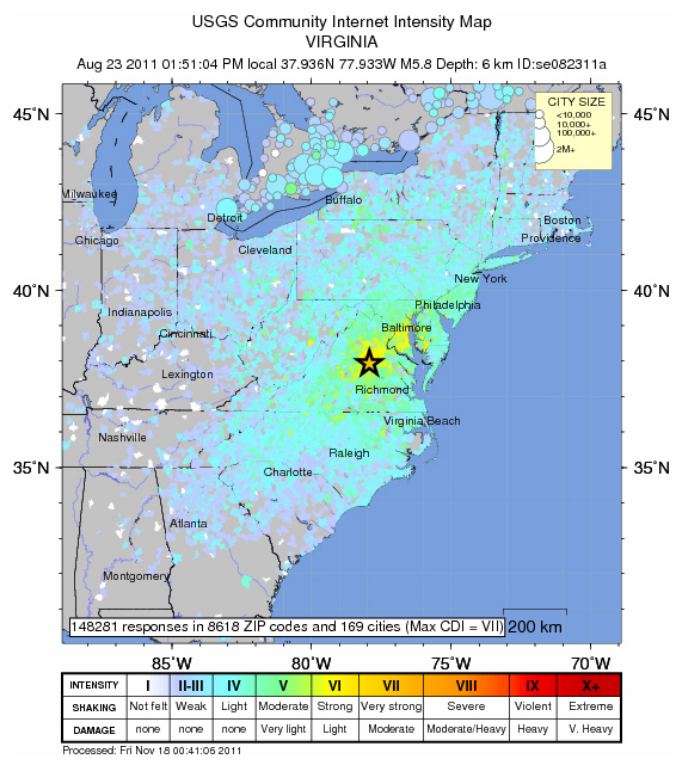

Figure 1. *Epicenter and intensity map made from 148,281 respondents to USGS DYFI site.*

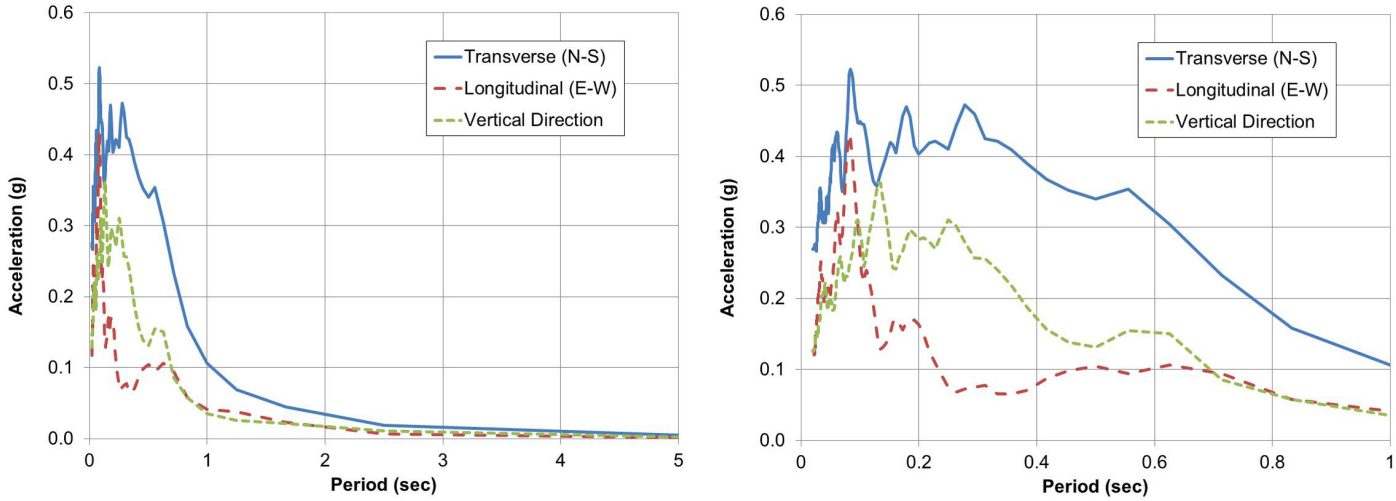

Figure 2. *Acceleration response spectrum with 5% damping recorded at the North Anna Nuclear Power Plant for periods up to 5 sec (left) and isolating low-period range (right) (adapted from Dominion, 2011).*

with the earthquake, as estimated from data contributed to the USGS "Did You Feel It?" (DYFI) web site. Reports of the shock came in from most zip codes within 800 km of the epicenter, and additional observations came in from zip codes at greater distances (Figure 1). According to the USGS, the large felt area is not unusual for an eastern U.S. shock; east of the Rockies, an earthquake may be felt over an area ten times larger than that for a similar magnitude earthquake on the West Coast.

A maximum intensity of VII is estimated from DYFI data, when observations are averaged over zip code regions. However, field observations indicate that an area in rural Louisa Country close to the causative faulting had shaking corresponding to Modified Mercalli Intensity VIII; the average DYFI intensity is VII for the entire 500-km² zip code region in which higher-intensity effects were observed.

A time history recording of the earthquake from the North Anna Nuclear Power Plant approximately 17 km from the epicenter shows a peak horizontal ground acceleration of 0.27g (Figure 2). The response spectrum also shows high energy content at short periods as compared to typical west coast earthquake spectra.

Regional Geology

The region is very old, with bedrock formed more than a billion years ago and a complex surficial geology that bears the imprints of continental collisions, long-dead mountains, and forgotten seas (Mittelbach & Crewdson, 1998). The regional geology is characterized by a distinct "fall line" that separates inboard bedrock (the Piedmont province) from the outboard Atlantic Coastal Plain. The fall line runs southwesterly from the District of Columbia-Montgomery County boundary near Silver Spring, Maryland, across the Potomac River north of Roosevelt Island (Figure 3).

Most bedrock beneath central Virginia was assembled as continents collided to form a supercontinent about 500-300 million years ago, raising the Appalachian Mountains. The rest of the bedrock formed when the supercontinent rifted apart about 200 million years ago to form what are now the northeastern U.S., the Atlantic Ocean, and Europe. The Central Virginia seismic zone is far from the nearest plate boundaries, which are in the center of the Atlantic Ocean and in the Caribbean Sea. The seismic zone is laced with known faults, though they are poorly located at earthquake depths, but numerous smaller or deeply buried faults remain undetected. Accordingly, few, if any, earthquakes in the seismic zone can be linked to named faults, and it is difficult to determine whether a known fault is still active and could slip and cause an earthquake.

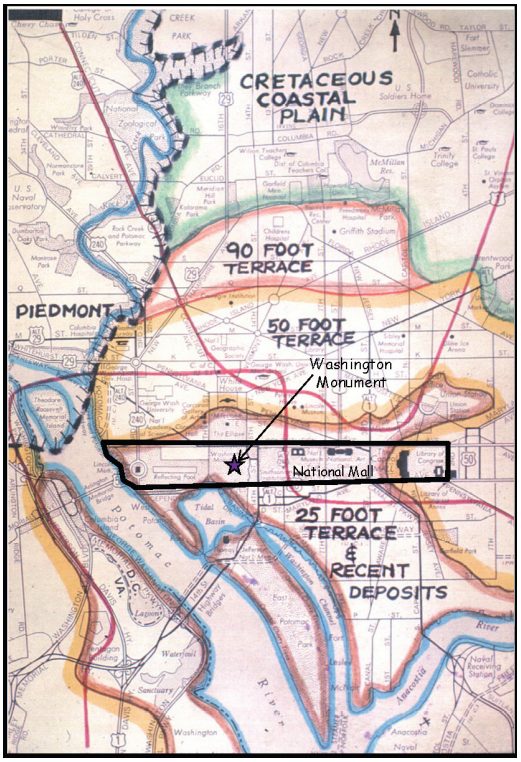

Figure 3. *The fall line (dashed) and terrace deposits in the vicinity of the Washington Monument (source: Collective Works of J. P. Gould).*

Figure 4. *Aerial image of the epicentral region showing locations of observed liquefaction sand boils. Also shown are the epicenters of the main shock and of >M3.0 aftershocks within two days of the main shock (source: GEER).*

Coastal Plain deposits include Cretaceous sediments, Pleistocene Terrace deposits, and river deposited alluvium of relatively recent origin. The Cretaceous sediments, known as the Potomac formation, were deposited in relatively shallow seas on the sloping bedrock surface by streams flowing eastward out of the continental interior. These sediments are primarily hard clays and compact sands, and a succession of river terrace deposits of Pleistocene times overlies them. While glacial ice did not reach south to the current Washington, D.C., area, the terrace deposits were formed by debris carried in streams charged by glacial melt water flowing from the northwest. Climatic changes resulted in wide variations in stream gradients, sediment load, and deposited materials, so the terrace deposits consist of mixtures of silty and sandy clays with clean sands and gravel interlayered and lensed in a complex pattern.

Over the period of the last five or six thousand years, the sea level has risen 25-30 feet with respect to land along the coast. This rise submerged the Potomac and Anacostia Rivers and resulted in the deposition of relatively fine grained alluvium in river channels.

The epicentral area is drained by South Anna River and its major, secondary, and tertiary tributaries. Alluvium (unconsolidated clay, silt, sand, and gravel of Tertiary to Quaternary age) appears along portions of these streams, typically at leeward-side point bars and horseshoe bend cutoffs, ranging from a few meters to tens of meters thick. Topographic sideslopes and hilltops are typically underlain by saprolite (decomposed bedrock chemically weathered in-place) beneath soil horizons; saprolite can range from a few meters to tens of meters thick.

Geotechnical Observations

Liquefaction. The soils in Louisa County are largely residual clay, so it was not expected that liquefaction would be pervasive during this event. However, the GEER team did find four small liquefaction sand boils at the locations marked in Figure 4. Also marked are epicenters of the main shock and major aftershocks and, if these epicenters define the general location/orientation of the rupture plane of the main shock, it can be inferred that the liquefaction features lie directly over the rupture plane. There may have been other liquefaction sites, but the undergrowth in the region is thick and sand deposits sparse. Several heavy rains associated with Hurricane Irene in the days after the main shock likely washed away any features in the river and creek beds.

Slumps and Subsidence. One small slump was found on the bank of the South Anna River very close to the liquefaction features, again likely directly over the rupture plane. What is believed to be earthquake-induced subsidence was found in an abandoned gold mine.

Rockfalls. Four rock falls were found in the epicentral region, two along the banks of the South Anna River and two in road cuts. The team determined that the area of rockfalls extended from just north of Harper's Ferry on the north, to the Virginia/West Virginia border on the west, and to about 10 miles north of the North Carolina border, along the Blue Ridge Parkway, on the southwest. They were not able to determine the eastern limit. The determined limits are shown in Figure 5.

Details of the geotechnical effects of this earthquake will be published in a forthcoming GEER report (GEER, 2012).

Damage to Structures

Most historic engineered structures located in the densely populated corridor along the Atlantic coast between Boston and Washington, D.C., were not designed against earthquake loading and, although the anticipated shaking intensities are moderate compared to more seismically active areas in the western United States, the density and high monetary value of East Coast structures puts them at considerable risk to costly earthquake damage (Nikolaou, 2004).

Louisa County, Virginia. Several EERI team members visited Min-

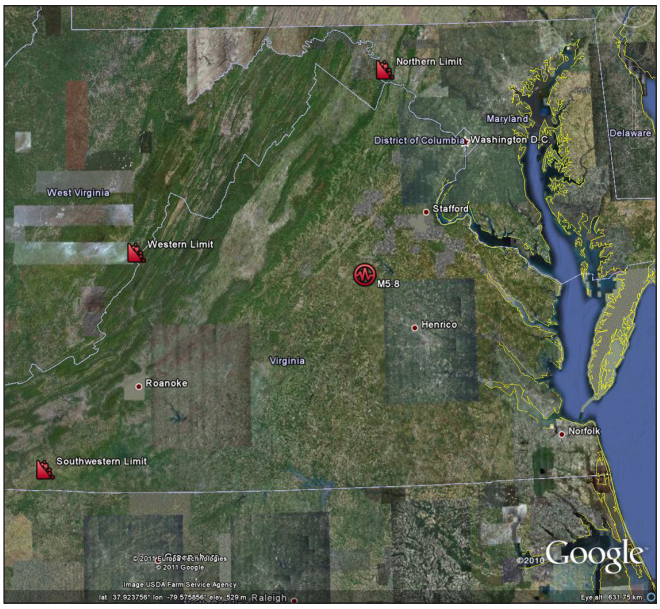

Figure 5. *Aerial image showing the areal extent of rock falls (source: GEER).*

Figure 6. *Damage to Louisa County High School (photo: R. Green, GEER).*

eral, the town closest to the epicenter, Louisa City, and other areas in Louisa County three and four days after the earthquake. They observed minor to moderate damage to unreinforced masonry homes and schools, failure of brick veneer, minor cracking in reinforced masonry and reinforced concrete structures, and failure of some residential carport structures.

The damage estimate for public buildings and equipment in the State of Virginia, as of October 20, was $30,598,300 (McDonnell, 2011). Most of this total is due to the costs of repairing the following schools: in Louisa County, Thomas Jefferson Elementary ($9.5M) and Louisa County High School (18.7M), and in Spotsylvania County, Germanna Community College ($1.1M) and Mary Washington University ($689,550). For Louisa County, the damage estimate for total residential damage as of October 20 was $13,730,000 (McDonnell, 2011).

The cost of repairing Jefferson Elementary represents 70.9% of the estimated $13.4M replacement cost, so it is planned to be rebuilt. Total costs of rebuilding the elementary school in approximately two years, repairing the high school (Figure 6) in approximately four years, and maintaining and demobilizing temporary facilities amount to $45M, which will exceed the available and applicable insurance by approximately $28.7M. This is based on assumptions made regarding the level of applicable insurance, which as of October 20 had not been fully defined by the insurance company (McDonnell, 2011). The indefinite school closure of Jefferson Elementary has been accommodated by bringing mobile units to Trevilians Elementary and staggering school shifts. Louisa County High School will share a middle school building until mid-January, at which time a mobile high school will be established on site and schedules will return to normal.

The fire alarms at the high school were activated during the earthquake, apparently because the fire alarm was triggered when the sprinkler system lost pressure due to a break in one of the sprinkler pipes. EERI team members were told that the schools did not have specific earthquake response procedures, but rather used the typical fire/tornado drill procedures in evacuating school buildings. One teacher in the high school knew what to do in an earthquake and had his students take cover under their desks; after the shaking stopped, he told the students to evacuate the classroom/school. Other teachers had their classes attempt to evacuate the building during the earthquake, and there were several minor injuries reported due to falling debris.

When the schools were evacuated, students left behind their backpacks, which included their cell phones. The students had no access to their backpacks for four days, and upon returning, commented on the inconvenience of being separated from their phones.

Other schools sustained some structural damage, according to school district officials, but can be occupied while repairs are being made.

The Louisa County Office of Emergency Management had no reported damage to its facility and was fully operational after the earthquake. The Mineral fire station had limited nonstructural damage and cracking in CMU walls, but the damage did not hamper response activities.

The Louisa City water tower, across from the County Court House, looked like it had been there at least 50 years, but the anchor bolts showed no movement or stretching. There was no damage to the Court House, to the historic jail next to the Court House, or to the Confederate monument in front.

Two historic unreinforced masonry buildings in the area were moderately damaged. The Gilboa Christian Church, built in Mineral in 1832,

Figure 7. *Damage to the historic Gilboa Christian Church.*

had considerable architectural and some structural damage. As shown in Figure 7, the outer wythe of a brick wall collapsed where there was no apparent connection between the wythes of the wall. A portion of a gable wall collapsed that did not appear to be well anchored to the roof diaphragm. A section of brick veneer also failed where ties between the brick and backup wall consisted of 16d nails driven into straight sheathing and then encased in the brick mortar joint. Approximately 20% of the vertical standing tombstones in the Gilboa Church cemetery were thrown over.

The Cuckoo House, a Federal style house in the small village of Cuckoo, near Mineral, was built in 1819 and was listed on the National Register of Historic Places in 1994. The unreinforced masonry building had considerable architectural and some structural damage, with partial collapse of some walls and both tall chimneys (Figure 8).

Post-event building inspections were conducted by approximately 12 inspectors that included Louisa County building inspectors as well as inspectors on loan from jurisdictions around Virginia. The inspections were conducted because the county needed an estimate of the total cost of damages in order to determine whether it was eligible to apply for aid from the Commonwealth of Virginia and the federal government. As such, the inspections focused on assessing costs (see Figure 9), not on restricting access to dangerous buildings. No damaged building was tagged.

North Anna Nuclear Power Plant. GEER and EERI team members visited the North Anna Nuclear Power Plant (NPP) a week after the earthquake. Operated by Dominion Power, the plant had gone on automatic shutdown immediately after the quake, which triggered back-up power generation. The plant had been designed for a Design Basis Earthquake (Safe Shutdown Earthquake [SSE]) of 0.12g, but the ground motion was recorded at 0.27g, a little more than twice the SSE. Although the SSE was not intended to be exceeded, the robustness in the seismic design resisted major damage, and North Anna is now back online following review by the owners and the Nuclear Regulatory Commission (NRC).

Figure 8. *Partial collapse of a gable wall and two chimneys at the Cuckoo House outside Mineral.*

The team examined several large water tanks, some of the noncritical buildings, the main service building, and the turbine building. Some of the CMU walls in one of the noncritical buildings showed hairline diagonal cracks. The turbine building is a tall, steel space-frame structure, and the crane was being tested while we were there. The crane appeared to be working fine, which implied very little residual displacement of the crane rails. There was almost no evidence that the big water tanks moved relative

Louisa County Damage Assessment

Name_____

Phone_____

Address_____

_____

Tax Map #_____

Own or Lease

What was the last assessed value of your property?_____

Do you homeowner's insurance Yes No

What percentage of your home is insured?_____

Do you have an "earthquake" rider? Yes No

Affected Moderate Major Destroyed

Approximate $ value of damage_____

Figure 9. *Damage assessment form used by Louisa County building inspectors after the earthquake (source: Scott Keim, Louisa County Fire & EMS Chief).*

Figure 10. *117-ton steel casks for dry storage of spent fuel rods (photos: Dominion Power).*

to the foundation, though they were not tied down; however, it was clear that 27 massive steel storage casks for spent fuel rods slid around on their concrete slab as much 4.5 inches (Figure 10).

Dominion Power had two accelerographs that recorded time histories, one on the mat foundation of the nuclear reactor (shown in Figures 11 and 2) and one on an elevated operating deck. Also present were multiple spectrum recorders, which record ordinates at 12 frequencies. Dominion is having the spectrum recorders analyzed, and then will turn the data over to the NRC, at which point the information will be made public.

The Washington Monument. In the 220 years since Pierre L'Enfant first envisioned the National Mall as our nation's "Grand Avenue," the land has been used for a multitude of purposes, such as military training and railroads, before it was developed into the serene, tree-lined home of museums and monuments that it is today. The Washington Monument stands at the center of the mall (Figure 12).

Background: The mall is located within the coastal plain that consists of a broad belt of flat sediments over bedrock. The top of the bedrock along the National Mall ranges from about -220 ft. in elevation at the Capitol to -20 to -40 ft. in elevation west of the Lincoln Memorial, with a localized high point at the east end of the Reflecting Pool (elevations are referenced to Mean Sea Level). Figure 13 presents a generalized geologic section. For the construction of the western half of the Mall, up to 30 ft. of fill was placed, and most of the monuments there are founded on deep piles.

The Washington Monument was one of the earliest structures built on the mall. Construction began in 1848 with private funds raised by subscription. The monument foundations were established at approximately +15 ft of elevation atop the terrace sand and clay deposits. When funds ran out in 1856, work was stopped with the monument at a height of +152 ft.

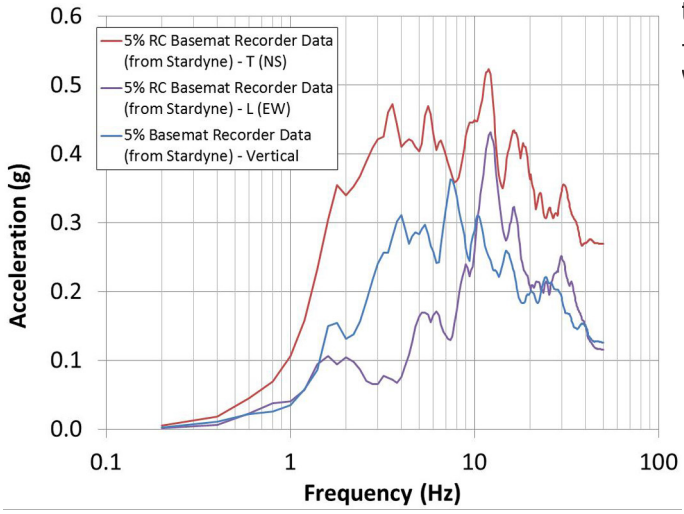

Figure 11. *Acceleration response spectrum for ground motion recorded at the North Anna Nuclear Power Plant (adapted from Dominion Power, 2011).*

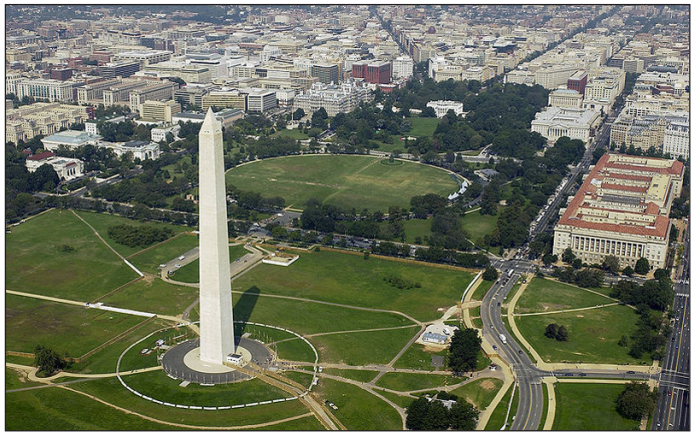

Figure 12. *Washington Monument (photo: Department of Defense, 2003).*

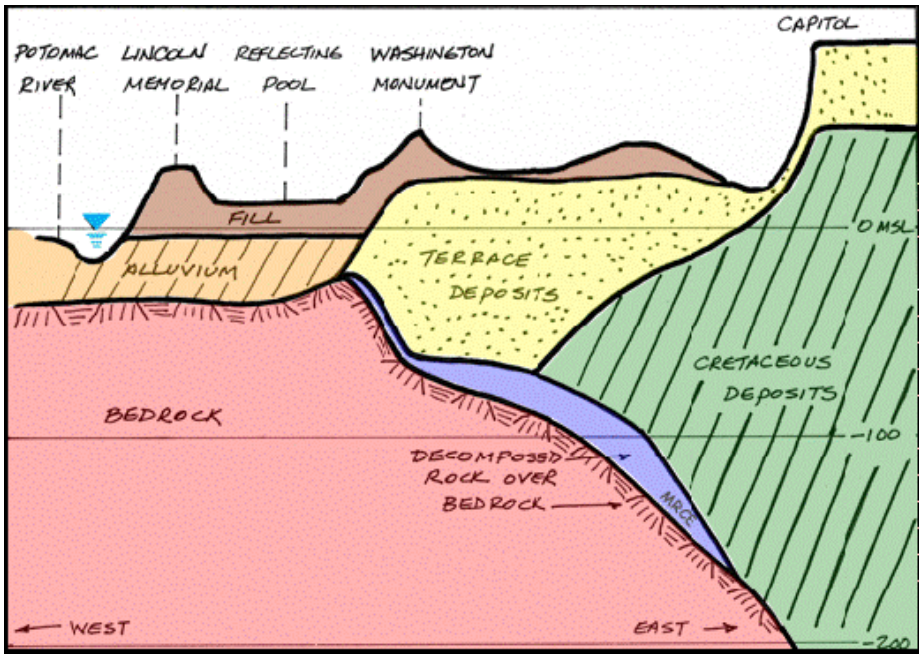

Figure 13. *Geologic section along the Mall, looking north (modified from Christie, 2002; original section in Collective Works of J. P. Gould).*

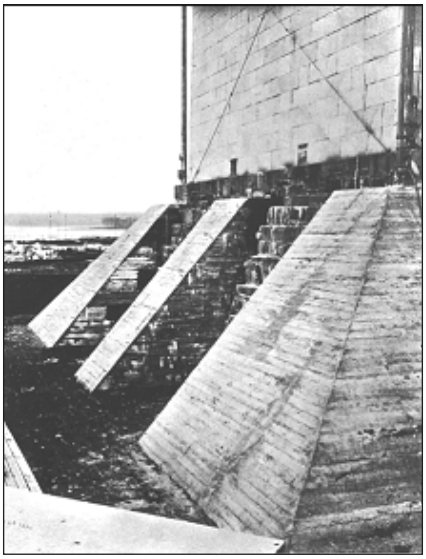

Figure 14. *Completed buttresses in 1879 (source: Library of Congress, 1880).*

Congress was repeatedly approached for funding, but the Civil War intervened. Construction was not resumed until the late 1870s, when funding was forthcoming from Congress. At that time, concerns were raised about the ability of the spread foundations bearing on these soils to carry the load of a masonry structure in excess of +500 ft. Thomas Lincoln Casey, an experienced lieutenant colonel from the U.S. Army Corps of Engineers, designed a scheme to underpin the foundations. Buttresses were added to provide load transfer to the underpinning, with excavations extending to approximately +3 ft. of elevation, which was the groundwater level at that time (Figure 14). The new foundations bear on the deeper, coarser grained terrace deposits stratum (Figure 15) and have generally performed satisfactorily.

The last piece of marble was placed on August 9, 1884, completing the shaft to 500 feet, which made it the tallest structure in the world.

It remained to construct the pyramidion — the uppermost 55 feet of the monument, beginning where the slope of the walls changes. Coincidently, an earthquake that was felt in the D.C. area hit the New York City metropolitan area a day later, on August 10, 1884 (Nikolaou, 2004; Tuttle & Seeber, 1989). The intensity at the epicentral region was VII, and the estimated local magnitude was 5.5 (USGS, 2009) . No damage to the monument was reported.

Work began on the pyramidion in September 1884, and on the afternoon of December 6th, Casey had the honor of setting the 3,300-pound capstone and securing the aluminum apex to the copper rod that passed through the capstone (Torres, 1984).

Total settlements since the beginning of underpinning are about 7 inches. However, more than 60% of this settlement occurred during underpinning and the second phase of construction, as the monument was built up from 152 ft. to 555 ft. in height. Contributing factors to the settlement that occurred after completion of the second phase include

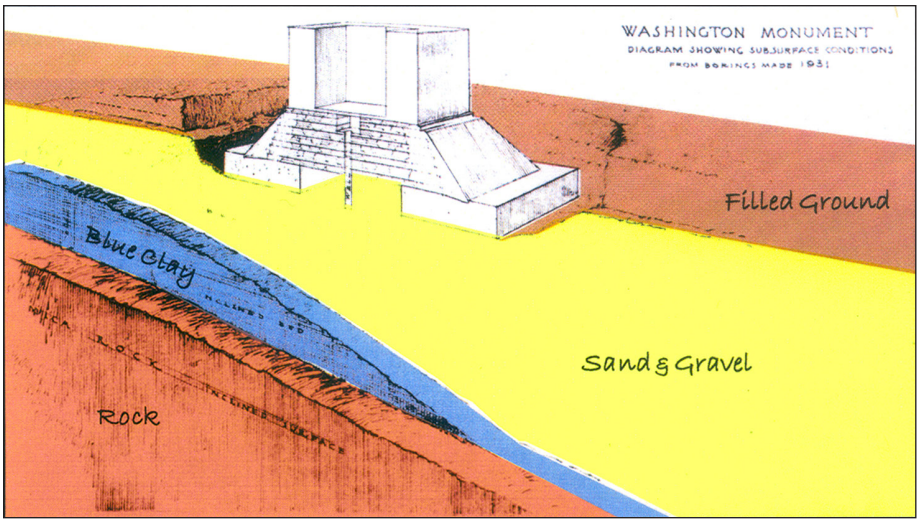

Figure 15. *Perspective view at the base of the Washington Monument (1931) (modified from Torres, 1984).*

Figure 16. *Inspectors from WJE conducting an exterior inspection (photo: National Park Service, 2011b).*

secondary compression, site regrading, construction activity, and nearby dewatering. Settlement monitoring in recent years has revealed minimal settlement, indicating that the monument is stable and that the underpinning operation was successful (Christie, 2008).

Damage: Video from a camera installed at the 500 feet level of the monument clearly shows shaking that can be attributed to the arrival of various seismic waves. To see the video, visit http://www.nps.gov/wamo/photosmultimedia/videos.htm (National Park Service, 2011a). At the distance of the monument from the earthquake epicenter (135 km), the P wave arrives about 24 seconds after the earthquake rupture begins. The S wave should arrive about 17.5 seconds later, and the video clearly shows an increase in shaking about 17-18 seconds after onset of the P wave. Debris begins to fall from the ceiling less than two seconds after the S wave arrival. Theoretically, the Raleigh and Love surface waves should arrive about 3-4 seconds after the S wave; although it is difficult to differentiate the arrival of the surface waves, a few seconds after S wave arrival does correspond to the point at which the majority of the debris falls from the ceiling. It is also clear that the monument continues to move *more than three minutes after the shaking began.* Late-arriving surface waves and reflected/scattered seismic waves account for the long shaking duration.

An official interior and exterior damage assessment was conducted by the National Park Service, including a climbing team to "rappel all four faces of the Washington Monument to perform a close range survey of the exterior surfaces" (Smith, 2011) (Figure 16). The National Park Service engaged two outside engineering firms (WJE Associates and Tipping Mar Associates) to assist with the investigation. Although the external inspection was officially completed in early October 2011, the Washington Monument currently remains closed to the public (Ruane, 2011a).

Initial published findings (WJE, 2011; Sullivan, 2011; Ruane, 2011b) of the post-earthquake damage assessment revealed:

Figure 17. *Crack in the Washington Monument (photo: National Park Service, 2011b).*

- Cracking and spalling of the exterior marble and underlying stone masonry elements;
- Loss of joint mortar;
- Debonding of cementitious patching material used throughout the monument;
- Debris consisting of mortar, stone/paint chips, and stone pieces surrounding the base of the monument and covering the interior stairs and observation deck;
- Damage to the elevator system (elevator could only ascend 250 ft of the 555 ft tall structure);
- Additional damage due to wind and water entering through cracks during Hurricane Irene, which hit D.C. on August 27th, 2011;
- Partially dislodged masonry blocks.

The most significant damage was found in the pyramidion at the top of the structure, where a 4-foot long, 1-inch wide crack was observed (Figure 17). Engineers and inspectors were assisted in the damage assessment by a study of the Washington Monument that was completed in 1999 prior to a rehabilita-

◄ ***Figure 18.*** *Wall cracking around Castle windows; this window moved outward about one-fourth inch.)*

▲ ***Figure 19.*** *Damaged chimneys of the Smithsonian Castle.*

tion effort (Ruane, 2011b). The information gathered during that study was used for comparison with current damage. Final determination was that the monument was structurally sound, but will not be reopened to the public until further notice.

With the damage assessment now complete, the National Park Service and other agencies will consider the repairs that must be made and the implications of this event on planning and emergency preparedness procedures.

The detailed special report to EERI on the Washington Monument (Nikolaou et al., 2011) that is excerpted in this section is available on EERI's clearinghouse site at http://www.eqclearinghouse.org/2011-08-23-virginia/category/geotechnical/.

Smithsonian Institution. Based on initial reports of very limited damage, the EERI team did not conduct general reconnaissance of structural damage outside the epicentral region; however, the GEER and EERI teams were invited by the secretary of the Smithsonian Institution (Wayne Clough, a geotechnical engineer and former EERI member) to document damage in two of the Smithsonian facilities: the administration building in D.C. and a large storage facility in suburban Maryland.

The Smithsonian Institute's structures represent a complex mix of structure types and uses. The Institution's administration building is located on the Mall; it was built in the mid-1800s of stone and masonry and is known as the Castle. There was considerable shear cracking throughout the building, especially around windows and major corners (Figure 18). The large chimneys cracked to the point that they had to be wrapped in plywood and restrained (Figure 19).

There were also reports of damage at a Smithsonian warehouse complex approximately six miles from the Mall in Maryland. There, five warehouse buildings (called pods) store thousands of historical artifacts from around the world. They are typical warehouse buildings of concrete-framed construction and infilled walls with double-T concrete roofs. The interior storage area consists of three floors of steel constructed as standard mezzanine floors that carry the loads to steel columns and down to the building foundations. The steel storage area is independent of the warehouse structure, except they share the same foundation.

In one pod there was damage in a stair well that consisted of concrete construction that transferred to

Figure 20. *Concrete stairwell. Notice infilled wall crack (blue tape) at framing beam in warehouse wall across from stairs.*

Figure 21. *Stairwell concrete column failure at first mezzanine floor level.*

steel mezzanine construction once one got to each floor level (see Figures 20 and 21).

In the steel artifact storage area of one pod there was evidence of considerable seismic load (Figure 22). Two approximately 1-inch anchor bolts completely sheared and the tension cross brace yielded. Not only did that steel brace yield in tension, but one brace actually ruptured.

The building and the independent steel-framed storage structure moved differentially during the earthquake, as evidenced by damaged insulation seen in vertical pipes (Figure 23). The differential displacement could have been as much as three inches.

Social Impacts

Perhaps the most significant social impacts associated with this earthquake were those in major metropolitan areas, particularly Washington, D.C., and parts of suburban Maryland and Virginia. These areas are unprepared to deal with even a moderate earthquake, particularly with respect to evacuation, communications, and transportation. Insights on these issues were gained by reconnaissance team members primarily through interviews with emergency management and transportation officials in the area. Additionally, two people who later became team members were in downtown Washington at the time of the earthquake and were able to observe the resulting evacuation, communication, and transportation problems. Team members from the Disaster Research Center (DRC) also interviewed local and national government officials and private citizens in Mineral and Culpeper, Virginia, as well as in Washington, D.C.

Earthquake Preparedness. As with other communities in moderate seismic risk zones on the East Coast, the inhabitants of the towns and cities affected by this earthquake have little earthquake

Figure 22. *Base floor of artifact storage area showing sheered steel framing support anchorage and brace yielding (flaked off paint) at plate connection.*

Figure 23. *Battered insulation of vertical pipe through mezzanine floors.*

awareness and no preparedness planning. The local emergency management agencies in Washington, D.C., and surrounding suburbs have capable, professional staffs and relatively good resources, this being one of the wealthiest areas in the country, but the organizations have given little or no attention to earthquake preparedness. Building security personnel have no training about earthquakes, and schools give scant attention to the earthquake risk, focusing instead on fires, as reflected in their regular fire drills, on nuclear incidents, or on school invaders.

Building Evacuation. Neither students nor the general public have been instructed on actions to take in case of an earthquake, including the generally accepted guidance to drop, cover, and hold on while inside a building. Instead, emergency planning is directed at potential terrorist attacks, and the public displays much greater awareness of that than the earthquake threat. Many building occupants decided to evacuate immediately when the shaking began — hardly surprising in light of their awareness of terrorism — though some residents who had lived in California reported that they sensed that the shaking was caused by an earthquake rather than a terrorist strike and therefore stayed in place.

One of the enduring images of response to the earthquake, captured by television and newspapers from around the country, were the tens of thousands of people who evacuated office and apartment buildings up and down the East Coast, most notably in downtown Washington and in New York City. Many moved out of buildings on their own initiative, or because they were prompted by co-workers and friends, while others were told to do so by authorities. Elevators were a favored means of evacuation unless people were directed to use stairs. Major landmarks were evacuated, including the White House, the Capitol, monuments on the National Mall, the National Cathedral, and City Hall in New York.

Those that left their buildings during the actual shaking violated the most basic rule of earthquake response in high seismic risk states like California, but at all the places the team collected information — from Mineral, Virginia, to Washington, D.C., — a great majority of people said they thought it was something else which with they are more familiar — a terrorist attack, transportation accident, or hurricane. Many indicated that they evacuated their buildings because evacuation was part of their fire drills, the emergency for which they practiced most. In Mineral, many respondents thought it was an incident at the North Anna Nuclear Power Plant, and they rushed around the neighborhood to check on older residents.

In Washington, people remained adjacent to their buildings, which exposed them to possible collapsing walls and parapets; those who congregated in the streets blocked traffic. A smaller number of evacuees went to the open areas of small parks and squares, which in many cases were still close to potential building hazards. Some patrons in outdoor restaurants next to large buildings were observed nonchalantly eating during and after the shaking.

Communication. In a disaster, people use both traditional and nontraditional ways to get critical information that will help them decide how to cope. The large crowds outside buildings were observed milling — moving about and talking with acquaintances, coworkers, and strangers on the street. Others sought news and information from the radio and their cell phones. People wanted to know exactly what had happened, whether or not they should return to work or go home, the condition of the transportation system and roads, and, most importantly, the status of family members and friends.

The demands placed on communication technology exceeded its capacity, forcing people to innovate in their quest for information and direction, as exemplified by the exchange of information in crowds on the streets and, later, on crowded subway platforms. If the earthquake had been a major disaster, the technological problems that emerged would have led to far greater disruption.

The surge in cell phone use in the metropolitan area and elsewhere brought about a two-hour period during which customers could not complete calls, even legitimate 911 calls. The major carriers — AT&T, Verizon, T-Mobile and Sprint — reported no physical damage to their wireless systems, but their networks were all overloaded. The performance of landline networks varied across the area. Evacuees that had gotten through to someone shared the information messages they had with others. Emergency services organizations relied on radio and satellites to communicate. Some employers sent emails to their staffs, while others used loudspeakers in the streets to communicate instructions and information to their employees. The speed of re-establishing cell networks varied among providers.

Transportation. After the earthquake, flights were delayed or suspended by the Federal Aviation Administration at airports in New York, Newark, and Washington, D.C., so the facilities could be inspected. Some trains and subways were delayed because tracks and bridges had to be inspected for damage. Travelers on streets and highways and subways also faced challenges. The surge of people using the highways and expressways to get home exacerbated delays in a region known for its traffic problems even in normal times. A surge in ridership also slowed service on parts of the Metro system. Many subway entrances and platforms became dangerously overcrowded.

In the aftermath of the quake, questions have arisen about the provision of sound and timely information by authorities. Transportation agencies tried their best to transmit news through radio announcements and social media, but many people have complained about a lack of useful intelligence. Communications difficulties are common to all crises — indeed define them to some extent — and only advanced planning and coordination can ameliorate the challenges. The Metropolitan Washington Council of Governments, a region-wide entity, is now working on a strategy to improve coordination of transportation information.

Recovery

Soon after the earthquake, EQECAT, the catastrophe risk modeling firm, estimated losses on the East Coast at $200-$300 million, with less than $100 million of that insured (*Washington Post,* 2011). These early estimates will undoubtedly be refined when more damage data becomes available. More recent inspections of some structures have determined that they were damaged more than originally thought.

For the most part, in undamaged evacuated buildings in Washington, D.C., activities resumed either hours after the earthquake or the next day. Communications networks throughout the East Coast rebounded a few hours after the earthquake, and disruptions to such transportation systems as airports and subways lasted only until safety inspections were completed on the day of the event.

Some school systems have had a longer road to recovery. For example, schools were closed in parts of the Washington, D.C., area and in Louisa County for an extended period, including the two damaged schools in Mineral, Virginia (see page 4). Also on a slow recovery trajectory are some of the damaged historic and highly symbolic structures in Washington, D.C., that are undergoing extensive inspections and repairs. Both the Washington National Cathedral and the Washington Monument have been closed to visitors. The National Park Service, which manages the Washington Monument, has announced that the structure will be closed indefinitely, and repairs on the National Cathedral are expected to take years.

Questions have arisen regarding the direction that can be taken in protecting historic buildings from future earthquakes, and how much can be done while still maintaining their historic integrity. These questions are familiar to those in any active seismic zone who have dealt with historic buildings before or after quakes, but new to most on the East Coast. National Cathedral officials interviewed shortly after the quake had no plans for rehabilitating the structure so that it might better withstand future seismic events. There is a need for strong-motion accelerometers to be installed in important structures to provide records of ground motions. This would help improve our understanding of the type of earthquakes that occur on the East Coast and the effects that the unique geology in this area could have.

An Alternative Future

The day after the earthquake, two of the emergency management agencies in the Washington, D.C., area — the District of Columbia Emergency Management Agency and the Montgomery County Office of Emergency Management and Homeland Security — posted guidelines for earthquake safety on their websites for the first time. Such simple acts suggest that improved earthquake preparedness is possible in the region. However, this requires increased earthquake awareness among policy makers and practitioners, and public education initiatives.

A first step would be to integrate earthquakes into preparedness planning for hazards that communities in the region are most familiar with, such as hurricanes, terrorism, and fire. Many principles apply to preparedness for all hazards; some principles differ, but good public education can provide the critical information in every case. For example, guidelines for building evacuations could incorporate earthquake information along with that for fire. Plans for inspecting hurricane damage could be expanded to include the particulars for earthquake-induced damage. Public and private decision makers should recognize that improving communications, such as assuring power to cell towers and prioritizing 911 calls, will be of significant benefit in all future crises, including earthquakes.

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