MAPPING NEHRP VS30 SITE CLASS IN PHILADELPHIA USING GEOPHYSICAL AND EXISTING SUBSURFACE DATA

J. Coe¹, S. Mahvelati², M. Senior³, and P. Asabere⁴

ABSTRACT

The 2011 M5.8 Mineral, Virginia earthquake in the Central Virginia Seismic Zone (CVSZ) affected a large area of the Eastern United States and reminded us of the potential negative consequences of seismic activity in that region of the country. The dense population density, older building stock, stiffer bedrock, and the lack of a comprehensive intraplate earthquake model all contribute to increased vulnerability or higher levels of uncertainty regarding seismic hazard in the Eastern United States. The city of Philadelphia sits near the center of the Northeast megalopolis in the corridor between Boston and Washington, D.C. and is not immune from these hazards. For example, window damage caused building evacuations, speed limits were enacted for regional rail to allow for track inspections, and bridges across the region were inspected for damage after the 2011 M5.8 Mineral earthquake. Moreover, Philadelphia is located approximately 80 km from the Lancaster Seismic Zone (LSZ), which has produced a number of moderate earthquakes in the past and has been persistently active over at least the last two centuries. In addition to the LSZ, the Huntingdon Valley Fault, which may have been responsible for the Abington-Cheltenham sequence of small earthquakes in March-May 1980, runs just within the northwestern limit of the consolidated Philadelphia city-county lines. However, despite this seismic setting and increased awareness of seismic hazard in the Eastern United States, very few studies have focused on characterizing seismic hazard in Philadelphia by incorporating widespread geophysical measurements and existing geotechnical data. This paper

¹Assistant Professor, Dept. of Civil Engineering, Temple University, Philadelphia, PA 19122 (email: joseph.coe@temple.edu)
²Graduate Student Researcher, Dept. of Civil Engineering, Temple University, Philadelphia, PA 19122 (email: smahvelati@temple.edu)
³Staff Professional, Schnabel Engineering, West Chester, PA 19382 (email: tue75671@temple.edu)
⁴Project Engineer, Civil Engineering Dept., Southeastern Pennsylvania Transportation Authority, Philadelphia, PA 19107 (email: PAsabere@septa.org)

provides results from efforts to evaluate the geographic distribution of National Earthquake Hazard Reduction Program (NEHRP) Vs30 site class within Philadelphia as a proxy for sediment stiffness. Vs30 was primarily estimated using the active and passive Multichannel Analysis of Surface Waves (MASW) method. Data from other geophysical methods as well as existing geotechnical borings were also incorporated into the study for mapping purposes. This paper discusses the field geophysical testing, efforts to catalog data from previous geotechnical investigations, and findings related to potential site amplification given the geographic distribution of Vs30 in relation to the geologic conditions within the Philadelphia metropolitan area.
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The 2011 M5.8 Mineral, Virginia earthquake in the Central Virginia Seismic Zone (CVSZ) affected a large area of the Eastern United States and reminded us of the potential negative consequences of seismic activity in that region of the country. The dense population density, older building stock, stiffer bedrock, and the lack of a comprehensive intraplate earthquake model all contribute to increased vulnerability or higher levels of uncertainty regarding seismic hazard in the Eastern United States. The city of Philadelphia sits near the center of the Northeast megalopolis in the corridor between Boston and Washington, D.C. and is not immune from these hazards. For example, window damage caused building evacuations, speed limits were enacted for regional rail to allow for track inspections, and bridges across the region were inspected for damage after the 2011 M5.8 Mineral earthquake. Moreover, Philadelphia is located approximately 80 km from the Lancaster Seismic Zone (LSZ), which has produced a number of moderate earthquakes in the past and has been persistently active over at least the last two centuries. In addition to the LSZ, the Huntingdon Valley Fault, which may have been responsible for the Abington-Cheltenham sequence of small earthquakes in March-May 1980, runs just within the northwestern limit of the consolidated Philadelphia city-county lines. However, despite this seismic setting and increased awareness of seismic hazard in the Eastern United States, very few studies have focused on characterizing seismic hazard in Philadelphia by incorporating widespread geophysical measurements and existing geotechnical data. This paper provides results from efforts to evaluate the geographic distribution of National Earthquake Hazard Reduction Program (NEHRP) $V_{s30}$ site class within Philadelphia as a proxy for sediment stiffness. $V_{s30}$ was primarily estimated using the active and passive Multichannel Analysis of Surface Waves (MASW) method. Data from other geophysical methods as well as existing geotechnical borings were also incorporated into the study for mapping purposes. This paper discusses the field geophysical testing, efforts to catalog data from previous geotechnical investigations, and findings related to potential site amplification given the geographic distribution of $V_{s30}$ in relation to the geologic conditions within the Philadelphia metropolitan area.

Introduction

The 2011 M5.8 Mineral, Virginia earthquake in the Central Virginia Seismic Zone (CVSZ) was a stark reminder of the negative consequences of seismic activity in the Central and Eastern United States (CEUS). The earthquake was felt by an extensive and densely populated area of the East Coast (Fig. 1). The effects of this earthquake were far-ranging, particularly in the nation’s capital city of Washington, D.C. The effects in Philadelphia were less severe but still noticeable. For example, buildings were evacuated due to window damage, speed limits were enacted for track inspections in the regional rail system, and bridges across the region were inspected for damage.
A number of key issues related to seismicity in the CEUS were highlighted in the 2011 M5.8 Mineral earthquake. For instance, intraplate locations are clearly not immune to seismic risk despite their historically lower rates of seismicity (Fig. 2). In fact, as much as 25% of the net seismic moment release in continental regions can be attributed to seismic activity at “passive” continental margins such as the eastern North American plate [1]. Intraplate seismicity is generally thought to reflect reactivation of ancient, favorably-oriented, faults created by previous continental collision and breakup [2]. However, a large knowledge gap still exists regarding the tectonic process that govern such intraplate earthquakes due to their slower deformation rates, relative infrequency in the historical catalog, lack of micro-seismic recordings, and little surficial evidence of faulting or displacement [2,3]. The lack of a comprehensive model to explain intraplate earthquakes leads to higher uncertainty when evaluating the seismic hazard of the CEUS. Additionally, a larger percentage of CEUS structures predate modern seismic codes and utilize unreinforced masonry construction. This means that the vulnerability of these areas is high despite the relatively modest risk of ground shaking [3] (Fig. 2). Based on the FEMA HAZUS®-MH software, the annualized earthquake losses in the CEUS can exceed tens of millions of dollars and account for up to 11% of the annualized earthquake losses across the United States [4]. Another complicating factor is the stiffer bedrock in the CEUS, as highlighted in higher values for the seismic Quality Factor (Q) [5]. This signifies that CEUS earthquakes can cause damage over a much broader area than similar events in the WUS. In fact, the 2011 M5.8 Mineral, Virginia earthquake was felt over a larger region than any other previous instrumentally recorded earthquake in the CEUS [6] (Fig. 6). Landslides were encountered at locations that
exceeded four times the limits established from previous events, which translated into the largest area affected by landslides for events of this magnitude in the US [7]. Additionally, there is evidence to suggest that seismic events in the CEUS radiate energy at higher frequencies given the theory that they result from reactivated fault mechanisms that may have healed over time [8]. Smaller residential structures may therefore experience strong shaking as their natural frequencies may approach resonant conditions with the higher frequency ground motions.

Figure 2. Historical seismicity of the Lancaster seismic zone and Central Virginia seismic zone (including the 2011 M5.8 Mineral, Virginia earthquake) [2].

The risk of seismic activity in the city of Philadelphia is lower than other parts of the CEUS. However, the estimated annualized earthquake losses (categorized between $10 to $20 million dollars) for Philadelphia reflects the lack of seismic resiliency and the large building inventory [4]. This estimate for Philadelphia is comparable to other urban areas within more active seismic zones (e.g. Evansville, Indiana in the Wabash Valley Seismic Zone). Additionally, the level of seismic risk for central Virginia and for Washington, D.C. was comparable to Philadelphia prior to the 2011 M5.8 Mineral earthquake. This risk has since been adjusted in the 2014 National Seismic Hazards maps to account for the wealth of new information garnered from this seismic event. And like Washington, D.C., Philadelphia is located near a zone where earthquakes have been recorded historically. In the case of Philadelphia, it is located approximately 80 km from the Lancaster Seismic Zone (LSZ), which is the most active seismic zone in the Commonwealth of Pennsylvania [9]. The LSZ has produced a number of moderate earthquakes in the past and has been persistently active over at least the last two centuries [10] (Fig. 2). The level of seismicity has been relatively uniform, but as recently as the 1960’s, a number of earthquake bursts with magnitudes as high as 4 have occurred. The 1984 M4.1 Martic earthquake was the significant event of the most recent burst. The LSZ is part of the larger belt of seismicity that surrounds the Newark Basin and is laced with known faults. However, numerous smaller or deeply buried faults remain undetected and even the known faults are poorly located at earthquake depths, have no seismicity at all associated with them, or undergo very low displacement rates rendering it difficult to estimate their characteristics [3,9]. In addition to the LSZ, the Huntingdon Valley Fault is inside the northwestern limits of the consolidated Philadelphia city-county lines. Evidence suggests that this fault was responsible for
the Abington-Cheltenham earthquake sequence of March-May 1980 (largest with Nuttli magnitude of 3.7) that struck northern Philadelphia and its suburbs [11]. It is difficult to determine if the Huntingdon Valley Fault and faults in the LSZ are seismogenic and capable of reproducing an earthquake of similar or higher magnitude to the 1984 M4.1 Martic earthquake and Abington-Cheltenham 1980 earthquake sequence.

Given the preceding discussion, it is evident that seismic hazards in the CEUS must continue to be evaluated more thoroughly to avoid future potentially catastrophic seismic events. This is particularly the case for a major Eastern United States (EUS) metropolitan area such as Philadelphia, which has a high population density, complex inter-related infrastructure systems, is relatively understudied when it comes to seismic hazard, and is generally less prepared from a policy and outreach standpoint compared to cities in the Western United States. Therefore, it is important that the unique characteristics of the regional geologic conditions are incorporated into seismic hazard assessments, site response, and ground motion characterization of the EUS. These efforts have been implemented for areas of the Central United States (CUS) affected by the New Madrid and Wabash Valley seismic zones such as Memphis, Tennessee [12], St. Louis, Missouri [13], and Evansville, Indiana [14]. The Memphis Earthquake Hazard Mapping Project (MAEHMP), St. Louis Area Earthquake Hazard Mapping Project (SLAEHMP), and Evansville Area Earthquake Hazards Mapping Project (EAEHMP) have all led efforts to develop urban earthquake hazard maps for their respective communities.

This paper describes similar mapping efforts to evaluate site amplification throughout the Philadelphia metropolitan area. NEHRP site class based on the average shear wave velocity in the upper 30 m (i.e., $V_{s30}$) was used as a proxy for site stiffness. $V_{s30}$ was evaluated using a combination of geophysical measurements with surface wave methods and existing geotechnical subsurface information from borings throughout the region.

**Geophysical Testing**

For this study, geophysical testing was performed at 13 locations within the Philadelphia city limits and 1 site in the adjacent suburbs of southern New Jersey (Fig. 3). These sites represented a broad range of anticipated geologic and subsurface conditions. Data acquisition and post-processing were performed based on the current standard of practice for surface wave measurements using the multichannel analysis of surface waves (MASW) method.

**Data Acquisition**

The data acquisition system used in the geophysical testing consisted of a 24 channel array of GiscoGeo 4.5 Hz vertical geophones connected to a Geometrics Geode seismograph. The seismograph was operated with a field laptop running the Geometrics Seismodule Controller Software (SCS). MASW was performed using both active sources (sledgehammers) and passive sources (ambient seismic noise). The array of geophones was linear in both cases. For active MASW testing, the geophones were spiked into the ground using 1.5 m (4.9 ft) spacing between receivers. This resulted in a total spread length of 34.5 m (113.2 ft). In the case of passive MASW testing, a larger receiver interval of 5.0 m (16.4 ft) was used, which resulted in a total spread length of 115 m (377.2 ft). Waveforms from active testing were sampled at a 0.125 ms interval for a total time of 2.048 s. For passive surveys, the sampling interval and total record length were increased to 32.768 s. The center location of the receiver spread is typically the
location to which the 1D \( V_s \) profile is assigned in MASW testing. Therefore, the active and passive arrays typically shared the same midpoint whenever possible. Surface waves were introduced into the subsurface using impacts from sledgehammers (20 lb, 8 lb, and 4 lb) on an aluminum plate resting on the ground surface. Multiple off-end sledgehammer shots were used on either side of the array during active MASW surveys. Typical source offsets included \( \pm 1d \), \( \pm 3d \), \( \pm 6d \), \( \pm 12d \), and \( \pm 24d \) from the closest receiver, where \( dx \) represents the receiver spacing of 1.5 m (4.9 ft). The multiple shots and use of different size sledgehammers ensured broad enough frequency content in the surface waves to sufficiently sample enough strata to estimate \( V_{s30} \). Most sites were urban and affected by significant background seismic noise. Signal to noise ratio in the active MASW surveys was therefore improved by combining at least 3 to 5 stacks while acquiring waveforms. In the case of passive surveys, multiple records (20+) were acquired to ensure the background seismic noise was sufficiently characterized. No stacking was performed for the passive surveys.

**Data Post-Processing**

All surface wave data was post-processed using the Geometrics SeisImager/SW software package. General steps in the data post-processing included stacking the waveforms recorded from different shots, transforming the stacked data from the space-time domain to the phase velocity-frequency domain, extracting a composite fundamental mode dispersion curve, and finally inversion to estimate the most probable \( V_s \) profile. For active MASW surveys, all possible pair of cross-correlations were computed for a given multichannel record and stacked [15]. The SeisImager/SW software was then used to implement the phase-shift method [16] and apply a wavefield transform that generates an image representing energy accumulation in the phase velocity-frequency domain (i.e., overtone image). A fundamental mode dispersion curve was then extracted from the overtone image. This process ensured that the resulting dispersion curve was a composite curve based on all source offset records at a given site. The raw passive records were processed using the spatial autocorrelation (SPAC) method [17]. After conversion into an overtone image, a composite fundamental mode dispersion curves was also extracted from these records. The active and passive fundamental mode dispersion curves were then merged into a single dispersion curve for the site. The resulting composite fundamental mode dispersion curve was then inverted using the genetic algorithm inversion routine available in SeisImager/SW [18]. The genetic algorithm is a nonlinear global search method that mimics the natural selection process to generate and evolve a population of candidate solutions to an optimization problem [19]. Large amounts of forward modeling are necessary using this inversion technique, but the resulting process is less sensitive to the starting \( V_s \) model and avoids getting trapped in local minima as can occur in the conventional iterative non-linear least squares method [18]. For the inversion parameterization, 12 layers were assigned and the search area for \( V_s \) was equal to \( \pm 20\% \) of the initial model \( V_s \). The number of population and generations was set to 75 (i.e., a total of 5625 models), the number of binary digits to 5, and the mutation and crossover probability were 50%. This parameterization ensured that a sufficiently broad range of potential \( V_s \) models were evaluated during the inversion process.

**Existing Geotechnical Information**

As part of this study, existing geotechnical information was used to supplement the geophysical
measurements. Boring logs were acquired from local geotechnical consultants and the Pennsylvania Department of Transportation for an additional 7 sites across the Philadelphia metropolitan area. These sites were chosen to augment areas of Center City Philadelphia for which geophysical testing proved difficult to perform due to logistical issues. They also provided an opportunity to compare the relative agreement between estimated site class using the two methods. At sites where existing geotechnical subsurface information was used, the weighted average blow count for the upper 30 m (100 ft) of the site was computed after the boring log was digitized and input into a spreadsheet. These efforts resulted in a total number of 20 sites for which site class was evaluated across the Philadelphia metropolitan region.

Results

The site classes for all locations investigated in this study are mapped in Figure 3. The most common site class was D (stiff soil) with half of all sites mapping to this site class. Site class C (very dense soil/soft rock) was also quite common with 8 of the 20 total sites mapping to this level. Notably, there were 2 sites that mapped as site class E (soft soil). A number of items are notable based on these preliminary results. First, there was a significantly large variation in site class across the relatively small area (approximately 500 km²) investigated in this study. Within a few kilometers of each other, locations near the Delaware River in Philadelphia may contain enough soft soils to classify as E sites subject to potentially high levels of site amplification, while sites in the central and western side of the city map to stiff sites such as C (and very nearly B). This is highly indicative of the distinct local geologic conditions in the southeastern Pennsylvania area. The city of Philadelphia is located on the Fall Line that separates the unconsolidated sediment deposits of the Atlantic Coastal Plain from the Piedmont physiographic regions. The Piedmont physiographic region near Philadelphia is primarily composed of hard metamorphosed rock (e.g. schists, amphibolite, and associated ultramafic rocks of the Wissahickon Formation) near its southern boundary and older metasedimentary rocks near its northern boundary [20]. In some areas, the bedrock is more feldspathic and less pelitic, indicative of the Fairmount member of the Wissahickon Formation [20]. Bedrock typically exhibits significant weathering and is overlain by saprolite of highly variable thickness and unconsolidated Atlantic Coastal Plain [21]. The highly weathered surface of the Wissahickon Formation is approximately located at sea level near the Schuylkill River on the western side of Center City Philadelphia and the thickness of unconsolidated sediments tends to increase towards the eastern side of the city near the Delaware River (Glynn and Fergusson, 1991). Given the large fluctuation in bedrock depth, weathering profile, and soil thickness across the city, it is unsurprising that a wide range of site classes are mapped within the city limits. Moreover, the general trend of increasing soil thickness towards the eastern side of the city is evident in Fig. 3 as the majority of the stiffer sites (site C and those nearly mapping to site class B) are located in the north and western areas of the city and the softer sites (site class D and E) are located closer to the Delaware River. It should also be noted that a few of the site class D sites exhibited \( V_{s30} \) values closer to the 180 m/s cutoff between site class D and E. This implies that a number of the stiff soil sites were actually borderline site class D/E sites with transitional site amplification behavior. Unfortunately, major regional infrastructure is located along the Delaware River, including ports, major bridges, and Interstate 95 (I-95). Based on the presence of site class E or D/E, some of this infrastructure may be vulnerable to resonant shaking conditions due to high site amplification effects. There is one final aspect worthy of note in Fig. 3. In a number of cases,
there appears to be relative inconsistency between the site classes from MASW and those evaluated based on blow counts from boring logs. For example, there is a cluster of SPT-estimated site class C locations near the center of the map that contrasts against two nearby site class D sites estimated from MASW V_s profiles. However, it is not completely clear whether the mapped inconsistencies point to the relative coarse nature of blow counts as a tool to estimate site class or whether the differences are attributable to small scale spatial fluctuations in bedrock and soil thickness conditions (e.g., presence of a paleochannel). This points to the need to collocate geophysical measurements in locations where SPT measurements have been made to reconcile discrepancies between the two approaches. This will aid in the development of a comprehensive site amplification map for Philadelphia because a wealth of existing geotechnical boring log data is available to aid in interpolating between geophysical measurements. Moreover, single station measurements of ambient vibrations such as those acquired in the horizontal-to-vertical spectral ratio (HVSR) technique may allow testing at a finer spatial scale across the city relative to MASW and can potentially address small scale spatial inconsistencies in site class.

Figure 3. Map of NEHRP site class in Philadelphia.

Conclusions

The results from this study demonstrate that site amplification varies tremendously across the relatively small area encompassing the city of Philadelphia. The distinct geologic setting of Philadelphia in which the city straddles the Atlantic Coastal Plain and Piedmont physiographic region no doubt contributes to this observation. This highlights the importance of continued efforts to incorporate local site conditions in seismic hazard analyses of Philadelphia. This is especially the case for the vital infrastructure located along the Delaware River, where soft soil sites were located in this study. Finally, given the wide spatial fluctuation in site class, future mapping efforts should consider strategies to increase the spatial resolution with which sites are characterized for site class maps. This can include the development of region specific SPT blow count and V_s correlations from collocated measurements of both parameters as well as the use of other geophysical techniques such as the HVSR method. These efforts will lead to better
characterization of seismic hazard in the city of Philadelphia and facilitation of code-based seismic design in this region. This is quite important given the relative uncertainty in intraplate seismic activity, the recent damage caused by the 2011 M5.8 Mineral, Virginia earthquake in Washington, D.C., and the relative similarities in seismic environments between Washington, D.C., and Philadelphia.

References


