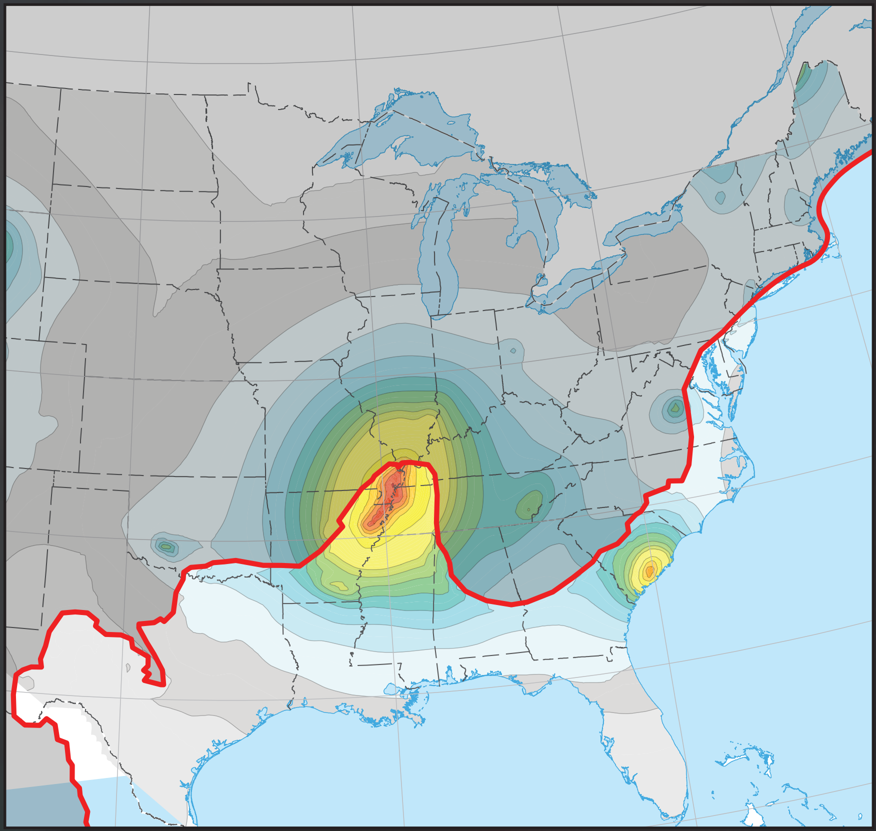
Natural Hazards Mission Area—Earthquake Hazards Program

Prepared in collaboration with North Carolina State University

2023 Earthquake Ground-Motion Workshop for the Central and Eastern United States, with a Focus on the Gulf and Atlantic Coastal Plains—Agenda and Abstracts



Scientific Investigations Report 2025–5025

U.S. Department of the Interior
U.S. Geological Survey

Cover. Map of Seismic hazard in the Central and Eastern United States and delineation of the Gulf and Atlantic Coastal Plains (regions to the southeast of the red solid line). Modified November 21, 2024, from Petersen and others' (2023) map of 1-second spectral accelerations having a 2-percent probability of being exceeded in 50 years for sites with a time-averaged shear-wave velocity within 30 meters of the Earth's surface of 760 meters per second.

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By Oliver S. Boyd, Julie A. Herrick, Ashly Cabas, and Sean K. Ahdi

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We are also grateful to Mark Petersen, Morgan Moschetti, and Emily Martin, all at the U.S. Geological Survey, for their constructive reviews of the workshop report.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Wave speed	
kilometer per second (km/s)	0.6214	miles per second (mi/s)
kilometer per second (km/s)	3280.84	feet per second (ft/s)
meter per second (m/s)	3.281	feet per second (ft/s)

Abbreviations

CEUS-SSC	Central and Eastern United States-Seismic Source Characterization
DYFI	Did You Feel It?
GMM	ground-motion model
Hz	hertz (cycles per second)
ln	logarithm
MMI	Modified Mercalli Intensity
NGA-East	Next Generation Attenuation Relationships for the Eastern United States
NSHM	National Seismic Hazard Model
PGA	peak ground acceleration
SA	spectral acceleration
USGS	U.S. Geological Survey
VSAP	Vertical Seismic Array in Paducah, Kentucky
M_W	earthquake moment magnitude
V_{S30}	time-averaged shear-wave velocity within the upper 30 meters of the Earth's surface
V_S	shear (*S*)-wave velocity

2023 Earthquake Ground-Motion Workshop for the Central and Eastern United States, with a Focus on the Gulf and Atlantic Coastal Plains—Agenda and Abstracts

By Oliver S. Boyd,[1] Julie A. Herrick,[1] Ashly Cabas,[2] and Sean K. Ahdi[1]

Abstract

The U.S. Geological Survey held a virtual workshop December 7–8, 2023, to share research and ideas about earthquake ground motions in the Central and Eastern United States, with a focus on the Atlantic and Gulf Coastal Plains. The workshop was organized to learn about potential regionalization of ground-motion characteristics (source, path, and site), consider new explanatory variables for site response, and hear and discuss updates on ground-motion research on the Atlantic and Gulf Coastal Plains. The workshop was organized into a series of contributed presentations and three panel discussions held during 2 days. This report documents the agenda, contributed abstracts, and panel summaries.

Introduction

On December 7–8, 2023, The U.S. Geological Survey (USGS) held a virtual workshop titled "2023 Earthquake Ground-Motion Workshop for the Central and Eastern United States, with a Focus on the Gulf and Atlantic Coastal Plains." Approximately 150 participants listened to 16 presentations and 3 panel discussions. The workshop aimed to (1) share research and ideas related to earthquake ground motions in the Central and Eastern United States, (2) learn about the potential regionalization of ground-motion characteristics (source, path, and site), (3) consider new explanatory variables for site response, and (4) hear and discuss updates on ground-motion research on the Atlantic and Gulf Coastal Plains. This topic was important because of the 2023 National Seismic Hazard Model (https://www.usgs.gov/programs/earthquake-hazards/science/national-seismic-hazard-model), released soon after the workshop, and ongoing recognition of avenues for improvement to the ground motion characterization, especially in the Gulf and Atlantic Coastal Plains. This workshop resulted in a renewed motivation among scientists to encourage community participation in acquiring more geophysical data and to better study and model earthquake ground motions in the Central and Eastern United States.

Agenda

Presentations and panel discussions for the virtual workshop were distributed during 2 days, in four 2-hour blocks, during December 7–8, 2023. The agenda for the virtual workshop is presented in table 1. The lightning presentations on available geophysical data are not discussed in this report, but relevant conclusions are included in the section "Panel Discussion 1—Data Resources and Gaps in the Central and Eastern United States and Coastal Plains."

[1]U.S. Geological Survey.

[2]North Carolina State University.

Table 1. Agenda for the virtual 2023 Earthquake Ground-Motion Workshop for the Central and Eastern United States, held on December 7–8, 2023.

[Titles in quotes refer to the titles of presentations from this workshop, which all have abstracts in this report. Times given are in Mountain Standard Time. USGS, U.S. Geological Survey; Lg, seismic S-wave trapped in the crust; NGA-East, Next Generation Attenuation Relationships for the Eastern United States; RMS, Risk Management Solutions]

Time	Session or presentation title	Presenter(s)
	Thursday, December 7, 2023	
10:00–10:10	Workshop overview	Julie A. Herrick (USGS), Sean K. Ahdi (USGS), Ashly Cabas (North Carolina State University), and Oliver S. Boyd (USGS)
10:10–11:00	Lightning presentations on available geophysical data	Ron Andrus (Clemson University), Sara Stone (South Carolina Department of Transportation), Youssef M.A. Hashash (University of Illinois Urbana-Champaign), Ellen M. Rathje (University of Texas at Austin), Jonathan P. Stewart (University of California, Los Angeles), Thomas Weaver (Nuclear Regulatory Commission), and Clint Wood (University of Arkansas)
11:00–11:20	“Estimating Bedrock Shear-Wave Velocity at Vertical Strong-Motion Array in Paducah, Kentucky (Upper Mississippi Embayment) Using Nodal Array Recordings of Ambient Noise”	N. Seth Carpenter (University of Kentucky)
11:20–11:40	“Joint Inversion of Surface-Wave Dispersion Curves and Horizontal-to-Vertical Spectral Ratios for Atlantic Coastal Plain Velocity Structure, Eastern United States, Using Crustal-Scale Refraction Data”	Thomas Pratt (USGS)
11:40–12:00	“Regional Seismic Velocity Model for the United States Atlantic and Gulf Coastal Plains Based on Measured Shear-Wave Velocity and Surface Geology”	Cassie Gann-Phillips (North Carolina State University)
12:00–1:00	Lunch	
1:00–1:40	Panel Discussion 1—Data Resources and Gaps in the Central and Eastern United States and Coastal Plains	Moderated by Ashly Cabas (North Carolina State University) • Ron Andrus (Clemson University) • Seth Carpenter (University of Kentucky) • Cassie Gann (North Carolina State University) • Thomas Pratt (USGS) • Jonathan P. Stewart (University of California, Los Angeles) • Thomas Weaver (Nuclear Regulatory Commission) • Clint Wood (University of Arkansas)
1:40–2:00	“Can ‘Did You Feel It?’ Intensity Data be Used in Ground-Motion Modeling?”	Pengfei Wang (Old Dominion University)
2:00–2:20	“Gulf Coast and Central and Eastern United States Boundary Delineation with Lg Amplitude-Distance Inflections”	William Levandowski (TetraTech)
2:20–2:40	“Physics-Based Broadband Ground-Motion Simulations of Scenario Earthquakes in the Central and Eastern United States Using High-Performance Computing”	Arben Pitarka (Lawrence Livermore National Laboratory)
2:40–3:00	“Central and Eastern United States Coastal Plain Seismic Amplification and Hazard Based on an Updated Regional Velocity and Geotechnical Model”	Chris H. Cramer (University of Memphis) and James Kaklamanos (Merrimack College)

Table 1. Agenda for the virtual 2023 Earthquake Ground-Motion Workshop for the Central and Eastern United States, held on December 7–8, 2023.—Continued

[Titles in quotes refer to the titles of presentations from this workshop, which all have abstracts in this report. Times given are in Mountain Standard Time. USGS, U.S. Geological Survey; Lg, seismic S-wave trapped in the crust; NGA-East, Next Generation Attenuation Relationships for the Eastern United States; RMS, Risk Management Solutions]

Time	Session or presentation title	Presenter(s)
	Friday, December 8, 2023	
10:00–10:20	"The 1886 Charleston, South Carolina, Earthquake—Source Properties, Ground Motions, and ShakeMap"	Susan E. Hough (USGS)
10:20–10:40	"Buckled Railroad Not Dextrally Offset in Famous Post-Seismic 1886 Photograph West of Charleston, South Carolina"	Roger Bilham (University of Colorado at Boulder)
10:40–11:00	"Geometric Spreading and Apparent Anelastic Attenuation of Response Spectral Accelerations"	Vladimir Graizer (U.S. Nuclear Regulatory Commission)
11:00–11:20	"Improving Central and Eastern North America Ground-Motion Models Using Improved Ground-Motion and Site-Data Resources"	María E. Ramos-Sepúlveda (University of California, Los Angeles)
11:20–11:40	"Development of Central and Eastern United States Ground-Motion Models for Use in the Coastal Plains Using Adjustment Factors"	Mohsen Akhani (University of Memphis)
11:40–11:55	"Lessons Learned from the Next Generation Attenuation Relationships for the Eastern United States (NGA-East) Project"	Christine Goulet (USGS)
11:55–12:35	Panel Discussion 2—Ground-Motion Modeling	Moderated by Sean K. Ahdi (USGS) • Mohsen Akhani (University of Memphis) • Ken Campbell (CoreLogic) • Chris H. Cramer (University of Memphis) • Christine Goulet (USGS) • Vladimir Graizer (U.S. Nuclear Regulatory Commission) • James Kaklamanos (Merrimack College) • Shahram Pezeshk (University of Memphis) • María E. Ramos-Sepúlveda (University of California, Los Angeles) • Emrah Yenier (Haley & Aldrich)
12:35–1:20	Lunch	
1:20–1:40	"Sediment-Thickness Map of the United States Atlantic and Gulf Coastal Plain Strata, and Their Influence on Earthquake Ground Motions"	Oliver S. Boyd (USGS)
1:40–2:00	"Ground-Motion Modeling Issues in the Central and Eastern United States for Future Updates of the U.S. National Seismic Hazard Model"	Morgan P. Moschetti (USGS)
2:00–2:20	"Central and Eastern United States Ground-Motion Model Updates for the 2023 National Seismic Hazard Model and Sensitivity Results"	Jason Altekruse (USGS)
2:20–2:50	Panel discussion 3—Implications and Next Steps	Moderated by Julie Herrick (USGS) • Jason Altekruse (USGS) • Morgan P. Moschetti (USGS) • Mark Petersen (USGS) • Peter Powers (USGS) • Sanaz Rezaeian (USGS) • Emel Seyhan (Moody's RMS) • Allison Shumway (USGS)
2:50–3:00	Closing Statements	Julie A. Herrick (USGS), Sean K. Ahdi (USGS), Ashly Cabas (North Carolina State University), and Oliver S. Boyd (USGS)

Abstracts of Workshop Presentations

Abstracts in this section are ordered alphabetically by first author's last name as opposed to the agenda where they are listed in the order presented.

"Development of Central and Eastern United States Ground-Motion Models for Use in the Coastal Plains Using Adjustment Factors"

By Mohsen Akhani (University of Memphis), Mehran Davatgari-Tafreshi (University of Memphis), and Shahram Pezeshk (University of Memphis)

Ground-motion models (GMMs), such as the one proposed by Pezeshk and others (2018), were originally developed for areas outside the Coastal Plains. This research aims to establish adjustment factors to make GMMs applicable inside the Coastal Plains regions (Akhani and others, 2024). We employed three distinct datasets: the Next Generation Attenuation Relationships for the Eastern United States (NGA-East) dataset (Goulet and others, 2014), the Chapman and Guo (2021) dataset, and a newly assembled and validated Thompson and others (2023) dataset. The residuals were calculated as the differences between the logarithm of the observed data and the logarithm of values estimated by GMMs, considering the site-amplification model developed by Stewart and others (2020). Furthermore, we conducted residual analyses using mixed-effects regression to partition the total residuals into components attributed to between-events, between-stations, and event-site corrected residuals. Sediment-thickness correction factors for stations within the Coastal Plains region are the difference between the observed residuals and the Pezeshk and others (2018) GMM. The sediment thicknesses were derived from a new contour map developed by Boyd and others (2023). Subsequently, we modeled the between-station residuals as a function of sediment thickness. The outcomes revealed that, for most periods, the residual trends of the site terms' time-averaged shear-wave velocity within the upper 30 meters (m) of the Earth's surface (V_{S30}) and sediment depth were mitigated following the application of the proposed sediment-thickness correction for stations within the Coastal Plains. We have successfully decreased the site-to-site standard deviation across all periods from peak ground acceleration (PGA) to 10 seconds by considering the proposed sediment-thickness correction for stations inside the Coastal Plains. Specifically, this reduction ranges from 1.1 percent to 27.9 percent for periods of 0.2 and 0.05 seconds, respectively. For the remaining periods, the reduction values fall within this same range (from 1.1 percent to 27.9 percent).

In another component of this study, we employed the primary NGA-East GMM (weighted average of the final recommended 17 GMMs) to identify any residual trends specific to the Coastal Plains. We observed the same trends and, in this instance, sought to correct the model not only through site-term adjustments but also by considering source and path terms. This modeling decision was prompted by the observed residual trends in the between-station and between-event residuals within the Coastal Plains. Correction factors were developed as a function of V_{S30}, sediment thickness, magnitude, and distance to improve the model's applicability within the Coastal Plains and eliminate the residual trends within the datasets specific to this region. The overall findings of this research hold significance for assessing seismic hazards and risks inside the Coastal Plains.

"Central and Eastern United States Ground-Motion Model Updates for the 2023 National Seismic Hazard Model and Sensitivity Results"

By Jason Altekruse (U.S. Geological Survey [USGS]) and Peter Powers (USGS)

The 2023 update of the USGS National Seismic Hazard Model (NSHM) for the conterminous United States (Petersen and others, 2024) includes effects on site response because of thick sedimentary deposits in the Atlantic and Gulf Coastal Plains and adjustments to the NGA-East GMMs based on an expanded NGA-East database. The update presents sensitivity results showing the impact of the Coastal Plain site amplification and the NGA-East adjustment models. The Chapman and Guo (2021) Coastal Plain amplification model, a sediment-thickness-based site response model, and the NGA-East adjustment model generally decrease ground motions at short periods and increase ground motions at long periods. We also discuss the implementation of other Coastal Plain amplification models for future NSHM updates.

"Buckled Railroad Not Dextrally Offset in Famous Post-Seismic 1886 Photograph West of Charleston, South Carolina"

By Roger Bilham (University of Colorado at Boulder) and Susan E. Hough (USGS)

William E. Wilson's iconic photograph of the Charleston and Savannah Railway near the town of Rantowles, South Carolina (Wilson, 1886) was printed as a picture postcard in the days following the 1886 Charleston, S.C., earthquake and has been widely reproduced since that time. Archival records allow the location, camera orientation, and date the photograph was taken to be established. The photography is frequently cited as evidence for shallow dextral faulting west of Charleston, S.C. However, a photogrammetric analysis indicates that the photograph depicts buckling and minor subsidence, refuting previous interpretations of dextral offset. The photograph captures approximately 1 kilometer (km) of track emerging from a 10-degree bend in a cutting behind the camera to an embankment heading 70 degrees east of north. Photogrammetric scale, focal length, and foreground distance can be derived from the standard railroad track width of 4 feet 8.5 inches and the 30-foot distance between the fishplates joining contiguous steel rails. The foreground tracks are bent to the north compared to rails approximately 70 m to the east (that is, into the photograph), consistent with neither simple dextral arc-tan deformation, nor with the mapped curvature of the 10-degree bend. Minor settlement of the embankment has occurred approximately 120 m east of the camera location. Buckling responsible for this short-wavelength curvature is additionally confirmed by displaced railroad ties whose lateral motions alternately overlap or expose railroad ballast.

The railroad was repaired within 24 hours, allowing the resumption of service along the line. Earle Sloan, who meticulously quantified railroad buckling and offsets along all the Charleston railroads, visited the site after the track had been repaired and reported no dextral offset at the site. On the back of his copy of the postcard, he noted that others had described a dextral offset (Peters and Herrmann, 1986). The absence of shallow faulting near Rantowles is consistent with a recent rupture model (Bilham and Hough, 2023) proposing that faulting was confined to the north of the Ashley River in 1886. The concentration of lateral spreading, sand venting, and severe railroad buckling in the swamps and drainages west of Charleston led Sloan to map an epicentrum 4 km east-northeast of Rantowles (also described as a "focus"; Dutton, 1889, p. 312). This interpretation reflected contemporary ideas about earthquake rupture processes involving subterranean explosions and a lack of appreciation for the potential severity and complexity of site response on saturated Atlantic Coastal Plains sediments. Dutton and Sloan's interpretations (Dutton, 1889), which were apparently confirmed by Wilson's photograph of putative surface faulting within kilometers of the identified epicentrum, may have overly influenced subsequent interpretations of neotectonics south of the Ashley River.

"Sediment-Thickness Map of the United States Atlantic and Gulf Coastal Plain Strata, and Their Influence on Earthquake Ground Motions"

By Oliver S. Boyd (USGS), David Churchwell (University of Colorado at Boulder Law School, formerly at USGS), Morgan P. Moschetti (USGS), Eric M. Thompson (USGS), Martin C. Chapman (Virginia Polytechnic Institute and State University), Okan Ilhan (Department of Civil Engineering, Ankara Yildirim Beyazit University), Thomas L. Pratt (USGS), Sean K. Ahdi (USGS), and Sanaz Rezaeian (USGS)

"With the recent successful accounting of basin depth ground-motion adjustments in seismic hazard analyses for select areas of the [W]estern United States, we move toward implementing similar adjustments in the Atlantic and Gulf Coastal Plains by constructing a sediment thickness model and evaluating multiple relevant site amplification models for [C]entral and [E]astern United States seismic hazard analyses. We digitize and combine existing sediment thickness datasets into a composite surface that delineates the base of Cretaceous sediments under the Atlantic Coastal Plain and the base of Mesozoic sediments under the Gulf Coastal Plain. Amplification models dependent on sediment thickness, site natural period, and source-to-site path length are compared with datasets of observed ground motions to evaluate the ability of the new models to improve ground motion estimates…the amplification models can account for observed trends in sediment-thickness and period-dependent residuals, but some tuning is required. For example, the model of Chapman and Guo [2021] requires a reference V_{S30}, the time-averaged shear-wave velocity within 30 m of the Earth's surface, for non-Coastal Plain sites, which we estimate to be between about 1 and 2 [km per second]" (Boyd and others, 2023, p. 89). We reformulate and scale the Harmon and others (2019) sediment-thickness based model, and, in conjunction with our map of Coastal Plain sediment thickness, we estimate a velocity profile for application to the Harmon and others (2019) site-natural-period-based model. Both Harmon models are optimized to minimize total ground-motion residuals. The NGA-East Gulf Coast path-based adjustment models (Goulet and others, 2021a) "can also account for seismic attenuation in the Coastal Plain sediments and reduce the standard deviation of total residuals. If enacted in the [USGS NSHM], these amplification models will reduce predicted short-period [(less than 1 second) ground motions] and increase predicted long-period [more than 1 second] ground motions in the Coastal Plains appreciably" (Boyd and others, 2023, p. 90). Looking toward the planned next round of NSHM policy map updates in 2029, applying datasets extracted from the USGS National Crustal Model (Boyd and Shah, 2018) could allow for a similar accounting of thick sedimentary deposits more broadly across the Central and Eastern United States.

“Central and Eastern United States Coastal Plains Seismic Amplification and Hazard Based on an Updated Regional Velocity and Geotechnical Model”

By Chris H. Cramer (University of Memphis), James Kaklamanos (Merrimack College), Cassie Gann-Phillips (North Carolina State University), and Ashly Cabas (North Carolina State University)

We incorporate a new site-amplification model for Atlantic and Gulf Coastal Plain earthquake ground motions into probabilistic seismic hazard analyses following the Dhar and Cramer (2017) approach. In addition to the Coastal Plain shear-wave velocity (V_S) model described in a companion presentation and abstract, “Regional Seismic Velocity Model for the United States Atlantic and Gulf Coastal Plains Based on Measured Shear-Wave Velocity and Surface Geology,” we describe our modeling decisions for geotechnical parameters used in site-amplification estimation: sediment density, water-table level, effective mean confining pressure with depth, modulus-reduction and damping curves, depth to assumed linear-elastic behavior of sediments, and small-strain damping. Equivalent linear geotechnical sediment response modeling was employed in site-amplification estimation because of its computational efficiency for the needed 109.8 million randomized response calculations and because of previous research showing similar response and limitations between fully nonlinear and equivalent linear estimations. We found that surface geology and the V_S in the top few hundred meters drive the amplification in our models. Initial amplifications using the Mueller (2000) model are simpler due to the simplified V_S and quality-factor model. Our improved model amplifications in the Coastal Plain are more complex. The initial and the improved V_S models have no lateral variations in amplification within the same surface geology, and our V_S model uncertainties are therefore large, likely because of unmodeled lateral variations at the same depth. To ensure reasonable linear low-strain amplifications, we reduced the observed V_S uncertainties to 20 percent of their values for the site-response calculations to avoid very low and negative V_S values during randomization. The improved V_S models do have bedrock to sediment V_S impedance response, but randomization broadens, smooths, and lowers the response. Our hazard maps show similar hazard values at long periods (1 second) but systematically different hazard levels at short periods relative to 2018 USGS site class D (V_{S30}=260 m per second [m/s]) hazard maps (Petersen and others, 2020). This corresponds to previously published research that overall sediment thickness is more important in hazard estimation than V_{S30}. Future work will seek to further refine the seismic velocity model, develop a more advanced sediment-attenuation model, and evaluate the resulting impacts on site amplification and seismic hazards in the Coastal Plains.

“Regional Seismic Velocity Model for the United States Atlantic and Gulf Coastal Plains Based on Measured Shear-Wave Velocity and Surface Geology”

By Cassie Gann-Phillips (North Carolina State University), Ashly Cabas (North Carolina State University), Chunyang Ji (North Carolina State University), Chris H. Cramer (University of Memphis), and James Kaklamanos (Merrimack College)

“The Atlantic and Gulf Coastal Plains…are characterized by widespread accumulations of low-velocity sediments and sedimentary rock that overlay high-velocity bedrock. Geology and sediment thickness [significantly] influence seismic wave propagation, but current regional ground motion amplification and seismic hazard models include limited characterization of these site conditions. In this study, a new…seismic velocity model for the Coastal Plains is created by integrating…[V_S] measurements, surface geology, and a sediment thickness model recently developed for the Coastal Plain. A…V_S of 3,000 m/s has been assumed at the bottom of the sedimentary columns, which corresponds to the base of Cretaceous and Mesozoic sediments underlying the Atlantic [and Gulf Coastal Plains], respectively. Measured V_S profiles throughout the Coastal Plains [were] sorted into five geologic groups of varying age, and median V_S profiles [were] developed for each…by combining V_S values with layer thicknesses defined by an assumed layering ratio. A power law model with geology-informed coefficients is used to extend the median velocity models beyond the depths where measured data were available” (Gann-Phillips and others, 2024, p. 1,269). Values of V_{S30} of the median profiles increase with geologic age, and comparisons with other generic V_S profiles applicable for the region indicate a good agreement. “The proposed median velocity profiles can be assigned within a grid-based model of the Coastal Plains according to the spatial distribution of geologic units at the surface” (Gann-Phillips and others, 2024, p. 1,270). Additionally, a sensitivity study using one-dimensional linear site response analyses is conducted to determine the influence of sediment thickness and reference condition assumptions within the model. Sediment thickness values of 100, 200, and 1,000 m are tested. Reference condition velocities of 2,500, 3,000, and 3,500 m/s at the base are also tested. Response spectra- and Fourier amplitude spectra-based amplification ratios are calculated. Overall, the amplification ratios estimated by the model are more sensitive to the change in sediment thickness than to the change in the V_S assumed at the reference depth. These critical seismic velocity model updates advance the characterization of site response at regional scales and enable their effective incorporation into seismic hazard models and building codes.

“Lessons Learned from the Next Generation Attenuation Relationships for the Eastern United States (NGA-East) Project”

By Christine Goulet (USGS)

The NGA-East is a large collaborative project that spans over a decade and has delivered several hazard-relevant products and GMMs for Central and Eastern North America. The GMMs (median and standard deviation) capture the full epistemic uncertainty in ground motions and have been integrated into the United States and Canada seismic hazard maps.

Ground motions result from complex physical systems that modelers decouple in source, path, site, and other terms to develop GMMs. Decoupling works reasonably well when data span wide ranges of magnitudes, distances, and source-site combinations. Central and Eastern North America, however, is a huge region with limited data coverage, both spatially and in terms of magnitude, requiring reliance on additional constraints (for example, simulations or knowledge from other regions) to correctly resolve the nonuniqueness of the solution for source, path, and site. The problem of incomplete and uneven data sampling is expected to remain in Central and Eastern North America for a long time because of its size and the long recurrence intervals of large-magnitude events. For these reasons, GMM development, involving a large community and undergoing a thorough and transparent review process, was critically important. Key lessons learned from the project are summarized below:

- Lesson 1—Simulations are critical for several aspects of GMM development and would benefit from being continually improved upon, validated, and understood so that they can defensibly be extrapolated for that purpose. Epistemic uncertainty is an important factor that impacts mean hazard and needs to be evaluated holistically. Work in NGA-East and by others showed that merely grouping individual GMMs, all constrained on the same (limited) data, underpredicts the range of ground motions for scenarios not in the dataset.

- Lesson 2—In data-poor regions, the epistemic uncertainty should not be less than that of a well-sampled region.

- Lesson 3—It would be beneficial to set reference site conditions as close as possible to the as-recorded conditions while remaining in the linear realm of site response. This would reduce the effect of uncertain site corrections on reference GMMs, favoring later adjustments as new data are gathered.

- Lesson 4—Site response proxies could be refined beyond V_{S30}, which does not work as well for Central and Eastern North America, where large impedance contrasts often exist.

- Lesson 5—Regionalization of ground motions, especially for a whole continent, needs to be assessed. Continued work in defining sediment thickness and addressing otherwise regional effects would inform non-ergodic or regional adjustments and region-specific GMMs.

- Lesson 6—Research could be conducted first. The evaluation and integration into GMMs, as well as the quantification of uncertainty, could be performed in a second step. Focusing the thorough review process (that is, the Senior Seismic Hazard Analysis Committee Level 3 for a product of such national impact) on that second step would probably be most effective.

“Geometric Spreading and Apparent Anelastic Attenuation of Response Spectral Accelerations”

By Vladimir Graizer (U.S. Nuclear Regulatory Commission)

This presentation summarizes Graizer (2022) and “discusses apparent anelastic (combination of intrinsic and scattering) attenuation of 5 [percent] damped response spectral accelerations (SAs) associated with the geometric spreading of surface waves. In contrast to the ‘seismological’ $Q(f)$ factor measured using Fourier spectra of S-, Lg- or coda-waves, SA quality factor $Q_{SA}(f)$ represents apparent anelastic attenuation of response spectral accelerations, which were first introduced in Graizer (2017). In the recent ground-motion prediction [equation] models for stable continental regions…(Graizer, 2017) and active crustal regions…(Graizer, 2018), I assumed large-distance geometric spreading of SA to be of the order of [geometric spreading (G_{geom}) approximately source-to-site distance to the power of −0.5$R^{-0.5}$]. Multiple inversions performed to estimate $Q_{SA}(f)$ demonstrated the best fit to be [approximately] $Q_{SAA}(f)=120f^{0.96}$ for the [active crustal regions] for frequencies between 0.1 and 100 [hertz (Hz)] and the best fit to be approximately $Q_{SAS}(f)=186f^{0.99}$ for the [stable continental regions] for frequencies between 0.1 and 40 Hz. Apparent anelastic attenuation was…magnitude dependent, with Q_{SA} factor increasing with magnitude. Resulting apparent attenuations of response spectral amplitudes at rupture distances of more than 50 km for the [active crustal regions] and more than 70 km for the [stable continental regions] are practically linearly dependent upon frequency, demonstrating significantly different behavior from the ‘seismological’ [quality] factor” (Graizer, 2022).

"The 1886 Charleston, South Carolina, Earthquake—Source Properties, Ground Motions, and ShakeMap"

By Susan E. Hough (USGS), Roger Bilham (University of Colorado at Boulder), and Eric M. Thompson (USGS)

The 1886 Charleston, South Carolina, earthquake was felt throughout much of the Eastern United States, with an earthquake moment magnitude (M_W) of 6.8–7.3 that was previously estimated from felt reports (Hough and Bilham, 2024). Despite extensive contemporaneous documentation by trained geologists, including Clarence Dutton (1889), the earthquake and the Charleston Seismic Zone have remained enigmatic. In a recent study, Bilham and Hough (2023) developed an elastic deformation model for the 1886 earthquake using three identified geodetic constraints, including a newly (re-)recognized approximately 4.5-m dextral offset in the South Carolina Railway line south of Summerville, S.C., where the track crosses the previously mapped Summerville Fault. The offset was described in contemporaneous accounts but never considered by subsequent studies. In contrast to the buckling of another railroad (west of Charleston, S.C.) captured in a widely reproduced photograph (discussed in the abstract "Buckled Railroad Not Dextrally Offset in Famous Post-Seismic 1886 Photograph West of Charleston, South Carolina"), the South Carolina Railroad offset cannot be readily explained by site response. The preferred deformation model yields M_W 7.3, but in contrast to the conclusions of previous studies, we find no support for significant slip south of the Ashley River. We also revisited the near- and far-field intensity distribution using extensive archival accounts. We compare the intensity distribution, constrained at nearly 1,300 locations, with predictions from modern (NGA-East) GMMs and ground-motion-to-intensity conversion equations. Although NGA-East models are characterized by significant epistemic uncertainty for large earthquakes, we show that the intensity distribution is highly consistent with average model predictions, assuming M_W7.3. Given the expected influence of site response on saturated Atlantic Coastal Plain sediments throughout the epicentral region, the fit to near-field intensities is insensitive to the rupture length or other detailed rupture properties. Macroseismic intensities can be used with model predictions to improve a ShakeMap (Worden and others, 2020) for the earthquake but cannot improve the independently determined rupture model or M_W. Of note, an apparent concentration of high intensities near the town of Rantowles, S.C., is constrained by a concentration of environmental effects now recognized as sand blows and lateral spreading. These observations are readily explained by site response in the swampy low-country setting west of Charleston.

"Gulf Coast and Central and Eastern United States Boundary Delineation with *Lg*-Amplitude-Distance Inflections"

By William Levandowski (TetraTech) and Daniel McNamara (EarthScope)

Earthquake ground motions differ on the tectonically extended Gulf Coastal Plain from cratonic portions of the Central and Eastern United States. In particular, site amplification tends to be greater on the Gulf Coastal Plain, and the loss of seismic energy with distance from an earthquake—seismic attenuation—is also higher. These competing effects understandably influence hazards for approximately 15 million Americans along the Central and Eastern United States and Gulf Coastal Plain boundary in Texas alone, yet previous studies to delineate the boundary have used metrics unrelated to attenuation, and the boundary mostly follows geologic age as understood in 1995. A nearly identical problem with the Central and Eastern United States and Western United States boundary was recently rectified using crustal *Lg* ground-motion amplitudes. Once geometric spreading is accounted for, the slope of logarithm (ln)-amplitude versus distance along a given *Lg*-ray path is proportional to attenuation. Therefore, inflections in amplitude-distance profiles pinpoint changes in attenuation. Mapping these inflections provides a high-fidelity delineation of the attenuation boundary, as well as constraints on its frequency dependence. The same dataset used for the Central and Eastern United States and Western United States delineation contains thousands of ray paths crossing the Central and Eastern United States and Gulf Coastal Plain boundary. Using this database and established approach, we present preliminary results from several thousand inflection picks for frequencies from 0.5–16 Hz. This new boundary model will be assessed jointly with crustal attenuation tomograms from across the Central and Eastern United States to provide constraint on the location, nature, and frequency dependence of the Central and Eastern United States and Gulf Coast Plain boundary.

"Ground-Motion Modeling Issues in the Central and Eastern United States for Future Updates of the U.S. National Seismic Hazard Model"

By Morgan P. Moschetti (USGS) and Eric M. Thompson (USGS)

We present ground-motion modeling issues in the Central and Eastern United States for consideration for the next update of the U.S. NSHM. Priorities include (1) making empirical adjustment factors to the existing NGA-East GMMs, (2) developing a consistent approach to epistemic uncertainty across all seismotectonic provinces, (3) developing GMM-consistent amplifications for the Atlantic and Gulf Coastal Plains, (4) improving site-response models, and (5) including spatially varying GMMs. For the 2023 NSHM, empirical period-dependent adjustment factors were applied to the Central and Eastern United States GMMs based on analyses of updated ground-motion recordings in the region. The discrepancy may be partly caused by differences in the relevant site-amplification models, though questions remain regarding whether these factors apply to all sites and how best to incorporate them with NGA-East. The NSHM currently uses several approaches to model epistemic uncertainty for active-crustal, subduction, and stable-continental GMMs. Future updates would benefit from modeling epistemic uncertainty in GMMs with a consistent approach across seismotectonic regimes. Building on recent USGS efforts to implement the NGA-East procedure, future updates could include updates to seed GMMs, evaluation and refinement of the NGA-East procedure, and development of regionally consistent additional variance models (that is, additional epistemic or target variance models). The 2023 NSHM included Coastal Plain adjustments and concerns regarding the definition of the reference-site condition for these adjustments, which resulted in a low weight for the Coastal Plain adjustments. Future updates could consider updated amplification models developed to be consistent with the NSHM GMMs. Further research into the causative reductions in short-period ground motions may improve future model updates. Compared with the Western United States, recent studies have shown that V_{S30} is a relatively poor predictor of site response in the Central and Eastern United States. Thus, alternative parameterization of site response is critical to accurately model hazard in this region. A promising alternative (or complement) to V_{S30} is the fundamental site frequency derived from horizontal-to-vertical spectral ratios. Shorter-term updates can include regionalized guidance on the use of gradient- or impedance-type amplification functions from simulations or alternative empirical adjustments. Lastly, future NSHM updates ideally would move toward GMMs that relax the ergodic assumption, that is, use models that capture the source, path, and site effects at finer spatial scales than available in ergodic GMMs. This effort requires conterminous United States-wide decisions to select or calculate aleatory variability models and the updated treatment of epistemic uncertainty for GMMs. Early discussions about future NSHM updates will be valuable to guide internal and external efforts to improve seismic hazard modeling in the Central and Eastern United States.

"Physics-Based Broadband Ground-Motion Simulations of Scenario Earthquakes in the Central and Eastern United States Using High-Performance Computing"

By Arben Pitarka (Lawrence Livermore National Laboratory), Vladimir Graizer (U.S. Nuclear Regulatory Commission), Arthur Rodgers (Lawrence Livermore National Laboratory), and Ana Aguiar (Lawrence Livermore National Laboratory)

We have developed a computationally efficient simulation platform that generates representative synthetic ground motions from crustal earthquakes in the stable continental regions of the Central and Eastern United States, using three-dimensional modeling and high-performance computing. In addition to producing ground-motion time histories for engineering applications, the main objective is to use synthetic ground motion to provide constraints to refinements of existing ergodic GMMs in the Central and Eastern United States region, for large-magnitude earthquakes and near-fault distances, for which these models are less reliable. After validating a crustal velocity model for Central and Eastern United States using recorded data from two small-magnitude earthquakes, we used physics-based broadband (0–5 Hz) ground-motion simulations to estimate the near-fault ground-motion amplitude and within-event and between-event variabilities associated with fault rupture characteristics. Additional validation analysis, based on comparisons with different GMMs for the Central and Eastern United States region and for an M_W6.5 earthquake, resulted in a very good match between the simulated and empirical GMMs.

During our investigation of within-event and between-event ground-motion variabilities for M_W6.5 scenario earthquakes on a strike-slip fault, and regardless of the rupture scenario, the simulated ground motions tended to fully saturate at short distances and for all periods. However, for similar M_W6.5 ruptures on a thrust fault, the ground motions undersaturate at short distances except for SA at periods longer than 5 seconds. Initial investigation of within-event and between-event ground-motion variabilities for M_W6.5 scenario earthquakes on a strike-slip fault suggests that the variabilities are strongly related to spatial-slip and slip-rate variations, rupture velocity, rupture area, and rupture initiation location.

"Joint Inversion of Surface-Wave Dispersion Curves and Horizontal-to-Vertical Spectral Ratios for Atlantic Coastal Plain Velocity Structure, Eastern United States, Using Crustal-Scale Refraction Data"

By Thomas Pratt (USGS), Stefano Parolai (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale—OGS and Universita Degli Studi di Trieste, Trieste, Italy), and Valerio Poggi Ilaria Dreossi (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale—OGS, Udine, Italy)

Shallow shear-wave velocities are sometimes estimated from joint inversions of surface-wave dispersion curves derived from ambient noise or small-active sources and horizontal-to-vertical spectral ratios. We evaluated carrying out these inversions using dispersion curves from crustal-scale seismic refraction data, which have been acquired over sedimentary basins of interest for hazard studies, including urban areas. We use data from the 2014–2015 Eastern North American margin experiment in Virginia and North Carolina (Lynner and others, 2019). The Eastern North American margin project deployed a pair of approximately 215-km-long northwest–southeast linear arrays with approximately 300-m receiver spacing to record 11 dynamite shots, and 80 continuously recording seismometers with 5–6-km spacing along the same arrays to record offshore air guns. The arrays crossed the on-land portion of the Atlantic Coastal Plain sediments, which are a seaward-thickening wedge of Cretaceous and younger sediments deposited mostly on crystalline bedrock (Lawrence and Hoffman, 1993). We computed surface-wave dispersion curves from 3- to 9-km-long portions of the receiver arrays near each dynamite shot, and we computed ambient-noise horizontal-to-vertical spectral ratios from the continuously recording seismometers. We use a genetic-inversion algorithm in which forward velocity models in each generation are evaluated for misfits compared to the observed data, with subsequent generations constructed from the models with the smallest misfits. Velocities to depths of 500 m are well-defined, and deeper velocities are less defined. Results are supported by the consistency of the profiles from nearby sites, correspondence of large velocity increases with estimated depths of basement rocks, and forward modeling of transfer functions made from the profiles. The resulting velocity cross section of the Atlantic Coastal Plain strata has seaward-dipping contours in the thinner portions of the plain, but more horizontal contours in the deeper portions. These results show that velocity contours in the Atlantic Coastal Plain strata are influenced by a combination of lithology and pressure.

"Improving Central and Eastern North America Ground-Motion Models Using Improved Ground-Motion and Site-Data Resources"

By María E. Ramos-Sepúlveda (University of California, Los Angeles), Jonathan P. Stewart (University of California, Los Angeles), Scott J. Brandenberg (University of California, Los Angeles), Youssef M.A. Hashash (University of Illinois), and Ellen M. Rathje (University of Texas)

An ongoing research program that represents a collaboration of multiple institutions seeks to improve GMMs for application in Central and Eastern North America using an updated version of the NGA-East database presented in Goulet and others (2021b). We have added 100 events and 6,892 recordings that were processed in a manner consistent with NGA-East procedures. This process was undertaken by updating the USGS processing code gmprocess (Hearne and others, 2019) to improve high-pass corner frequency selection and to enable user interaction with the code to fine-tune corner frequency selections. Metadata have been assigned in a consistent manner, including new V_S profiles for V_{S30} assignments and sediment-depth assignments using models provided by Boyd and others (2023). We used the improved database to evaluate bias in the GMMs when applied with site factors (from Stewart and others, 2020) applied in the 2018 and 2023 NSHMs. The results of this work have been integrated into the development of the 2023 NSHM and are described in Ramos-Sepúlveda and others (2024). We are now embarking on an effort to quantify path misfits from the NGA-East GMMs for particular regions of Central and Eastern North America, which were observed in the bias analysis. To facilitate this work, we are developing an equation version of the central branch NGA-East GMM, so that adjustments with a clear physical basis (for example, mismatched anelastic attenuation) can be easily implemented. Once that is complete, we will evaluate site response using a nonreference site approach for various subregions of Central and Eastern United States, including the Atlantic Coastal Plain, the Gulf Coastal Plain, and non-Coastal Plain sites. The results will be used to test the Stewart and others (2020) V_{S30}-scaling model, and additional dependencies on sediment depth will be evaluated. Models developed by this approach will have the advantage of being compatible with the NGA-East GMMs, thereby reducing uncertainties in implementation.

“Estimating Bedrock Shear-Wave Velocity at Vertical Strong-Motion Array in Paducah, Kentucky (Upper Mississippi Embayment) Using Nodal Array Recordings of Ambient Noise”

By Russel C. Rogers (University of Kentucky), N. Seth Carpenter (University of Kentucky), Zhenming Wang (University of Kentucky), and Edward W. Woolery (University of Kentucky)

Sites on unlithified soils overlying stiff bedrock will experience ground-motion amplifications because of the increasing seismic impedance with depth. Additional, potentially profound amplification will occur at specific frequencies because of the shear-wave resonance within the soil layers. Because the amplifications depend on the ratio of the bedrock impedance to that of the overlying sediments, reliably predicting the site-amplification function (that is, site response) at such sites requires accurate, site-specific V_S profiles from the surface into the bedrock. The Vertical Seismic Array in Paducah, Kentucky (VSAP) sits in the upper Mississippi embayment on 100 m of sediments underlain by limestone bedrock and consists of strong motion accelerometers at the surface and in the top of the bedrock. Site characterization studies at or near VSAP using invasive and noninvasive techniques have produced a variety of V_S profiles. The greatest V_S variability in these profiles is in the bedrock; V_S estimates in bedrock range from 1,630 m/s to 2,770 m/s. The consequence of the large uncertainty of the bedrock V_S is a large uncertainty in predicted amplifications. Here, we develop a new estimation of the V_S profile into bedrock at VSAP using the passive ambient-noise technique. We developed a Rayleigh wave dispersion curve using the high-resolution frequency-wavenumber method on recordings of ambient noise acquired in a 13-hour period by an array of 17 nodal geophones deployed at VSAP. We inverted the dispersion curve for the best-fitting V_S profiles using differing sets of constraints, including previously developed sediment V_S profiles, and the known depth to bedrock. Bedrock velocities were allowed to range from 1,600 m/s to 3,500 m/s. We also evaluated a gradient just below the sediment-bedrock interface that accounts for a “rubble zone” observed in a nearby borehole. The bedrock V_S is sensitive to the inversion scenario, but a range from 2,500 m/s to 2,900 m/s yields dispersion curves that explain the empirical curve. The one-dimensional linear site responses calculated using the preferred V_S profiles are consistent with the weak-motion empirical transfer function determined at VSAP but suggest that the resolved sediment layers may be slightly too fast. Consistent with the empirical transfer function, amplifications greater than a factor of 5 are predicted at the fundamental frequency (approximately 1.3 Hz).

“Can ‘Did You Feel It?’ Intensity Data be Used in Ground-Motion Modeling?”

By Pengfei Wang (Old Dominion University) and Busra Bocekli (Old Dominion University)

“Did You Feel It?” (DYFI, https://earthquake.usgs.gov/data/dyfi/) is an online USGS program that allows citizens to report their feelings and responses to a list of questions related to earthquake shaking and damage. Modified Mercalli Intensity (MMI) is calculated from the reports as a quantitative metric representing earthquake shaking and damage level. Compared to ground-motion data recorded at strong motion stations, MMI data have a much denser and larger spatial coverage, especially in urban and low-seismicity areas. However, because they are derived from subjective responses, MMI data have not been used in ground-motion modeling, although they can fill the spatial distribution gaps of strong motion stations. For example, whereas the short-distance ground motions are most critical (because short-distance ground motions potentially produce more damage than longer distances), very few ground-motion records at short distances (less than 50 km) are available in the Central and Eastern United States. If MMI data proved to provide consistent trends as ground-motion records, the GMM for the Central and Eastern United States would be better constrained at short distances by incorporating MMI-inferred ground motions. Given the benefits, this study investigates the consistency between recorded ground motions and inferred ground motions by MMI data, aiming to answer whether MMI data can be used in ground-motion modeling. We first collected colocated (within 1 km apart) ground-motion records and MMI data from the extended California ground-motion database and USGS DYFI repositories. We then found a strong association between MMI and peak ground acceleration (PGA) using the resultant 3,257 pairs of data. A new MMI-to-PGA relationship was developed and applied to convert MMI data to PGA for the 2011 Virginia earthquake. The inferred ground motions by MMI data exhibited statistically significantly consistent attenuation as ground motion.

Panel Summaries

Panel summaries were held on both days of the workshop. Refer to table 1 for the moderators and participants for each panel.

Panel Discussion 1—Data Resources and Gaps in the Central and Eastern United States and Coastal Plains

The panel discussion on data resources and gaps in the Central and Eastern United States and Coastal Plains was primed by a series of lightning talks and longer presentations on the data available in the Central and Eastern United States that characterize seismic properties in the upper crust. The consensus was that data are exceptionally limited. Panelists and attendees supported the idea that more data should be acquired, especially away from locations where much of the data are presently clustered (for example, the upper Mississippi embayment and Charleston, South Carolina), and to include extremes in various site conditions (soft soils and hard rock) and geologic units. Such data include horizontal-to-vertical spectral ratios, fundamental periods where ground-motion amplification is greatest, and characterizations of seismic-wave velocities and attenuation at recording stations down to bedrock. Currently, only approximately 10 percent of stations in the Central and Eastern United States are partially characterized with these parameters using noninvasive methods. Ideally, this data acquisition would involve, given adequate resources, the acquisition of borehole-based measurements.

Panelists and attendees also asserted that all data (ground motions and geophysical characterization) should be available in accessible online databases (for example, the University of California, Los Angeles Shear-Wave Velocity Profile Database—http://vspdb.org). Successfully achieving this goal would be more likely by adopting common data formats to facilitate inclusion into databases, for example, the Data Interchange for Geotechnical and Geoenvironmental Specialists (https://www.geoinstitute.org/special-projects/diggs). Pursuing a more systematic approach to identifying locations where further subsurface characterization could be obtained should also be a community effort.

Panel Discussion 2—Ground-Motion Modeling

The process of developing new and consensus-based GMMs can be opaque to end-users and time consuming, both of which hinder the advancement and adoption of more accurate models. The panel suggested that decoupling basic research from the Senior Seismic Hazard Analysis Committee review process for GMM development could be more efficient. Furthermore, greater transparency in the statistical methods that are used to develop GMMs and bring GMMs together (for example, Sammon's Mapping; Sammon, 1969) will allow end-users to better understand the input parameters and possible modifications relevant to user's applications. The underlying statistical methods and resulting hazard products would also benefit from a better representation of uncertainty in input parameters.

Improvements to more fundamental aspects of GMM development were also explored. Panelists and attendees foresee (1) the expanded use of machine learning; (2) non-ergodic methods that allow for spatially variable source, path, and site effects; and (3) physics-based simulations to help constrain how local-to-regional three-dimensional variations in seismic properties affect magnitude scaling, distance scaling, and site response. Panelists and attendees also foresee the expanded use of reported ground-motion intensity data, such as data reported by the public to the USGS "Did You Feel It?" website, to better constrain GMMs (likely at shorter shaking periods, larger magnitudes, and certainly in areas where there are few recording stations), and expanded learning from data-rich regions via hybrid GMMs. In this context, "hybrid" refers to a class of GMMs that are developed for data-poor regions by adjusting GMMs developed for data-rich regions. Hybrid models could also aid in estimates of near-source large-magnitude scaling and geometric spreading. In the recent NGA-East effort to develop GMMs for Central and Eastern North America, the GMM and site-response model were decoupled. Panelists and attendees supported the idea of concurrently developing GMMs and site-response models, and suggested that the site condition to which GMMs are referenced should be more aligned with observed conditions at recording stations in the Central and Eastern United States, which typically have V_{S30} values less than 760 m/s.

Panel Discussion 3—Implications and Next Steps

This panel began with a presentation on effective site coefficients in the 2024 International Building Code, which are based on the 2018 USGS NSHM and are defined as the ratio between ground motion at one site class to the reference site class (traditionally classified as the National Earthquake Hazards Reduction Program BC boundary by V_{S30}=760 m/s; Building Seismic Safety Council of the National Institute of Building Sciences, 2020). This topic is critical to the building code and engineering design communities and one in which significant changes are occurring. The 2023 USGS NSHM (Petersen and others, 2024) could exacerbate the changes from the previous cycle. For example, Central and Eastern United States site coefficients decreased appreciably at many locations from 2014 to 2018. In 2023, modeling the effect of thick sediments on earthquake ground motions in the Gulf and Atlantic Coastal Plains and correcting for frequency-dependent bias elsewhere in the Central and Eastern United States further decreased short-period ground motions but increased long-period ground motions. Future ground-motion modeling efforts are likely to lead to additional changes and a potential yo-yo effect, potentially leading to ambiguity for engineers attempting to determine the correct values to use for design. Non-ergodic efforts are continuing throughout the community, which likely would reduce uncertainty and improve site response and hazard estimates, but these methods are computationally expensive and will complicate the construction of probabilistic hazard curves on a national scale, especially when disaggregation and hazard fractiles are considered. A consistent approach is needed to characterize epistemic uncertainties, which are critical for estimating mean hazard and fractiles, and may help mitigate complications arising from the adoption of non-ergodic methods.

Panelists and attendees strongly encouraged continued community involvement for assessing the effects from and consensus on seismic hazard models. Researchers, developers, and end-users must understand the importance of changes from calculating hazard on design ground motions.

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