FUTURE DIRECTIONS

Physics-based ground-motion modeling

10–13 October 2023 • Vancouver, BC

Welcome to Vancouver!

Thank you for participating in SSA's second-ever topical conference, co-sponsored by the Seismological Society of Japan. Our goals this week are to take advantage of this focused gathering to share new research and perspectives, while leaving plenty of time for networking. We are especially looking forward to your questions for the panel discussions at the end of each session.

A few items to remember for the week:

- Breakfast & Poster Session begins each day at 7 AM
- Lunch & Poster Session begins each day at 1 PM
- Information on uploading your slides and hanging your poster can be found on page 2

Your feedback on the meeting is important to SSA in planning future meetings, so please do not hesitate to talk with us or the meeting staff about your thoughts on this event.

Finally, we want to thank our sponsors for supporting this topical meeting. We're looking forward to an engaging and informative program.

Best,

Annemarie Baltay
Hiroshi Kawase
SSA Physics-Based Ground Motion Modeling Conference Co-Chairs

SSA Code of Conduct

SSA is committed to fostering the exchange of scientific ideas by providing a safe, productive and welcoming environment for all SSA-sponsored meeting participants, including attendees, staff, volunteers, and vendors. We value the participation of every member of the community and want all participants to have an enjoyable and fulfilling experience. Please do your part by the following the SSA Code of Conduct (seismosoc.org/ meetings/code-of-conduct) throughout the entire conference.

Audio and Video Recording Policy

Audio and video recording by individuals for personal use and for social media use is allowed only in public spaces throughout the meeting. Audio and video recording can be disruptive to the presentation and the attendees, and there may be copyright and other legal considerations that preclude attendees from making recordings. Please be respectful and considerate of others, and do not record people under 18 years of age in any setting without permission from their guardian or parent. SSA staff and contractors who capture content from oral or poster presentations, or other meeting events are excluded from this prohibition.

WiFi Information

- Network: Westin_Conference
- Password: ssa23

Important Presenter Information

Poster Presenters: Your poster number is listed in the schedule below as well as in the Abstracts section of this program book. There are three times to view posters each day, and we encourage presenters to be at their posters for at least two sessions during the time their poster is up.

Poster Presenters: Tuesday, 10 October and Wednesday, 11 October

Please hang your poster on Tuesday by 5 PM. You will need to remove your poster after 6:30 PM on Wednesday.

Poster Presenters: Thursday 12 October and Friday, 13 October

Please hang your poster prior to breakfast on Thursday morning. You will need to remove your poster after 4:30 PM on Friday.

Oral Presenters: Please bring your slides to the A/V tech in the Stanley Park Ballroom, so they can be loaded onto the conference laptop. The A/V tech will be available for slide upload 4–6 PM on Tuesday, 10 October and during breakfast and morning coffee breaks Wednesday through Friday.

Congratulations to Our Travel Grant Recipients

Each of the recipients below received complimentary registration to the Ground Motion conference, as well as a stipend for travel expenses. SSA is grateful to our members and friends who gave generously to the Society's Kanamori Fund and General Fund, which make these grants possible.

- Simona Gabrielli, *Istituto Nazionale di Geofisica e Vulcanologia*
- Sajan K C, *University of Southern California*
- Jiayue Lin, *Politecnico di Milano*
- Irene Y. Liou, *University of California, Davis*
- Luis C. Muñoz Heinen, *Imperial College London*

Technical Program

The following schedule of events and abstracts are valid as of 30 August 2023. See addendum for changes to the program.

Tuesday, 10 October 2023

- Registration Open, 4–7:30 PM
- Opening Reception & Posters, 5–6 PM
- Opening Session & Keynote Presentation, 6–7:30 PM

Wednesday, 11 October 2023

- Breakfast & Posters, 7–8:30 AM
- Session: Complex Kinematic Source Modeling, 8:30–10:30 AM
- Coffee Break, 10:30–11 AM
- Session: Dynamic Rupture Propagation Analysis, 11 AM–1 PM
- Lunch & Posters, 1–3 PM
- Session: Empirically Modeling Source Effects as Inputs to Models, 3–5 PM
- Reception & Posters, 5–6:30 PM

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nanometrics

Thursday, 12 October 2023

- Breakfast & Posters, 7–8:30 AM
- Session: Physical Modeling Issues of Site Effects, 8:30–10:30 AM
- Coffee Break, 10:30–11 AM
- Session: Empirical Modeling of Site Effects, 11 AM–1 PM
- Lunch & Posters, 1–3 PM
- Panel Discussion: Physical Modeling Issues of Site Effects and Empirical Modeling of Site Effects, 3–4 PM
- Session: Regional Differences in Quantification of Path Effects, 4–6 PM
- Reception & Posters, 6–7:30 PM

Friday, 13 October 2023

- Breakfast & Posters, 7–8:30 AM
- Session: Challenges for Model Extrapolations Outside of the Data Range, 8:30–10:30 AM
- Coffee Break, 10:30–11 AM
- Session: Overall Prediction Accuracy and Simulation Validation for Real-World Applications, 11 AM–1 PM
- Lunch & Posters, 1–2:30 PM
- Panel Discussion: Overall Prediction Accuracy and Simulation Validation for Real-World Applications, 2:30–3 PM
- Closing Session & Final Discussion, 3–4:30 PM
- Closing Reception, 4:30–5:30 PM

Keynote Speakers

- Fabrice Cotton, GFZ German Research Centre for Geosciences: *Quantifying and Partitioning Ground-Motion Variability in the Era of Big Data and Massive Physics-Based Simulations*
- Alice-Agnes Gabriel, Scripps Institution of Oceanography, University of California, San Diego: *Dynamics and Complexities of Large Earthquake Rupture Sequences: Data-driven and Physics-Based Models of the 2019 Ridgecrest and 2023 Kahramanmaraş, Turkey Multi-fault Sequences*
- Christine A. Goulet, U.S. Geological Survey: *Incorporating Novel Techniques and Concepts into Ground Motion and Hazard Modeling*
- Robert Graves, U.S. Geological Survey: *Characterization of Complex Kinematic Ruptures for Ground Motion Simulation*
- Shinichi Matsushima, Disaster Prevention Research Institute, Kyoto University: *Physical Modeling of Site Effects Using Ground Motion and Microtremor Data*
- David B. McCallen, Lawrence Berkeley National Laboratory, University of Nevada: *Integrated Geoscience: Engineering Earthquake Simulations at the Exascale with Focused Application on Infrastructure Risk Assessment*
- Hiroe Miyake, Earthquake Research Institute, University of Tokyo: *Recipe for Predicting Strong Ground Motion on the SCEC Broadband Platform*
- Marco Pilz, GFZ German Research Centre for Geosciences: *Modeling of Site Effects: Recent Developments, Challenges and Lessons Learned*

Technical Sessions

Tuesday, 10 October, 6–7:30 PM

Opening Session Introduction

Annemarie Baltay, U.S. Geological Survey; Hiroshi Kawase, Disaster Prevention Research Institute, Kyoto University

Keynote Presentation

Incorporating Novel Techniques and Concepts into Ground Motion and Hazard Modeling. Christine Goulet, U.S. Geological Survey

Complex Kinematic Source Modeling

Wednesday, 11 October, 8:30–10:30 AM

Understanding the complex source process during an earthquake has long been a target of earthquake scientists and engineers, since the establishment of homogeneous rectangular fault modeling. Complex kinematic source modeling through the inversion of observed ground motions over wide frequency ranges and spatial resolutions—from several seconds on the scale of tens of kilometers to several Hz on the order of a few hundred meters—allows us to infer the earthquake rupture and then forward propagate again ground motions. Varying kinematic representations of the source, such as size, shape and variability of the rupture patch, slip distribution and source time function, as well as the velocity structure of the model domain, can be validated through comparison to observed ground motion, and give us insight into plausible rupture dynamics. In this session we look at kinematic source inversions with novel parameterizations, complex source characterization, and the development of modeling techniques for ground motion simulation of future earthquakes.

Dynamic Rupture Propagation Analysis

Wednesday, 11 October, 11 AM–1 PM

While the basic concept of dynamic rupture simulation has been well established, due to increased computational power and spatially complex parameterization, we can generate ever more complex and realistic ground motions. Dynamic modeling allows for feedback of the behavior of the earthquake itself, dependent on initial conditions on the fault, material properties including velocity and elasticity and relations between spatial/temporal stresses and slip. However, there are still outstanding issues for dynamic modeling, such as correlation between kinematic and dynamic parameters of the fault; validation of ground motions, source parameters and slip velocity as output, and consideration of different input relations such as dependency of stress drop on depth, elasticity and friction laws. This session focuses on the recent progress on dynamic rupture propagation analysis for realistic ground motion simulations over a wide frequency range, considering complex input and output validation.

Empirically Modeling Source Effects as Inputs to Models

Wednesday, 11 October, 3–5 PM
Determining a data driven source model of slip, rise time, stress and other source parameters that can replicate the observed ground motion in a forward manner is key to accurately connecting our physical understanding of the genesis of strong ground motion. However, determination of these source models is still an underdefined problem and portraying that accurately in simulations in a manner that can be extrapolated is still challenging. Also, it is necessary to have the quantitative formula for source scaling based on the empirical evidence. This session focuses on new advances in both source characterization as well as the synthesis of the source models into ground motion models and simulations.

Physical Modeling Issues of Site Effects

Thursday, 12 October, 8:30–10:30 AM
Early numerical modeling of site effects included one-dimensional stacked layers, representing only body waves in the upper crust and sedimentary basin. However, many advances using two- and three-dimensional structure are better able to reproduce both the spatial complexity of ground motion, and particularly the observed long durations of motions. For physics-based site effect evaluation, we need both a complex velocity structure and observed ground motion records at the target site for model calibration. Presenters discuss a variety of methods for physical modeling of site effects and their accuracy.

Empirical Modeling of Site Effects

Thursday, 12 October, 11 AM–1 PM
Empirical, observationally driven estimates of site amplification or attenuation can be more accurate than physics- and parameter-based methods. Separation of the site effects from observed seismic motions and subsequent modeling of site effects has been a major target in this field of research. Because of the complexity of geology and velocity around target sites, many features and parameters are challenging to model, such as 3D basin effects, high frequency response, spatial variations and azimuthally dependent effects. This session focuses on techniques and novel methods for describing site effects that improve our ability to characterize ground motion in regionalized and non-ergodic ways, and applying complex models into hazard analysis.

Regional Differences in Quantification of Path Effects

Thursday, 12 October, 4–6 PM
Path effects play an important role in both simulations and empirical modeling, especially over various spatial scales. For example, similarity and variations of attenuation have been observed between regions on both a small scale (tens of kilometers) and a large scale (hundreds of kilometers). The empirical measuring of path effects is fraught with tradeoffs, and it is important to understand how reliable they are. Of particular importance is the applicability of path effects established in one region to other regions with different tectonic setting. Thus, we focus this session on methods for estimating the path and the variability of path effects in different regions on various scales globally, as well as discussion of methodological differences in estimating path effects.

Challenges for Model Extrapolations Outside of the Data Range

Friday, 13 October, 8:30–10:30 AM
While our ground motion datasets have increased and modeling powers have improved, and our interpolation abilities within model domains are excellent, difficulty still arises in extrapolating existing, verified models and techniques to domains outside of our data, such as very near-source, large magnitude events or new regions that are currently seismically quiet—ranges that are arguably the most important for hazard modeling. Both emerging technologies and increased physical understanding, along with validated simulation capabilities, can move this forward. This session focuses on novel ways to bring existing methods and datasets together, as well as novel approaches to ensure that we are accurately representing important model domains.

Overall Prediction Accuracy and Simulation Validation for Real-World Applications

Friday, 13 October, 11 AM–1 PM
Simulated earthquake ground motions are often used to fill in gaps in the instrumental record by considering anticipated future earthquakes or past earthquakes for which we have relatively few, if any, recordings. A variety of methods can be used to generate synthetic ground motions, from stochastic methods for 1D Earth structure to deterministic

methods using 3D Earth structure. In this wrap-up session, presentations will focus on comprehensive ground motion simulations and validation for future damaging earthquakes with applications from around the world. In such simulation projects, validation and extrapolation against empirical data is critical, with the methods of accuracy measurement also a target of discussion. This session will be geared towards the outlook of the community, and presenters and participants will discuss various applications and future directions.

Schedule

Please note: Presenting author is bold in the schedule below.

Tuesday, 10 October 2023

4–7:30 PM	Registration Open
5–6 PM	Opening Reception & Posters
6–6:40 PM	Opening Session Introduction Remarks. **Baltay, A., Kawase, H.**
6:40–7:10 PM	Keynote Presentation—Incorporating Novel Techniques and Concepts into Ground Motion and Hazard Modeling. **Goulet, C. A.**

Wednesday, 11 October 2023

7–8:30 AM	Breakfast & Posters
Session: Complex Kinematic Source Modeling	
8:30–9 AM	KEYNOTE: Characterization of Complex Kinematic Ruptures for Ground Motion Simulation. **Graves, R.**
9–9:15 AM	INVITED: Studying the Viability of Kinematic Rupture Models and Source Time Functions with Dynamic Constraints. **Tinti, E.**, Locchi, M., Mosconi, F., Casarotti, E.
9:15–9:30 AM	Direct Observation of Surface Fault Ruptures during the 2023 South-Eastern Türkiye Earthquake of Mw 7.8. **Iwata, T.**, Asano, K., Sekiguchi, H.
9:30–9:45 AM	Theoretical Examination for the Wide Width Velocity Pulses Generated by Shallow Low Angle Thrust. **Takai, N.**, Shigefuji, M.
9:45–10 AM	Ground-Motion Variability from Kinematic Rupture Models and the Implications for Nonergodic PSHA. **Moschetti, M. P.**, Parker, G. A., Thompson, E. M.
10–10:30 AM	Panel Discussion: Complex Kinematic Source Modeling
10:30–11 AM	Coffee Break

Session: Dynamic Rupture Propagation Analysis	
11–11:30 AM	KEYNOTE: Dynamics and Complexities of Large Earthquake Rupture Sequences: Data-driven and Physics-Based Models of the 2019 Ridgecrest and 2023 Kahramanmaraş, Turkey Multi-fault Sequences. **Gabriel, A.**
11:30–11:45 AM	INVITED: Slip-weakening and Velocity-strengthening Friction Law for Near-surface Layer in Dynamic Earthquake Rupture Simulations. **Kase, Y.**, Irie, K., Torita, H.
11:45–12 PM	Modeling the Rupture Dynamics of Strong Ground Acceleration in Strike-Slip Fault Stepovers. **Lozos, J.**, Akçiz, S., Ladage, H.
12–12:15 PM	Dynamic Rupture Models, Fault Interactions and Ground Motion Simulations for the Gulf of Aqaba Fault System. **Li, B.**, Mai, P., Ulrich, T., Jonsson, S., Gabriel, A., Klinger, Y.
12:15–12:30 PM	Towards Physics-Based Seismic Hazard Assessment in Iceland Based on New Fault System Models and Ground Motion Modeling from Dynamic and Kinematic Rupture Simulations. **Halldorsson, B.**, Li, B., Gabriel, A., Bayat, F., Kowsari, M.
12:30–1 PM	Panel Discussion: Dynamic Rupture Propagation Analysis
1–3 PM	Lunch & Posters

Session: Empirically Modeling Source Effects as Inputs to Models	
3–3:30 PM	KEYNOTE: Recipe for Predicting Strong Ground Motion on the SCEC Broadband Platform. **Miyake, H.**, Pitarka, A., Iwaki, A., Morikawa, N., Maeda, T., Fujiwara, H., Irikura, K.
3:30–3:45 PM	3D Kinematic Modeling of the Impact of the Seismic Source Characteristics on Its Propagation for Recent Large Magnitude Earthquakes Occurred in Mexico. **Chavez, M.,** Cabrera, E., Salazar, A.

3:45–4 PM	Investigating the Origin of High-frequency Earthquake Ground Motions of Earthquakes: A Case Study from Southern California. **Chatterjee, A.**, Trugman, D. T., Hirth, G., Lee, J., Tsai, V. C.
4–4:15 PM	Correlation Between Fault Network Complexity and Observed Stress Drops in California, Japan, and Italy. **Lee, J.**, Tsai, V. C., Hirth, G., Trugman, D. T., Chatterjee, A.
4:15–4:30 PM	Constraining Simulation Rupture Parameters for Unusual "Tsunami Earthquakes." **Nye, T.**, Sahakian, V. J., Melgar, D.
4:30–5 PM	Panel Discussion: Empirically Modeling Source Effects as Inputs to Models
5–6:30 PM	Reception & Posters

Tuesday, 10 October and Wednesday, 11 October—Posters

Complex Kinematic Source Modeling

1 Source Parameterization on Complex Faults Represented by Unstructured Meshes. **Herrero, A.**, Murphy, S.

2 Simulated and Observed Ground Motions from Earthquakes on the Central Calaveras Fault, Northern California. **Hirakawa, E. T.**, Parker, G. A., Baltay, A., Withers, K. B.

3 Slip Distribution in Shallow Areas Above Seismogenic Zone for the Inland Crustal Earthquakes. **Miyakoshi, K.**, Matsumoto, Y., Inoue, N., Kumamoto, T., Kamae, K., Irikura, K.

4 The Interpretation of Double-corner-frequency Source Spectral Model Considering the Heterogeneous Slip Distribution for Crustal Earthquakes in Japan. **Somei, K.,** Miyakoshi, K., Irikura, K.

5 Rupture Process of the 2021 and 2022 Fukushima-Oki, Japan, Intra-Slab Earthquakes (Mw7.1, Mw7.4) Inferred from Broadband Strong Motion Records. **Yoshida, S.**, Tsuda, K., Miyakoshi, K., Sato, T.

Dynamic Rupture Propagation Analysis

6 From Dynamic Source Inversions to Broadband Ground Motion Modeling, With Applications. **Gallovič, F.**, Valentová, Ľ.

7 A New Method for Dissipating Energy in Dynamic Earthquake Rupture Simulations: Nonlinear Radiation Damping. **Harris, R. A.**, Barall, M.

9 Testing the Impact on Surface Rupture of Dynamic Rupture Parameters: An Example from the Shallow 2019 Mw4.9 Le Teil (France) Event. Sassi, R., **Hok, S.**, Klinger, Y., Delouis, B.

10 Quantifying the Effects of Absolute Friction and Geometrical Symmetry on Thrust Fault Rupture. **Margolis, A.**

11 Physics-Based Ground Motion Simulation for the 2017 Mw 6.5 Botswana Intraplate Earthquake. **Su, H.**

12 Asperity Location Identification of the 2016 Kumamoto Earthquake Mainshock by Dynamic Rupture Modeling with 3D Basin Structure. **Sun, J.**, Pitarka, A., Kawase, H., Nagashima, F., Ito, E.

14 Supershear Cascading Ruptures Envelopes. **Zaccagnino, D.**, Herrero, A., Stabile, T., Telesca, L., Akinci, A., Doglioni, C.

Empirically Modeling Source Effects as Inputs to Models

15 The Effect of Azmiuthal Variation on Measured Stress Drop: A Case Study of the 2019 Ridgecrest Sequence. **Chu, S.**, Baltay, A., Abercrombie, R.

16 Slip Pulses and PSHA. **Heaton, T.**

17 Quantitative Assessing the Variability of Earthquake-source Models to Ground Motion Prediction for an M8 Scenario Earthquake in the Ryukyu Subduction Zone. **Hsieh, M.**

18 Near-source Ground Motions During the 2008 Wenchuan Earthquake. **Kurahashi, S.**, Irikura, K.

43 Quantifying Earthquake Rupture Complexity from Theory and Observations: A Review. **Mai, P. M.**

19 Simple Source Modeling and Strong Ground Motion Simulations of the 2023 Mw 7.8 Türkiye-Syria Earthquake. **Nagasaka, Y.**, Nozu, A.

20 Assessing the Accuracy of Earthquake Stress Drop Estimation Methods for Complex Ruptures Using Synthetic Earthquakes. **Neely, J. S.**, Park, S., Baltay, A.

21 Long-range Fiber-optic Earthquake Sensing by Active Phase Noise Cancellation. **Noe, S.**, Husmann, D., Müller, N., Morel, J., Fichtner, A.

22 Break in Self-similar Source Parameter Scaling for Shallow Crustal Earthquakes. **Shimmoto, S.**

Physical Modeling Issues of Site Effects

23 Effect of Liquefiable Double Sand Lenses Position on Surface Settlement of Clayey Soil: Numerical Simulation. **Besharatinezhad, A.**, Nokande, S., Khodabandeh, M., Masoudi, M., Török, Á.

25 3D Simulations of Strong Ground Motion and Site Effects in the Pohang Basin, Korea. **Joshi, L.**, Jo, K., Kim, S.

26 Effects of Input Ground Motion Selection Techniques on Site Response Analyses: Insights from Different Tectonic Settings. **Kaklamanos, J.**, Chowdhury, I. N., Cabas, A., Kottke, A. R., Gregor, N.

27 Physical Modeling of the Influence of Vertical Drain Length on Mitigating Liquefaction-induced Tunnel Uplift. Nokande, S., Haddad, A., Jafarian, Y., **Khodabandeh, M.**, Besharatinezhad, A., Török, Á.

28 Numerical Simulations for Site Effect Estimation in a Complex Sedimentary Basin: A Comparison Between Different Approaches for Designing 3D Seismic Models of the Subsurface. **Lavoué, F.**, Gélis, C., Chaljub, E., De Martin, F., Gisselbrecht, L., Stehly, L., Boué, P., Pilz, M., Beauprêtre, S., Bagayoko, N., Do Couto, D., Cushing, E. M., Moiriat, D., Froment, B.

29 Soil Seismic Response Modeling of KiK-net Downhole Array Site Based on a Multi-input Neural Network. **Li, L.**, Jin, F.

30 Hessian Preconditioners for Sensitivity Kernels Calculation and Uncertainty Quantification in Full Waveform Tomography Application for the Upper South Island Region, New Zealand. **Nguyen, T. T. D.**

31 3D Wave Propagation Simulations of M6.5+ Earthquakes on the Southern Whidbey Island Fault, WA, Considering Surface Topography and a Geotechnical Gradient. **Stone, I.**, Wirth, E. A., Grant, A., Frankel, A.

32 Calculation of Full Nearfield Motion on and Above the Sea Bottom Due to Seismic and Tsunami Waves Excited by an Offshore Earthquake with the Discrete Wavenumber Method. **Takenaka, H.**, Watanabe, T., Komatsu, M., Nakamura, T.

34 Effect of Water Saturation on Ground Motion from a Fault Rupture and an Underground Explosion. **Vorobiev, O. Y.**

35 Site Response Analysis for the Istanbul Region Using Simulated Ground Motions, **Zhang, W.**, Arduino, P., Taciroglu, E.

Regional Differences in Quantification of Path Effects

37 Understanding the Impact of Anelastic Attenuation on Ground Motion Parameter Estimation in Central Italy. **Gabrielli, S.**, Akinci, A., Gutiérrez, C., Ojeda, J., Arriola, S., Ruiz, S.

38 Constraining Large Magnitude Earthquake Source and Path Effects Using Ground Motion Simulations. Meng, X.**, Graves, R.**, Goulet, C. A.

44. Separation of Intrinsic and Scattering Seismic Attenuation in the Crust of Alaska. **Mahanama, A.**, Cramer, C. H., Gabrielli, S., Akinci, A.

Thursday, 12 October 2023

7–8:30 AM	Breakfast & Posters
Session: Physical Modeling Issues of Site Effects	
8:30–9 AM	KEYNOTE: Physical Modeling of Site Effects Using Ground Motion and Microtremor Data. **Matsushima, S.**
9–9:15 AM	INVITED: A Futuristic Look on Site Effects Modeling from the Junction of Earthquake Physics and Engineering. **Oral, E.**, Ampuero, J., Asimaki, D., Bonilla, L.
9:15–9:30 AM	Incorporating Near-surface Structure Into the 3D Cascadia Seismic Velocity Model for Earthquake Hazard Estimates in the Pacific Northwest. **Wirth, E. A.**, Grant, A., Stone, I., Frankel, A., Stephenson, W. J.
9:30–9:45 AM	Physics-Based Ground Motion Modeling for Better Understanding of Historical Earthquakes. **El Khoury, C.**, Hok, S., Gélis, C., Jomard, H., Lyon-Caen, H., Lancieri, M.
9:45–10 AM	Physical and Empirical Site Response Analyses at Selected Borehole Strong-motion Arrays from the United States and Japan. **Wang, Z.**, Carpenter, S.
10–10:15 AM	Challenges in Differentiating P and SV Waves Within Vertical GM Using SW4. **Kamai, R.**, Frid, M.
10:15–10:30 AM	Consequences of Underground Explosions on Soil and Structures Using Non-linear Hydrodynamic Simulations: Application to the August-4-2020 Beirut Explosion. **Ezzedine, S. M.**, Vorobiev, O. Y.
10:30–11 AM	Coffee Break

Session: Empirical Modeling of Site Effects	
11–11:30 AM	KEYNOTE: Modeling of Site Effects: Recent Developments, Challenges and Lessons Learned. **Pilz, M.**
11:30–11:45 AM	INVITED: Understanding and Reducing Tradeoffs Between Empirical Seismic Site Response and Other Ground Motion Effects: Recent Examples from California. **Parker, G. A.**, Baltay, A.

11:45–12 PM	Challenges for Direct Estimation of Site Amplification Factors in Metro Vancouver, Canada from Microtremor H/v Spectral Ratios by Deep Neural Network. **Miura, H.**, Mori, T., Miyazu, Y.
12–12:15 PM	Contamination of "Free-Field" Ground Motion by the Neighboring Built Environment: A Case Study in the Tokyo Area. **Bard, P.**, Nakano, K., Ito, E., Sun, J., Wang, Z., Kawase, H.
12:15–12:30 PM	Non-ergodic Ground-Motion Models for the Wasatch Front, Utah Based on Empirical Data and 3D Simulations. **Sung, C.**, Abrahamson, N. A.
12:30–12:45 PM	Observed Nonlinear Site Amplification of Vertical Ground Motion in Taiwan and Its Impacts on Seismic Design Code. **Chao, S.**
12:45–1 PM	Challenges and Opportunities in High-frequency Ground Motion Modeling Incorporating Site Effects. **Ji, C.**, Cabas, A.
1–3 PM	Lunch & Posters
3–4 PM	Panel Discussion: Physical Modeling Issues of Site Effects & Empirical Modeling of Site Effects

Session: Regional Differences in Quantification of Path Effects

4–4:30 PM	KEYNOTE: Quantifying and Partitioning Ground-Motion Variability in the Era of Big Data and Massive Physics-Based Simulations. **Cotton, F.**, Bindi, D., Esfahani, R., Pilz, M., Razafindrakoto, H., Wheatherill, G.
4:30–4:45 PM	Updating a 3D Vs Model for Southwest British Columbia: From Regional Geodata to Ambient Noise Tomography. Ghofrani, H., Ojo, A., Salsabili, M., Adhikari, S. R., **Molnar, S.**
4:45–5 PM	Numerical Insights of the Model Perturbation and Q on Regional Ground Motions. **Saikia, C. K.**, Solomon, M., Gao, K., Modrak, R. T.
5–5:15 PM	Simplified 3D Basin Velocity Model of the Nakdonggang Delta Region, South Korea, Developed by HVSR and MAM. **Jeong, S.**, Kim, J., Heo, G., Kwak, D.
5:15–5:30 PM	Performance Evaluation of the USGS Velocity Model for the San Francisco Bay Area. **Pinilla Ramos, C.**, Pitarka, A., McCallen, D. B., Nakata, R.
5:30–6 PM	Panel Discussion: Regional Differences in Quantification of Path Effects
6–7:30 PM	Reception & Posters

Friday, 13 October 2023

7–8:30 AM	Breakfast & Posters

Session: Challenges for Model Extrapolations Outside of the Data Range

8:30–8:45 AM	INVITED: Application of Seismological Models and Weak-Motion Data in Engineering Applications. **Kottke, A. R.**
8:45-9 AM	Ground Motion Model Extrapolated to Large Magnitudes by Combining Local and International Records. **Kwak, D.**, Ryu, B.
9–9:15 AM	Regional Ground Motion Models for Western Canada: British Columbia. **Hassani, B.**, Atkinson, G. M., Farihurst, M., Yan, L.
9:15–9:30 AM	Ground-Motion Models in Earthquake Early Warning: Performance Assessment Considerations. **Saunders, J. K.**, Boese, M.
9:30–9:45 AM	The MyShake GM Database: Initial Observations and Utility to Ground Motion Modeling. **Marcou, S.**, Allen, R. M.
9:45–10 AM	Using Offshore Geophones for PGA and PGV Analysis of the 21 March 2022 (Mw=5.1) Earthquake on the Norwegian Continental Shelf. **Zarifi, Z.**, Dehghan Niri, R., Ringrose, P., Tvedt, E.
10–10:30 AM	Panel Discussion: Challenges for Model Extrapolations Outside of the Data Range
10:30–11 AM	Coffee Break

Session: Overall Prediction Accuracy and Simulation Validation For Real-World Applications

11–11:15 AM	KEYNOTE: Integrated Geoscience—Engineering Earthquake Simulations at the Exascale with Focused Application on Infrastructure Risk Assessment. **McCallen, D. B.**, Pitarka, A.

11:15–11:30 AM	The Next Generation of 3D Ground Motion Simulations of Cascadia Subduction Zone Megathrust Earthquakes. **Dunham, A.**, Wirth, E. A., Grant, A., Stone, I., Frankel, A.
11:30–11:45 AM	Variability of Simulated Earthquake Ground Motions in Thessaloniki (Greece) from a Suite of Fault Rupture Realizations. **Lin, J.**, Smerzini, C.
11:45–12 PM	Validation of Hybrid Ground Motion Simulation for Engineering Application in South Korea. **Jeong, S.**, Kim, J., Oh, J., Bae, S., Bradley, B.
12–12:15 PM	Validation of Sedimentary Basin Models Through Comparison of Real and Simulated Resonance Frequencies: Application to the Fucino Intramountain Basin (Apennines, Italy). **Sgattoni, G.**, Molinari, I., di Giulio, G.
12:15–12:30 PM	What's Shaking in the Adriatic Sea?—Implications of Ground Motion Simulation of the 2021 Central Adriatic Earthquake. **Latečki, H.**, Molinari, I., Stipčević, J.
12:30–12:45 PM	Implications of the Use of Physics-Based Simulations in the (Re)insurance Sector. **Stupazzini, M.**, Paolucci, R., Allmann, A., Mazzieri, I., Kaeser, M., Smerzini, C.
12:45–1 PM	Moving Numerical Simulations of Ground Motions from Research to Practice. **Abrahamson, N. A.**
1–2:30 PM	Lunch & Posters
2:30–3 PM	Panel Discussion—Overall Prediction Accuracy and Simulation Validation for Real-World Applications
3–4:30 PM	Closing Session & Final Discussion
4:30–5:30 PM	Closing Reception

Thursday, 12 October and Friday, 13 October–Posters

Challenges for Model Extrapolations Outside of the Data Range

1 Can Non-linear Degradation Curves Be Extrapolated to Large Depth? Insights From the Observed Response of Thick Sedimentary Deposits in Japan. **Bard, P.**, Wang, Z., Sun, J., Ito, E., Kawase, H., Derras, B., Régnier, J.

2 Deterministic Ground Motions from an Earthquake Simulator Are Consistent With NGA-West2 Ground Motion Models. **Shaw, B.**, Milner, K. R., Callaghan, S. A., Goulet, C. A., Silva, F.

3 Perfecting Ground Motion Model for Induced Seismicity in Groningen, the Netherlands. **Spetzler, J.**

4 Ground Motion Modeling in Tectonically Active and Complex Geological Region–Israel and the Dead Sea Transform. **Tsesarsky, M.**

Empirical Modeling of Site Effects

5 On the Empirical Assessment of Ground Motions in Sedimentary Basins and Testing Regional Site Response Models across Tectonic Regimes. **Ahdi, S. K.**, Aagaard, B. T., Moschetti, M. P., Boyd, O. S., Parker, G. A., Stephenson, W. J.

6 Site Response and a New Empirical Ground-Motion Prediction Equation for the Korean Peninsula. **Ahn, B.**, Kang, T., Yoo, H.

7 Stiffness Wave Propagation 1D Numerical Modeling and Experimental Transfer Function Using Cross- and Auto-Power PSD Functions from Earthquakes Recorded in Tri-Axial Accelerometers Vertical Array, and Ambient Vibration Measurements at Ground Surface. **Huerta-López, C. I.**, Suárez-Colche, L. E., Martínez-Cruzado, J. A.

8 Evaluation of the Site Amplification Factors on the Severely Damaged Sites During the 1923 Kanto Earthquake for Delineating the Complex Source Process. **Ito, E.**, Nagashima, F., Sun, J., Wang, Z., Kawase, H.

9 Five Fundamental Rules for Successful Implementation of Spectral Site Amplification Evaluation. **Kawase, H.**, Nakano, K., Nagashima, F., Ito, E., Sun, J., Wang, Z.

11 Development of Taiwan Generic Rock Seismic Velocity Profile. **Kuo, C.**, Abrahamson, N. A.

12 Site Database for the Strong Motion Stations of NCREE in Taiwan. **Lin, C.**, Chao, S., Huang, J., Kuo, C.

13 Estimation of Kappa Within a Low Seismicity Region in Northern New Mexico. **Maier, N.**, Larmat, C., Roberts, P. M.

14 Velocity Structure Identification and Site Amplification Estimation at Rock Sites in Japan. **Nagashima, F.**, Kawase, H., Ito, E., Sun, J.

15 Evaluation of the Characteristics of Group Delay Time as a Phase Property and the Whole-Duration to S-wave Spectral Ratio based on Generalized Inversion Technique with Subsequent Application to the Ground Motion Prediction. **Nakano, K.**, Kawase, H.

16 Geometric Parameters for Seismic Site Response in Sedimentary Basins, **Shams, R.**, Nweke, C. C., Parker, G. A.

17 Classification Algorithms for Sedimentary Basins in Southern California, **Shams, R.**, Nweke, C. C.

18 Empirical Functions for Obtaining Horizontal Site Amplification Factors Considering Soil Nonlinearity.

Wang, Z., Kawase, H., Sun, J., Ito, E., Nagashima, F., Matsushima, S.

19 Estimation of Subsurface Wavefields from Surface Ground Motion Records: A Method Without Conventional Assumption of Plane-wave Incidence. **Watanabe, T.**, Takenaka, H., Oshima, M.

20 Using Multiple HVSR Shape Parameters for Non-Ergodic Site Effects Modeling, Zhan, W., Baise, L. G., **Kaklamanos, J.**

Overall Prediction Accuracy and Simulation Validation for Real-World Applications

21 Developing International Standards and Guidelines for Curating, Disseminating and Validating Simulated Earthquake Ground-Motion Data. **Aagaard, B. T.**, Askan, A., Rezaeian, S., Ahdi, S. K., Yong, A.

23 NDSHA Scenario Seismic Hazard Map, Vancouver, B.C. Area–Xeris Methodology. **Bela, J.**, Panza, G. F., Zhang, Y.

24 Verification and Validation of Physics-Based CyberShake PSHA Simulations. **Callaghan, S. A.**, Maechling, P. J., Meng, X., Milner, K. R., Silva, F., Graves, R., Olsen, K. B., Goulet, C. A., Kottke, A. R., Jordan, T. H., Ben-Zion, Y.

25 Potential Strong Ground Motions and Seismic Hazards in Seoul, South Korea. **Hong, T.**, Kim, B., Lee, J., Park, S., Lee, J.

26 Influence of Site Effect in Evaluation of Near-fault Velocity Pulses Simulated by a Stochastic Finite-fault Derived Method—Validation Cases from Recent Worldwide Large Earthquakes. **Huang, J.**, Lin, C., Chao, S., Kuo, C.

27 Investigating Ground Motion Bias in Finite-fault Simulations of Moderate Magnitude Earthquakes in Southern California. **K C, S.**, Nweke, C. C., Stewart, J. P., Graves, R.

28 Short Period Full Waveform Inversion for Seismic Hazard Analysis in the Aegean. **Lanteri, A.**, Van Herwaarden, D., Noe, S., Keating, S., Pienkowska-Cote, M., Fichtner, A.

30 Comprehensive Validation of Physics-Based Ground Motion Simulations in New Zealand Using Historical Data. **Lee, R.**, Bradley, B., Graves, R., Dupuis, M.

31 Aleatory Variability and Epistemic Uncertainty for Real-world Application of Ground-Motion Simulations in Physics-Based PSHA. **Liou, I. Y.**, Abrahamson, N. A.

32 Realistic 3D Simulations and Ground Motion Prediction in the Offshore Area near Crotone, Ionian Calabria. **Molinari, I.**, Sgattoni, G., Lipparini, L., Faenza, L.

33 Advancements in 3D Seismic Wave Propagation Simulations of Scenario Earthquakes in Southwest British Columbia. Ghofrani, H., **Molnar, S.**

34 Machine Learning Based Estimator for Ground Shaking Maps. **Monterrubio Velasco, M.**, Blanco, R., Modesto, D., Callaghan, S. A., de la Puente, J.

35 Joint Distribution of Input Source Parameters for Physics-Based Ground Motion Modeling Obtained from Simple Dynamic Cycle Simulations. **Munoz Heinen, L. C.**, Stafford, P. J.

36 Physics-Based Broadband Ground Motion Simulations of M6.5 Scenario Earthquakes in Central and Eastern US, Including Surface Topography: Ground Motion Variability Related to Earthquake Rupture Characteristics. Pitarka, A., **Graizer, V.**, Rodgers, A., Aguar, A.

37 Physics-Based Probabilistic Seismic Hazard Analysis of Mumbai City, India. **Podili, B.**, STG, R.

38 Instant Physics-Based Ground Motion Time Series Using Reduced-order Modeling of 3D Wave Propagation Simulations. **Rekoske, J. M.**, Gabriel, A., May, D. A.

40 Adjusting Cascadia Ground Motion Models based on M9 Cascadia Earthquake Simulations. **Smith, J.**, Moschetti, M. P., Thompson, E. M.

41 A Framework for Incorporating 3D Simulation Data into Non-ergodic Ground Motion Models. **Sung, C.**, Abrahamson, N. A., Lacour, M.

42 Some Views on the Physics Based Ground Motion Synthesis. **Tao, X.**, Tao, Z.

43 A Simulation-based Method to Generate Spectrum-matched Ground Motions Considering Spectral Variability. **Wang, X.**, Wang, J., Zeng, Q., Ren, X.

45 Near Source High-frequency Ground Motions from Physics-Based Dynamic Rupture Simulations. **Withers, K. B.**, Ma, S., Ulrich, T., Gabriel, A., Ampuero, J., Oral, E., Daluger, L., Wang, Y., Goulet, C. A., Duan, B., Liu, D., Asimaki, D.

46 Comparative Analysis of Physics- and Empirical-Based Ground Motion Predictions: A Case Study of Hanaore Fault in Kyoto, Japan. **Yadanar, T.**, Chou, Y., Matsushima, S., Nagashima, F.

Oral Presentation Abstracts

Presenting author is in bold.

Opening Session and Keynote Presentation

Oral Session • Tuesday, 10 October • 6 PM Pacific

Incorporating Novel Techniques and Concepts into Ground Motion and Hazard Modeling

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Ground Motion Models (GMMs) are combined with earthquake rupture forecasts (ERFs) to provide deterministic of probabilistic seismic hazard analyses (DSHA, PSHA) results that are used in the design of buildings and infrastructure. Traditionally, GMMs were developed through regression of empirical data using physics-informed functional forms, providing ground motion estimates for the average conditions represented in the dataset. Over time, new parameters have been added to better represent specific site and/or regional conditions, for example. A similar but separate process evolved for the development of ERFs. While we continue to develop increasingly more complete databases, empirical data are still sparse, especially for large magnitude earthquakes and for close recording distances, so new techniques are being considered to improve the representation of non-ergodic (*i.e.*, source-, path-, site-specific) conditions in hazard modeling. Advances in computational capabilities now allow large-scale physics-based simulations to be conducted and new computational methods to be applied to empirical and hybrid datasets. In this presentation, I will summarize some of these new methods and the critical role that verification and validation play in their incorporation into hazard modeling both in the context of research and practical design applications.

Complex Kinematic Source Modeling

Oral Session • Wednesday, 11 October • 8:30 AM Pacific

Characterization of Complex Kinematic Ruptures for Ground Motion Simulation

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Kinematic rupture formulations provide a cost-effective alternative to more physically robust, but computationally intensive, dynamic rupture calculations. Physical consistency of kinematic representations can be constrained via guidance from dynamic models as well as rupture model inversions of past earthquakes. For application to ground motion simulations, most kinematic rupture generators create slip distributions using spatially random fields with magnitude-dependent correlation lengths. Typically, rupture propagation times are determined by specifying the rupture speed as a fraction of the local shear wave speed and the slip rate is represented as a Brune-pulse or Kostrov-like function with the average risetime scaling with seismic moment. Stochastic variations of rupture time and risetime along with geometric fault roughness can be incorporated to reduce coherency in the rupture and better match observed higher frequency (f > 1 Hz) ground motion features (e.g., homogenization of radiation pattern). For surface rupturing events it has been noted that the shallow portion of the fault is relatively depleted in radiation of higher frequency energy. This may correspond to a low dynamic stress drop or velocity strengthening region of the fault, which can be kinematically represented by a reduction of rupture speed and lengthening of risetime. In my talk, I will focus on three main topics related to the characterization of kinematic ruptures for ground motions simulations: 1) scaling and correlation of local risetime with local slip, 2) depth dependence of high- and low-frequency radiation and 3) recommended subfault size as a function of maximum ground motion simulation frequency. These topics will be illustrated with examples from the Graves-Pitarka kinematic rupture generator. I will also discuss how kinematic parameterizations might be improved with particular emphasis on characterization of higher frequency radiation.

Studying the Viability of Kinematic Rupture Models and Source Time Functions with Dynamic Constraints

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Earthquake is one of the greatest natural hazards. Progresses on the knowledge of the seismic source have been made in both modeling the increasingly dense geophysical data and through laboratory experiments. Kinematic modeling is a standard tool to provide important information on the complexity of the earthquake rupture process and for making inferences on earthquake mechanics. Despite recent advances, kinematic models are characterized by uncertainties and trade-offs among parameters (inherent non-uniqueness of the problem). It has been documented that, for the same earthquake, source models obtained with different methodologies can exhibit significant discrepancies. Prescribing the slip velocity on causative faults (source time function) is one of the crucial components in the models because it contains key information about the dynamics. Such function is nonetheless one of the most poorly observationally constrained characteristics of faulting.

Recently, slip velocity time histories have been studied with laboratory earthquakes and a systematic change of mechanical properties and traction evolution has been observed to correspond with a change in the shape of slip velocity.

To investigate the effect of the slip velocity function on the ground motion and on the inverted slip history on the fault we run a series of forward and inverse models. We generate spontaneous dynamic models and use their ground motion as real events and we invert the data with kinematic models and different source time functions. Finally we use the retrieved kinematic history on the pseudo-dynamic models to examine how different kinematic assumptions lead to a variability in the shear stress evolution. We focus on some dynamic parameters such as the breakdown work, the stress drop, and the Dc parameter. Those results provide a glimpse of the variability that kinematic source time functions (dynamically consistent or not) might have when used as a constraint to model the earthquake dynamic.

Direct Observation of Surface Fault Ruptures during the 2023 South-Eastern Türkiye Earthquake of Mw 7.8

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On February 6, 2023, at 4:17 local time, an earthquake of Mw 7.8 occurred in southeastern Türkiye, causing destructive damage in the source area and adjacent northwestern Syria. The Disaster and Emergency Management Authority (AFAD) has released strong-motion observation records through Turkish National Strong Motion Network, where many strong motion records have been obtained. We estimated the source fault rupture velocity using the near-fault records along the Amanos segment that comprising the southwestern part of the Mw 7.8 source fault. Aki (1968) showed that the rupture passing time at the station along the fault could be estimated from the time of the maximum displacement of the fault normal component. We have checked the effect of the shape of the slip function on the estimation of the rupture passing time and applied it to the records. As a result, along the Amanos segment, the rupture speed in the earlier part was estimated as a super-shear rupture, whereas that in the later part was averagely almost the shear wave speed. Total rupture time was estimated about 80 s from the origin time.

We offer my condolences to the victims. We used Turkish National Strong Motion Network, Türkiye, strong motion data. We acknowledge those involved in the strong motion observation.

Theoretical Examination for the Wide Width Velocity Pulses Generated by Shallow Low Angle Thrust

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The strong motion record observed at Nishihara village during the 2016 Kumamoto earthquake (Mw 7.0) was a long-duration, high-velocity, single-sided pulse ground motion known as the "fling step". This type of ground motion differs from the long-period ground motion excited in sedimentary basins and is considered a characteristic feature of the strong motion near the surface fault.

The fling step has been observed only near the surface rupture zone of earthquakes such as the 1992 Landers earthquake and the 1999 Chi-Chi earthquake in Taiwan. On the other hand, strong motion records obtained in the Kathmandu basin during the 2015 Nepal Gorkha earthquake revealed that the destruction of a shallow, low-angle fault plane at a depth of approximately 10 km influenced the ground motion. Even in cases where major surface faulting was not observed, the characteristic velocity pulse ground motion with a single-sided pulse occurred, consistent with the empirical relationship between the pulse duration of MW and the Fling Step.

In this study, we conduct a fundamental examination to generate long-duration, high-velocity pulse ground motion, referred to as "slip pulse", which is like the fling step and occurs directly above a fault plane at a depth of approximately 10 km with a low-angle reverse fault. In this examination, a fundamental investigation was conducted using the representation theorem to examine how pulse-like ground motion generated by low-angle reverse faults occurs for multiple seismic sources. According to the findings, it became evident that the single amplitude velocity pulses observed in the FN and UD components are influenced by the near-field term and intermediate P wave term from the nearest seismic sources. The ground motion observed at the rock site, which was the subject of this investigation, is significantly amplified on the sedimentary basin, becoming a threatening ground motion for long-period structures.

Ground-Motion Variability from Kinematic Rupture Models and the Implications for Nonergodic PSHA

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The variability of earthquake ground motions has a strong control on probabilistic seismic hazard analysis (PSHA), particularly at the low frequencies of exceedance that are used for designing critical facilities. One approach to investigating the ground-motion variability of large-magnitude earthquakes is through the use of multiple realizations of rupture scenarios in earthquake simulations. The simulations for this work were developed by varying kinematic rupture parameters for 96 scenarios of 3D ground-motion simulations for M_W7 earthquakes on the Salt Lake City segment on the Wasatch Fault Zone. We investigate ground-motion variability using a crossed mixed-effects model that treats the kinematic rupture parameters as random effects and a partially nonergodic framework (i.e., accounting for site terms) to partition the variance components. Use of kinematic rupture models for the simulations provides information about the rupture parameters that cause simulated ground motions. Total variance in the simulated ground motions is approximately equivalent to empirical models. The crossed-effects method also provides estimates of the contributions to variance from each of the kinematic parameters. Contributions from the kinematic parameters to total uncertainty suggest approaches to improving future simulations and to reducing the uncertainty in site-specific earthquake hazards studies. Furthermore, simulations show a ground-motion variability that varies spatially and manifests from directivity effects. We illustrate the impact of this spatially varying uncertainty using a partially nonergodic PSHA framework. Significant and period-dependent effects on hazard curves manifest at sites affected by directivity emerge. The results highlight the need for directivity effects to be included in nonergodic PSHA, where additional information about the earthquake source, site response, and path attenuation are paired with reductions in the modeled ground-motion variability.

Dynamic Rupture Propagation Analysis

Oral Session • Wednesday, 11 October • 11 AM Pacific

Dynamics and Complexities of Large Earthquake Rupture Sequences: Data-driven and Physics-Based Models of the 2019 Ridgecrest and 2023 Kahramanmaraş, Turkey Multi-fault Sequences

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The observational difficulties and the complexity of earthquake physics have rendered seismic hazard assessment largely empirical. Despite increasingly high-quality geodetic, seismic, and field observations, data-driven earthquake imaging yields stark differences, and physics-based models explaining all observed dynamic complexities are often elusive.

I will present three-dimensional dynamic rupture models of the 2019 Ridgecrest, California foreshock and mainshock and the 2023 Kahramanmaraş, Turkey, earthquake doublet. By employing high-performance computing, we can integrate data-driven and physics-based modeling to elucidate the mechanics of complex multi-fault systems and decode complex earthquake sequence dynamics. We offer comprehensive explanations of interdisciplinary datasets, unveiling how regional structure, ambient stress, and dynamic and static fault system interactions shape the dynamics (and delays) of seismic sequences.

Dynamic rupture models of California's biggest earthquakes in more than 20 years use supercomputing to find the link between the two events. We conjointly explain strong-motion, teleseismic, field mapping, high-rate GPS, and space geodetic datasets integrating regional structure, ambient long- and short-term stress, and fault system interactions driven by overpressurized fluids and low dynamic friction.

Modeling the Kahramanmaraş earthquake doublet includes unexpected rupture dynamics across multiple fault segments, providing mechanically consistent explanations for observed subshear and supershear rupture speeds, multiple slip episodes, and strong localized shaking. The rapid development of these models can explain unexpected fault system mechanics shortly after large earthquakes, thereby shedding light on both short and long-term fault system interactions worldwide.

This talk aims to stimulate discussions on the importance of bridging the gap between data-driven observations and HPC-empowered physics-based understanding. By embracing the complexities of earthquake physics, we can pave the way for future seismic hazard mitigation.

Slip-weakening and Velocity-strengthening Friction Law for Near-surface Layer in Dynamic Earthquake Rupture Simulations

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In conventional earthquake ground motion predictions (Irikura and Miyake, 2011), slip in a near-surface layer shallower than a seismogenic layer has not been modeled because its contribution to strong-ground motion was considered small. Recently, however, necessity of long-period slip near the ground surface has been pointed out to synthesize the long-period seismic waveforms and permanent displacements near the fault observed in the main shock of the 2016 Kumamoto earthquake (e.g., Irikura et al., 2019). It is difficult to reproduce the long-period slip with small slip rate in a dynamic source model with an elastic medium and slip-weakening friction law.

In the near-surface layer, confining pressure is lower than in the seismogenic layer, and a fracture zone is formed around a fault plane, where energy loss significantly affects a rupture process on the fault. Andrews (2005) showed that an inelastic behavior in the off-fault fracture zone prevents slip rate on the fault from increasing, but a numerical simulation considering the inelasticity can be complex and expensive. To avoid the difficulty in the simulation, Barall and Harris (2023) proposed an addition of a nonlinear radiation damping term to the friction law, with the surrounding medium remaining linear elastic.

In rock experiments, on the other hand, it has been shown that friction coefficient increases with increasing slip rate in the intermediate (about 0.05-0.2 m/s) velocity range (e.g., Tsutsumi and Shimamoto, 1997; Reches et al., 2010). The velocity-strengthening mechanism can be expected to suppress an increase of slip rate at the beginning of slip and a stop at the end of slip. We propose a velocity-strengthening friction law below a certain velocity in addition to a slip-weakening law. We applied our friction law to a rupture simulation in an elastic medium, and our results showed large slip and small slip rate time histories on a fault in the near-surface layer and long-period seismic waveforms near the fault (within about 1 km).

Modeling the Rupture Dynamics of Strong Ground Acceleration in Strike-Slip Fault Stepovers

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Following the July 2019 Ridgecrest earthquakes, multiple field investigators noted that pebble- to boulder-sized rocks had been displaced from their place in the desert pavement along the right-lateral strike-slip M7.1 rupture trace. This implies localized ground motions in excess of 1 g, in contrast to instrumentally recorded ground motions which peak at ~0.7 g. However, these features are not pervasive along the entire rupture; they are concentrated entirely within extensional stepover region near the southern end of the M7.1 rupture. Similar observations of displaced rocks concentrated in stepovers exist for the predominantly right-lateral strike-slip 2010 M7.2 El Mayor-Cucapah earthquake. Together, the Ridgecrest and El Mayor-Cucapah examples suggest that some aspect of how earthquake rupture negotiates a strike-slip fault stepover produces extremely localized strong ground acceleration.

Here, we use the 3D finite element method to investigate how the geometry and connectivity of stepovers in strike-slip faults influences strong ground acceleration. In particular, we focus on how the amount of overlap between the two fault strands, and the width of the stepover, influences the location and intensity of the strongest ground motion, for both subshear and supershear rupture velocities. For subshear ruptures, we find that the presence of a stepover in general matters more than its dimensions; the strongest ground accelerations occur at the end of the first fault, but whether or not rupture jumps to the second fault strand controls just how strong the shaking is. For supershear ruptures, the stepover is effectively irrelevant, since the strongest particle accelerations occur at the point of the supershear transition on the first fault. Our specific choice of initial conditions does not produce accelerations above 1 g in any of our simulations, the location of our strongest ground motions in the subshear cases is consistent with the locations of displaced rocks and localized strong shaking in both the Ridgecrest and El Mayor-Cucapah earthquakes.

Dynamic Rupture Models, Fault Interactions and Ground Motion Simulations for the Gulf of Aqaba Fault System

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The ~180 km long Gulf of Aqaba (GoA) fault system, southern part of the Dead Sea Transform Fault (DSTF), is a left-lateral strike-slip plate boundary separating the Arabian plate from the Sinai micro-plate. With the potential to produce Mw 7.3 or larger earthquakes, the GoA fault system poses a high seismic risk for the rapidly developing NEOM and nearby coastal communities. However, the offshore fault system and limited data availability make reliable seismic hazard assessments (SHA) challenging.

In this study, we run 3-D spontaneous dynamic rupture simulations to explore the dynamics and fault interactions of a number of rupture scenarios in the GoA fault system, and investigate the resulting local ground motions. We construct various fault geometries based on the recent high-resolution multibeam imaging and local seismicity. All models account for regional seismotectonics, topo-bathymetry, off-fault plasticity, and we explore the effect of fault roughness. The results show that the fault system geometry, hypocenter location, and prestress affect the rupture propagation across the multi-segment GoA fault system and thus lead to varying slip distributions and magnitudes. A Mw 7.4 scenario occurs if the entire main fault segments break. All simulations yield heterogeneous ground motion distributions, with strong shaking at geometric fault complexities and in the forward rupture direction. Such locally ground motion characteristics captured in dynamic simulations can improve the site-specific hazard assessment. Topographic effects either amplify or diminish ground motion amplitudes. Notably, the potential supershear rupture results in distinct ground motion patterns with subshear scenarios and can significantly intensify the ground shaking ~10-20 km away from the faults, which greatly increase the seismic risk for the coastal communities. The ensemble of physics based and observationally informed earthquake scenarios and the resulting ground motions can complement empirical SHA methods in the data-scarce region, such as the GoA.

Towards Physics-Based Seismic Hazard Assessment in Iceland Based on New Fault System Models and Ground Motion Modeling from Dynamic and Kinematic Rupture Simulations

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Iceland is the most seismically active country in Northern Europe. An island in the North Atlantic Ocean, it straddles the Mid-Atlantic Ridge (MAR) between the Eurasian and North American plates. The presence of the Icelandic hot spot under central Iceland drives the volcanism of the country and causes a ~150 km eastwards ridge-jump of the MAR, forming two large transform zones, the on-land Southwest Iceland transform zone and the larger and largely offshore Tjörnes Fracture Zone (TFZ) in Central North Iceland. It has recently been shown that strong earthquake occurrence in both zones primarily takes place on complex bookshelf fault systems, with the exception of the Husavik-Flatey Fault Zone (HFFZ) in the TFZ, the largest conventional strike-slip fault in the country. The largest earthquakes in Iceland up to ~M_w7-7.2 take place in these zones and cause both dynamic and static triggering of other faults and cause damage. We present the modeling progress of time-independent fault slip rates on 3D fault system models of the transform zones that are calibrated to the rate of tectonic extension in the country. Their equivalent magnitude-frequency distributions effectively explain the historical earthquake catalogue. The physics-based fault system models thus constitute a common foundation for the timely revision of seismic hazard for Iceland. We present dynamic rupture modeling results for scenario earthquakes on the HFFZ and analyze the rupture dynamics, fault interactions, and the associated ground motions up to 2.5 Hz based on three modeling-levels of complexity of the HFFZ. We show how fault system geometry and segmentation, hypocenter location, and prestress can affect the potential for rupture cascading, leading to varying slip distributions across different portions of the fault system. Finally, we present the provisional seismic hazard maps for the Southwest Iceland transform zone and plans for incorporating near-fault effects from kinematic rupture modeling.

Empirically Modeling Source Effects as Inputs to Models

Oral Session • Wednesday, 11 October • 3 PM Pacific

Recipe for Predicting Strong Ground Motion on the SCEC Broadband Platform

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The recipe for predicting strong ground motions has been used for national seismic hazard mapping as well as the computation of design basis ground motions for nuclear power plants in Japan. The first objective of the recipe is to provide a tool that can be flexible in representing earthquake rupture models. The second is the capability to simulate damaging rupture directivity pulses that affect the near-fault response spectra. The third is the generation of calibrated characterized earthquake rupture models that are applicable to simulations employing empirical Green's functions, including realistic complexity of velocity structure and site response. The recipe for crustal earthquakes has been validated using 1D and 3D velocity models with a hybrid method. We validated random realization by changing the rupture starting points, location of asperities, and rupture velocity to assess simulated ground motion variability. Recently, two methods based on the recipe were implemented on the SCEC (Southern California Earthquake Center) Broadband Platform. The Irikura Recipe Method 1 is applicable to single- and multiple-segment rupture models. The source module allows the variable rupture velocity of the characterized source model, and 80% of S-wave velocity is set to an initial value. The wave propagation module is identical to the GP (Graves and Pitarka) method. As for the Irikura Recipe Method 2, the source module is identical to the one used in Method 1. The wave propagation is handled by the low-frequency module using the FK method, and the high-frequency wave propagation is handled by the high-frequency module using the stochastic Green's function method. Comparisons between the high-frequency wave propagation modules in Methods 1 and 2 show that they produce slightly different ground motion amplitudes due to the attenuation modeling. We will show the performance of both methods in simulations of broadband ground motion for crustal earthquakes using the SCEC Broadband Platform.

3D Kinematic Modeling of the Impact of the Seismic Source Characteristics on Its Propagation for Recent Large Magnitude Earthquakes Occurred in Mexico

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To take into account the spatial characteristic of the seismic sources of Ms 7^{+} mexican earthquakes, a set of three attenuation relations of Modified Mercalli Intensity with magnitude and distance were proposed by Chavez and Castro in 1988. This was accomplished by using a parameter, as a proxi to the seismic sources rupture areas obtained from the regressions of 42 Ms 7^{+} mexican historical earthquakes dating from 1845 to 1980. Recently, by using USGS information about the source mechanism of Mw 7^{+} mexican earthquakes, Chavez et al. (2011, 2014, 2016) have succefully modeled the low frequency propagation of several of those events. Those studies made use of a 3D finite-difference wave propagation code applied by Chavez et al. (2010) to obtain the low-frequency synthetic 3D wave velocity propagation field of the Mw 7.9 Wenchuan earthquake.

To study of the role of the characteristcs of the seismic sources on the propagation of Mw 7^{+} earthquakes occurred in Mexico since 2017, we modeled with the mentioned code, the low frequency propagation of the following earthquakes: the 08 09 2017 intraplate Tres Picos Mw 8.2, the 19 09 2017 intraplate Puebla-Morelos Mw 7.1, the 23 06 2020 interplate Oaxaca Mw 7.3, the 08 09 2021 Acapulco interplate Mw 7.1 and the interplate 19 09 2022 Tecoman Mw 7.1.

Among other results the following conclusions can be drawn: 1) The propagation patterns obtained for the 2 intraplate and the 3 interplate modeled events shows that the former generate larger amplitudes for epicentral distances < 200 km; and 2) that excepted for the epicentral region, for the latter the maximum amplitudes are produced for epicentral distances of more than about 200 km. These results , roughly agree with the ones obtained in the 1988 study.

Investigating the Origin of High-frequency Earthquake Ground Motions of Earthquakes: A Case Study from Southern California

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Understanding the cause of damaging high-frequency earthquake ground motions is important from both a fundamental physics perspective and to better prepare for earthquake hazards. There are several competing theories over the origin of high-frequency ground motions. The standard paradigm is related to heterogeneity in slip on the rupture plane, but it remains challenging for these models to explain the variety of observed high-frequency ground motions with physically consistent parameters like stress drop and fault roughness. Alternatively, high-frequency earthquake radiation has recently been associated with fault complexity, though the underlying physical mechanisms are still not well understood. To untangle this problem, we measure response spectral accelerations at different periods for small and moderate earthquakes in Southern California and compare these measurements to predicted values from NGA-West2 ground motion models. We use the integrated nested Laplace approximation (INLA) method, which is a Bayesian inference approximation approach, to calculate the event terms. By adopting this approach, we incorporate a non-ergodic component to the existing ground-motion model to measure robust spatial variations in earthquake event terms. Doing so enables us to quantify how earthquake ground motions at different frequencies correlate with different tectonic and geophysical parameters. By exploring the connections between event terms at different periods with source and fault zone characteristics, our objective is to gain a deeper understanding of the mechanisms behind the generation of high-frequency ground motions in real fault systems.

Correlation Between Fault Network Complexity and Observed Stress Drops in California, Japan, and Italy

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Geometric complexities of fault systems can significantly affect earthquake rupture processes and the resulting ground motions. While recent studies have concentrated on identifying and incorporating the effects of non-planarity in fault surfaces into earthquake rupture models, the contribution of fault network geometry has often been overlooked. The underlying physical mechanisms are still not well understood, and exploring the correlation between fault complexity and seismologically observable parameters can offer insights into the role of fault network geometry in earthquake rupture dynamics. In our study, we test the hypothesis that elastic collisions between discrete fault structures during earthquake rupture enhance high-frequency seismic radiation. We identify correlations between fault complexity metrics and measured earthquake stress drops in Southern California, Japan, and Central Italy, using earthquake stress-drop catalogs and high-resolution fault trace maps. Employing random sampling techniques, we estimate areas of coherent fault network characteristics across multiple length scales and calculate metrics of fault misalignment and fault density in these areas. Our analysis reveals consistent positive correlations between the fault metrics and individual stress drop measurements. Notably, we observe stronger correlations of stress drop with fault misalignment compared to fault density. These findings agree with previous studies and support the notion that fault interactions within networks of misaligned faults can lead to enhanced high-frequency seismic radiation. Our study introduces a novel perspective on characterizing earthquake source spectra in terms of fault complexity, and suggests that future earthquake models should aim to incorporate the complex interaction between fault strands within the fault system.

Constraining Simulation Rupture Parameters for Unusual "Tsunami Earthquakes"

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We constrain values of key rupture parameters for the 2010 Mentawai tsunami earthquake (TsE). TsEs are rare earthquakes that generate tsunamis much larger than expected for their magnitude, which poses a challenge for current tsunami early warning (TEW) systems. Methods involving energy-related ratios of teleseismic data have previously been used to discriminate TsEs because these events radiate high frequency energy inefficiently. However, near-field data, and models replicating it, are critical for timely warnings. Currently, near-field TsE data only exist for the 2010 M7.8 Mentawai TsE. We use a combination of near-field simulated and observational data for the Mentawai event to better understand the source physics of TsEs.

Using a set of semistochastic forward-modeling codes, we generate synthetic rupture scenarios and waveforms patterned after the 2010 event slip model. We modify the stress drop, rise time, and rupture velocity (V_{rupt}), as each of these rupture parameters is believed to be characteristically extreme for TsEs, to determine which combinations best reproduce the Mentawai TsE. We vary the stress drop between 0.01–5 MPa, the average rise time between 5–25 s, and the average V_{rupt} between 0.8–2.2 km/s. We compare the synthetic waveforms with observed by evaluating the intensity measures (IMs) peak ground displacement, time-to-reach peak ground displacement (t_{PGD}), peak ground acceleration (PGA), peak ground velocity (PGV), and

Fourier amplitude spectra (FAS) bin averages. We find that lowering the stress drop captures the energy-deficiency of TsEs, whereas increasing the rise time and decreasing the V_{rupt} capture the longer duration of TsEs. Our final product is the expected mean and standard deviations for these rupture parameters, which can be used to generate synthetic TsE scenarios in other subduction zone environments. By characterizing TsE rupture parameters, we can improve TEW machine learning algorithms to be able to better identify these rare, but destructive events.

Physical Modeling Issues of Site Effects

Oral Session • Thursday, 12 October • 8:30 AM Pacific

Physical Modeling of Site Effects Using Ground Motion and Microtremor Data

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Physical modeling of site effects requires information of velocity structure of the subsurface beneath a target site. For the first order approximation, and for simplicity, the velocity structure is often assumed as 1D, while the actual structure is 3D. In order to derive the velocity structure of a site, ground motion and microtremor data observed at the site can be used. As an example of deriving 1D velocity structure using ground motion data, Nagashima et al. (2014) developed a method to invert the velocity structure from earthquake horizontal-to-vertical spectral ratios (EHVRs) based on the diffuse field theory. The results indicated that it is essential that layers from the bedrock to the surface to be considered in order to invert the peaks of EHVRs in broad frequency range. This shows that high frequency peaks cannot be inverted by only considering the shallow subsurface, but needs to consider the higher modes of the lowest frequency peak that reflects the structure down to the bedrock depth.

The effect of 3D structure to amplify ground motion was revealed during the 1995 Kobe Earthquake that caused a "Disaster Belt". This was a result of the "Basin Edge Effect" and highlighted that for sites close to an area where lateral heterogeneity of the bedrock exists, considering 1D structure just beneath the site is not sufficient to estimate the site effect but the 3D effect will have a large effect in the resulting ground motion. The effect of 3D structure can be seen in observed microtremor horizontal-to vertical spectral ratios (MHVRs) at sites with lateral heterogeneity as directional dependence of the MHVRs.

Recently, a blind prediction exercise to estimate the 1D velocity structure as well as weak and strong ground motion was conducted as part of "The 6th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion (ESG6)" that was held in August 2021. This exercise revealed the ability of current methods to physically model site effects.

A Futuristic Look on Site Effects Modeling from the Junction of Earthquake Physics and Engineering

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Ground motion is traditionally formulated as the end product of a chain that starts with source and path effects, and ends with near-surface variations induced by site effects. While the interdependence of the components of the ground motion chain is not fully understood, the advances in site characterization and physics-based modelling allow for addressing still-open questions related to each. In my talk, reading this chain backwards, I will expand on the questions of "how to approximate near-surface soil nonlinearity, how sensitive is the site response to incident waves, and how to account for site effects in the near field in presence of sediments inside the fault zone?" through real case applications from California to Nepal. Lastly, I will briefly discuss how to integrate such physic-based models into site-specific hazard prediction practice in the context of natural and induced earthquakes.

Incorporating Near-surface Structure Into the 3D Cascadia Seismic Velocity Model for Earthquake Hazard Estimates in the Pacific Northwest

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The USGS' 3D Seismic Velocity Model for Cascadia is used for a variety of purposes, including 3D earthquake simulations and seismic hazard assessment in the Pacific Northwest. In addition to large-scale geologic and tectonic structure, near-surface site effects significantly impact amplification and frequency content of earthquake ground shaking and thus, are a critical component of estimating ground motions. We develop region-specific shear wave velocity models based on hundreds of measured velocity profiles across the Pacific Northwest, which are modeled as a function of site condition (i.e., time-averaged Vs in the top 30 m, Vs30) and depth. Separate functional forms were produced for sites located on fill and alluvium, the Puget Lowland, the Willamette Valley, and rock sites outside of these specified regions. We apply these geologic and regional Vs profiles to the Cascadia model to approximate more realistic shallow (<1 km depth) seismic velocity structure. To assess the impact of these updates on ground motion estimates, we run linear 3D numerical simulations of the 2001 M6.8 Nisqually earthquake in Washington State up to 2 Hz and with a minimum shear wave velocity of 150 m/s. We find that the addition of realistic near-surface seismic velocities improves the fit to recorded observations of peak ground velocities and Fourier spectra at frequencies >0.5 Hz compared to simulations without the geotechnical layer, particularly for sites with Vs30<400 m/s. These results also allow us to evaluate how near-surface material interacts with the response of the Seattle Basin to enhance ground shaking in the vicinity of Seattle, Washington. For example, sites on artificial fill and alluvium experience the compound effects of frequency-dependent amplification due to shallow soft soils, as well as from basin-edge surface waves and S-wave focusing due to basin structure. Overall, this work demonstrates the importance of incorporating realistic near-surface structure into regional seismic velocity models for estimating ground shaking intensity from simulated earthquakes.

Physics-Based Ground Motion Modeling for Better Understanding of Historical Earthquakes

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Situated in the north of Florence, Italy, the Mugello basin is a sedimentary basin bordered by two fault systems, with a thickness of several hundred meters. Over time, the region has experienced significant seismic events, particularly in 1542 (M 6) and 1919 (M 6.4), resulting in extensive damage throughout the area. These events caused disorders, repairs, and restorations to the bell towers located in the region. As part of the ACROSS ANR project framework, historians, archaeologists, petrologists, and civil engineers are currently studying these bell towers. These historical buildings serve as important indicators of past seismic events and can be used as "stone seismometers" to analyze the ground motions that caused damage or repairs to the structures.

The primary objective of the project is to reconstruct the seismic ground motion associated with the past earthquakes. To achieve this goal, numerical modeling of the seismic ground motion is conducted, taking into account the complexity of source rupture and wave propagation in a 3D sedimentary basin. The initial step involves creating a rupture scenario by investigating the physical parameters of the fault model, primarily focusing on fault geometry and fault kinematic model parameters that may have been responsible for the 1542 and 1919 earthquakes. It is important to note that there is an ongoing debate regarding the specific fault system accountable for these earthquakes. The next step is to construct a 3D basin model with accurate geometry and mechanical properties. This model is validated by comparing recorded seismic ground motions in the area (such as local sequences and teleseismic events) with the computed seismic ground motions in the model. Finally, 3D ground motions produced by the selected fault rupture scenarios and propagating within the area including the basin are computed, with a particular focus on the bell towers studied within the project.

Physical and Empirical Site Response Analyses at Selected Borehole Strong-motion Arrays From the United States and Japan

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Ground motion is a complex 3D wave-propagation phenomenon and requires an accurate velocity structure for reliable physics-based modeling. Physics-based modeling of site response is challenging and 1D modeling remains the dominant approach because higher frequencies (10 Hz or greater) and nonlinearity must be considered for engineering applications. In this study, we evaluated the reliability of 1D shear-wave (Vs) profiles at 10 selected strong-motion borehole arrays from the United States and 77 from Japan (KiK-net) and tested the applicability of 1D physical modeling for site response at these 87 sites. We selected borehole arrays based on the availabilities of 1) relevant site information and 2) ground-motion records (≥ 5 events). All the selected borehole arrays penetrate bedrock with Vs greater than 1,000 m/s in the US and 2,000 m/s in Japan. We collected weak and strong ground motion time-series for the selected borehole arrays. We calculated empirical transfer functions (TFs) and horizontal-to-vertical spectral ratios (HVSRs) from the ground motions and derived theoretical TFs and HVSRs from 1D linear and full-wave modeling. We extracted the fundamental-mode frequency and its associated amplification and peak-mode frequency and its associated amplification from the linear empirical and theoretical TFs and HVSRs. We evaluated the reliability of Vs profile at each borehole array based on two criteria: 1) the ratio of fundamental frequencies between empirical and theoretical linear TFs and 2) the ratio of fundamental frequencies between empirical and theoretical HVSRs. Our results show that the Vs profiles are reliable at eight of the 10 U.S. boreholes and only 36 of the 77 Kik-net boreholes. Our results also show that the 1D modeling can predict site response, including nonlinearity, at the borehole arrays with reliable Vs profiles. This study demonstrates that it is essential to obtain reliable Vs profiles into bedrock and that 1D response modeling could provide reliable and high frequency site response characteristics, which are as yet unattainable with 3D modeling.

Challenges in Differentiating P and SV Waves Within Vertical GM Using SW4

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Vertical ground motions have been traditionally neglected in seismic-hazard analysis because they were believed to have minor effects on civil structures. Specifically, the vertical site-response and the physical parameters which influence it are still poorly understood. Despite studies showing that the P-wave contribution to VGM may be higher than that of the SV-waves for some frequencies, recently-published vertical GMPEs still use V_{S30} as a single site-characterization parameter. Therefore, understanding the relative contribution of different wave types within VGM will enable us to use both P- and S- wave site parameters within VGM site-response for prediction.

In this project, the relative contribution of P- and SV waves to the VGM is explored using the SW4 finite-difference platform: First, we compare partial derivatives of the recorded motion to seismological ray-theory computations of wave arrivals, finding significant discrepancies between the physically expected motions and numerical results. In this talk, we will openly share the challenges associated with using wave mechanics in the finite difference scheme and discuss possible reasons for such discrepancy, as well as possible solutions. We will elaborate on one of such possible solutions, in which we use wave radiation patterns to differentiate P and SV waves, by exploring the V/H ratio of large 3D, fully deterministic simulations at varying fault mechanisms and subsurface geology models. We will share preliminary results of this ongoing effort.

Consequences of Underground Explosions on Soil and Structures Using Non-linear Hydrodynamic Simulations: Application to the August-4-2020 Beirut Explosion

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Predicting a propagating blast wave in urban environment is a complicated task especially when dealing with a dense and a complex urban environment such as Beirut city. Furthermore, when the shockwave is simultaneously interacting with sea water, air, and ground, then it further complicates the non-linear interaction of the shockwave with the environment and its response to the urban geometry and structures. Empirical and semi-empirical engineering tools are then limited, and it is required to use state-of-the-art hydrodynamic codes which has led us to develop a physics-based framework to seamlessly simulate the event from source, chemical explosion, to ground and sea-water impacts, to wave generation, propagation. The non-linear effects of the explosion are simulated using the hydrocode GEODYN to create the nearfield source for the shallow water wave propagation code, SWWP and the ground propagation SW4. The GEODYN-SWWP coupling is based on the structured adaptive mesh refinement infrastructure; SAMRAI developed at LLNL, while GEODYN-SW4 coupling is based on mapping the explosion source as a boundary condition to SW4. We illustrate both couplings and compare them to a direct solution where all the physics is solved fully using GEODYN. Only a fraction of the total explosion energy is converted into hydroacoustic and seismoacoustic waves that are propagated beyond the source region. The remaining energy is consumed by the "evaporation" of the water and pulverization of the surrounding ground and structures. We predicted the crater at ground zero and assessed key parameters and their uncertainty on the overall hydroacoustic and seismoacoustic responses. We also use a scaled versions of Source Physics Experiments (SPE) to assess the impact of underground and above ground explosions on nearby surface structure. Finally, we apply the end-to-end simulation framework to the August 4th, 2020 Beirut explosion.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Empirical Modeling of Site Effects

Oral Session • Thursday, 12 October • 11 AM Pacific

Modeling of Site Effects: Recent Developments, Challenges and Lessons Learned

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The effects of shallow geological layers and interfaces (within the upper 1-2 km) on the seismic-induced ground motion recorded at the ground surface have been the focus of numerous studies over the past few decades. Though the physics governing the main aspects of site is relatively well understood, amplification at many actual sites is too complex to be fully described by a set of differential equations under certain initial conditions. Nevertheless, there are a number of physical principles which have recently found their way into modelling of site effects. Here we illustrate recent developments in physics-based modelling emphasizing the limits of classical 1D models to reproduce site-amplifications. This includes, for example, attempts to quantify complex (2D/3D) site effects as well as modelling approaches considering the duration of ground motion. While it might be difficult to identify single geological / geotechnical factors that control ground motion and its variability, we will discuss and illustrate new working hypotheses (i.e. time dependency of ground motion, site-city interaction) that might partially explain it. Spatially high-resolution experiments (e.g. using Distributed Acoustic Sensing) might also help in better explaining complex behaviour.

Understanding and Reducing Tradeoffs Between Empirical Seismic Site Response and Other Ground Motion Effects: Recent Examples from California

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We present novel advances in partitioning techniques for earthquake ground motion residuals that improve our physical understanding of, and mitigate tradeoffs between, source, path, and site effects. In empirical ground motion modeling, any one intensity measure can be split into components that represent different physical processes such as moment release, rupture directivity, seismic wave propagation, and site amplification effects, among others. Ground-motion observations are relatively sparse, and the data suffer from uneven spatial sampling of both source and receiver locations. Here we review the non-reference site approach to estimating site response and expand upon it with methods that better account for data sampling biases. In southern California we develop a nonergodic site response model by interpolating numerous site-specific estimates at station locations. To account for repeated and uneven sampling of wave propagation paths, we apply an earthquake location clustering technique and develop novel uses of the earthquake clusters as random effects in our residuals partitioning. The result is a model for azimuth-independent site response that can be used in general forward applications such as the USGS ShakeAlert system, as well as models for azimuth-dependent site response conditioned on the wave incident angle into Los Angeles basin. In northern California, we observe strong rupture directivity and azimuthal trends in ground-motion amplitudes from the 2022 M5.1 Alum Rock earthquake. Here, we develop two new techniques: The first is an azimuthal resampling of data in the calculation of event terms, which can change the estimates by up to 30%, and the second is an empirical Green's function (eGf)-type approach where we utilize ground motions from smaller earthquakes co-located with the mainshock. We estimate repeatable path and site effects from the eGf events and use them to adjust the mainshock residuals to isolate directivity effects. These more nuanced characterizations of source and path effects improve the accuracy and precision of our site response models.

Challenges for Direct Estimation of Site Amplification Factors in Metro Vancouver, Canada from Microtremor H/v Spectral Ratios by Deep Neural Network

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Site effect is one of the important factors in evaluating seismic ground motions at ground surface. Site effect has been generally represented as site amplification factor (SAF) in frequency domain. SAFs can be evaluated by theoretical approach from shear-wave velocity profile and/or empirical approach from generalized spectral inversion analysis of observed ground motion records. However, it was not easy to apply these approaches at arbitrary sites because of the limited financial and instrumental resources. Recently one of the authors has proposed a new and simple method to estimate SAF from microtremor horizontal-to-vertical spectral ratio (MHVR) based on deep neural network (DNN), one of the artificial intelligence (AI) techniques. The DNN model consists of multiple layers such as Affine layers, nonlinear activation layers and Dropout, and it can automatically and directly estimate SAF by giving observed MHVR at the frequency range of 0.3 to 20 Hz. The DNN model was developed from the microtremor and earthquake motion records observed in Japan, and the applicability of the model has been discussed in other regions/countries. In this study, we applied the DNN model to the microtremor data observed near the seismic observation sites in Metro Vancouver regional district, Canada for estimating SAFs at the sites. We found that larger amplifications were expected at low frequency around 0.6 to 1.5 Hz in the delta area along the Fraser river. The accuracies of the estimated SAFs were discussed by comparing with the seismic site responses in previous studies.

Contamination of "Free-Field" Ground Motion by the Neighboring Built Environment: A Case Study in the Tokyo Area

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It is well known that soil-structure interaction (SSI) may significantly modify the structural motion. As the radiation damping associated to SSI is actually associated with emission of seismic waves from the structure foundation, a number of authors have investigated the possible feedback of SSI on the "free-field" ground motion, with a special focus on densely urbanized areas. These investigations involved either numerical simulation with a more or less sophisticated accounting of underground soil and/or structural characteristics, or laboratory experiments at reduced scale using centrifuge, shaking tables or acoustic devices, and sometimes full scale on analogs such as forests. Most of them provide consistent results indicating the plausibility of measurable, significant effects on ground motion, with an overall decrease of the average ground motion in specific frequency bands together with an increased spatial variability. However, such effects could never be unambiguously identified in seismological recordings from real earthquakes in real cities. The present study takes advantage of the long duration of sensitive strong motion instrumentation in the Kanto area thanks to the KiK-net, K-NET and JMA (Shin-dokei) networks, to investigate the possible changes in site response with time in the Kanto area. An analysis of the event-specific site terms derived from Generalized Inversion Techniques (Nakano et al., 2015) indicates a systematic reduction of the low frequency (0.2 – 1 Hz) site response in the central-south Tokyo area, also characterized by the recent construction of many high-rise buildings. This frequency band corresponds to both the site frequency (Kanto plain) and high-rise buildings, indicating a possible relation with the extensive construction in some areas of downtown Tokyo over the last 2 decades, and the potential need to include such effects in ground motion simulation for densely urbanized areas with comparable site and structural frequencies.

Non-ergodic Ground-Motion Models for the Wasatch Front, Utah Based on Empirical Data and 3D Simulations

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As data sets of ground motions from 3D simulations and from empirical recordings increase, the large systematic path and site effects can be seen. The dense 3-D simulations show the systematic path effects of the 3D crustal structure on the long-period ground motions. The empirical data show the systematic site and path effects for the full frequency range but with much more sparse spatial coverage as compared to the 3D simulations. The empirical ground-motion data set consists of 1509 local recordings from 62 small to moderate-sized earthquakes and the 2020 M 5.7 Magna event. We show an example of the development of a non-ergodic ground-motion model (GMM) for Fourier Amplitude Spectra (FAS) for the Salt Lake Utah region using empirical data. The simulation data set consists of 3D simulations for M7 events on the Wasatch fault developed by Moschetti et al. (2017). We develop a second non-ergodic GMM for long periods using 3D simulations. Overall, the standard deviation of the non-ergodic GMM is about 15-25% smaller than the ergodic standard deviation for both the simulation and empirical data sets. We convert the median FAS predictions of the empirical model to PSA by the random vibration theory (RVT), which can be compared with the non-ergodic site term from the 3D simulation in the same region. At long periods, the non-ergodic adjustment terms based on the 3D simulation are stronger than seen in the observed data, leading to a range of a factor of 1.2 increase or decrease relative to average scaling based on basin depth terms.

Observed Nonlinear Site Amplification of Vertical Ground Motion in Taiwan and Its Impacts on Seismic Design Code

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Chao et al. (2019, 2020) have proposed horizontal and vertical GMPEs that are applicable to crustal and subduction earthquakes in Taiwan; herein, these GMPEs are denoted as NCREE19 horizontal and vertical GMPEs. In contrast to the observations based on four vertical GMPEs in the NGA-West2 project, NSA has been observed in vertical ground motions in Taiwan, and the level of nonlinearity is similar to that of horizontal ground motions in Taiwan. The objective of this study is to evaluate the possible reason for the observed nonlinear site amplification (NSA) of vertical ground motions in Taiwan as illustrated by NCREE19 vertical GMPE. First, we observe that NSA generally occurs simultaneously in both the horizontal and vertical components of a ground-motion record and that the NSA levels are similar between these components. We also observe that most vertical peak ground acceleration (PGA) and vertical peak oscillator spectral acceleration (SA) responses for different periods occur during the shear wave (S-wave) window after S-wave arrival. The differences in the source, path, and site effects on PGA and SA responses occurring during the pressure wave (P-wave) and S-wave windows are evaluated individually through a regression analysis. We determine that NSA is observed only when PGA and SA responses occur during the S-wave window. This evidence demonstrates that the observed NSA of vertical ground motions in Taiwan may result from the hysteresis of the soil layer subjected to S-waves. This study provides physical evidence for the observed NSA of vertical ground motions in Taiwan. Besides, NCREE19 horizontal and vertical GMPEs have been used to develop updated vertical design spectrum of seismic design code in Taiwan. We have shown that the site amplification factors of vertical design spectrum can be defined conservatively as the site amplification factors of horizontal design spectrum due to the observed nonlinear site amplification of vertical ground motion in Taiwan.

Challenges and Opportunities in High-frequency Ground Motion Modeling Incorporating Site Effects

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In recent decades, the increase in earthquake ground motion (GM) observations has enabled the quantification of systematic variations of GMs with different earthquake source mechanisms, source-to-site paths, and local site conditions. The latest advances in nonergodic GMMs offer an opportunity to explore regionalization techniques including path and site-specific contributions to GMs and the spatial variability of different GM intensity measures. Characterizing high-frequency GM is also critical to advance our understanding of source processes and attenuation. Measuring, analyzing, and modeling high-frequency GMs are necessary steps to advance the simulation of GMs at broader ranges of frequencies and improving GMMs. High-frequency seismic waves tend to be affected by near-surface deposits and lateral heterogeneities in the lithosphere, hence their appropriate modeling and interpretation are essential to understand site effects more holistically. The high-frequency spectral decay parameter kappa and its site-specific component have shown their ability to describe near-surface attenuation, which can inform FAS-based GMMs explicitly as a site proxy. However, the correlations among the seismic quality factor Q, kappa, and soils' energy dissipation properties such as material damping ratio are not well understood and can contribute to a physics-based characterization of path and site attenuation. The absence of physics-based understanding of kappa also prevents its application in the development of next generation FAS-based site-specific GMM. Thus, this work will present the multi-physics and multi-scale nature of the attenuation of seismic waves as well as the limitations of existing parameterizations of this phenomenon as typically used in existing GMMs. A new framework for decomposing path and site contributions to attenuation will be proposed, and example applications will be presented using the new DesignSafe GM database for California and neighboring states.

Regional Differences in Quantification of Path Effects

Oral Session • Thursday, 12 October • 3 PM Pacific

Quantifying and Partitioning Ground-Motion Variability in the Era of Big Data and Massive Physics-Based Simulations

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What strategies and methods can be developed to quantify and constrain the natural variability of possible vibrations for a given site and a given earthquake scenario? Ground-motion variability has several origins: the properties of seismic rupture vary from one earthquake to another and waves propagate in heterogeneous and even time-varying media. How can we best combine simulations and observations to calibrate both the best estimate and the variability of future ground-motions? Modern accelerometric databases and generalised inversion methods make it possible to partition the variability of observed ground-motions and separate the effects of source, propagation and site. Under certain conditions and bearing in mind that these inversions may be non-unique, this separation can be used to calibrate the variability of seismic movements due to these three effects. Using European accelerometric databases, the effect of regionalisation on the different components of seismic variability (comparison between variabilities observed on a fault system, regional or continental scale) will be quantified and presented. Physics-based simulations make an important and undeniable contribution to the collection of ground motions representing near-field seismic conditions of large magnitude earthquakes. From these simulations we can attempt to better constrain variability that is potentially under-represented in the limited set of observed records in these conditions. Nevertheless "classic" simulations still have difficulty reproducing the variability of propagation effects on a regional scale, as we will illustrate in an exercise conducted in the Rhine Valley. The possible use of AI methods and hybrid databases (observations and simulations chosen for their complementarity) to train simulation models capable of producing non-stationary ground-motion time histories and reproducing their variability will finally be discussed.

Updating a 3D Vs Model for Southwest British Columbia: From Regional Geodata to Ambient Noise Tomography

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We present our multi-year efforts and multi-data types at multi-depth scales to update the 3D velocity model of southwestern British Columbia (BC), including the Late-Cretaceous Georgia sedimentary basin and targeting the high seismic risk Metropolitan Vancouver (MV) area. Over five years, the MV seismic microzonation mapping project (MVSMMP) developed a comprehensive regional database of seismic site characteristics, including compilation of datasets from ~25 sources in combination with multi-method non-invasive seismic testing: over 2,000 microtremor horizontal-to-vertical spectral ratio (MHVSR) measurements provide peak frequency(ies) at an average 800-m spacing across the area, and over 120 combined active- and passive-seismic surface wave dispersion surveys provide well resolved shear-wave velocity (Vs) depth profiles (< 200 m) from joint inversion with MHVSR peak frequency(ies). These MVSMMP datasets are utilized to develop high-resolution map surfaces of major seismic layers (post-glacial and glacial sediments) via empirical Bayesian kriging to generate a 3D "geotechnical layer" Vs model of MV (discontinuous grid mesh to 1 km depth). In parallel, the MVSMMP performed ambient noise tomography (ANT) studies to refine Georgia basin structure in the larger-scale southwest BC model (250-m lateral resolution; 60 km depth), using earthquake and passive-seismic data from existing seismic networks in BC and Washington state (version 1) and supplemented from 60-day installation of 19 seismometers in MV (version 2). In addition, large diameter (1-4 km) passive-seismic surveys were performed in 6 locations and inversion of their combined low frequency dispersion data with previous year's higher frequency dispersion data provide well resolved deep Vs depth profiles (< 4 km) to aid in merging the 3D geotechnical-layer and 3D ANT Vs models. The presented 3D Vs modelling improvements in southwest BC will improve generation of synthetic earthquake ground motions and can be incorporated into future 3D community velocity models of the Pacific Northwest (Cascadia subduction zone).

Numerical Insights of the Model Perturbation and Q on Regional Ground Motions

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We are examining attenuation characteristics for high-frequency regional Pg and Lg waves using numerical seismograms for generic 1D/2D/3D velocity models that extend into the mantle by several tens of kilometers. In this study, we use 1D FK/reflectivity, and SW4 codes to compare synthetic explosion seismograms at receivers every 50 km interval over a range of 100 to 1400 km. 1D FK/Reflectivity seismograms showed a frequency upper limit of 6 Hz to be consistent with regional synthetics computed using SW4 in the phase complexity with some level of discrepancy, especially for the greens functions, We introduced a velocity perturbation using laminar model in the shallow crust, mid-crust and crust-mantle boundaries separately, including the Q effect to excite extended high-frequency coda waves, thus enabling to understand the various velocity perturbation effects on Pg and the Lg waves. The upper frequency limit of 6Hz is based on the model discretization that was controlled by the available computational resource. Scattering was introduced by perturbing the geophysical parameters in various parts of the 3D model using criteria described in Frankel and Clayton (1986). The von Karman function was used to specify the extent of the scatterers (Goff and Jordan, 1988). This provided an insight on how the regional Pg and Lg waves are influenced by the velocity perturbation in random locations. Using these simulated Pg and Lg waves in different frequency bands, we are testing AI/ML techniques for evaluating the event identification.

Simplified 3D Basin Velocity Model of the Nakdonggang Delta Region, South Korea, Developed by HVSR and MAM

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In this study, we employed the microtremor horizontal-to-vertical spectral ratio (HVSR) method and the microtremor array method (MAM) to rapidly develop a 3D shear wave velocity (Vs) model of the Nakdonggang delta region in South Korea, for applications in local and regional scale ground motion simulations and site response analyses. This region is known for its loose Holocene sedimentary soils, which can reach depths of up to 100 meters, filling a half-graben structure formed by the movement of the Yangsan Fault.

We generated a natural period (T0) map of the study area by applying the Kriging method to T0 values obtained from over 250 sites using the HVSR method. Additionally, we conducted MAM tests at eight sites, where we installed eight seismometers in circular arrays with diameters ranging from 15 m to 400 m. Vs profiles were derived through the joint inversion of HVSR and Rayleigh wave dispersion curves using the Neighborhood algorithm (Wathelet, 2008).

The obtained HVSRs indicate that this region is susceptible to ground motion amplification for periods T > 1 s. Inversion results reveal that the Vs values of sediments in the Nakdonggang delta region can be represented by a power-law function dependent on depth. Furthermore, we examined the performance of the simplified velocity model at selected locations by comparing the results of 1D site response analysis with those based on inverted 1D velocity profiles.

To construct a simplified 3D basin model, we combined the results of HVSR and surface wave tests, with the shear wave velocity of sedimentary soils described by a power-law equation. We further constrained the model based on the bedrock depths obtained from the geotechnical boring logs. The findings indicate that the bedrock in the study area can reach depths of up to 80 m at certain locations, exceeding 50 m in many places. According to the Korean seismic design standard (KDS 17 10 00), these sites are classified as S6 sites, requiring site-specific response analysis to determine the design ground motion.

Performance Evaluation of the USGS Velocity Model for the San Francisco Bay Area

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The exponential growth of the processing power in the last decades pushed the development physics-based seismological simulations, allowing to solve the wave equation at higher frequencies and softer materials. The primary sources of epistemic uncertainty in the physics-based seismological simulations are the source characterization, the deformation and attenuation properties of the velocity model at elastic deformation regimes, and alternative ways of solving non-linear deformation regimes, especially important at materials close to the surface. This work is part of the EQSIM project, which assesses the San Francisco Bay Area (SFBA) seismic hazard using 3D physics-based seismological simulations. We quantify the epistemic uncertainty induced by propagating waves through the community velocity model for the SFBA developed by the USGS. As a methodology, we simulated seven small-magnitude earthquakes that occurred in the SFBA in the last 12 years. Because of the low level of the ground-motion amplitude, the soil response during these small earthquakes is believed to be linear at all recording sites, leading to assume that the epistemic uncertainty induced by a linear constitutive model is zero. Furthermore, given the small rupture area of these events, their source can be modeled by a double-couple point source mechanism. Therefore, the simulated variability and bias between observed and synthetic waveforms can be mainly attributed to the misrepresentation of the local geology, and a lesser extent, to the source parameterization, including location, depth, and focal mechanism. The simulations solved the wave equation up to 4.5 Hz with a minimum shear wave velocity of 250 m/s, allowing the inclusion of geotechnical layers in the simulations. The inclusion of geotechnical layers on the velocity model has a strong impact on the waveforms, especially at high frequencies. The analysis shows areas where the velocity model systematically induces over-prediction or under-prediction. Recognizing these areas provides space to identify where and how the velocity model can be improved.

Challenges for Model Extrapolations Outside of the Data Range

Oral Session • Friday, 13 October • 8:30 AM Pacific

Application of Seismological Models and Weak-Motion Data in Engineering Applications

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Engineering design and evaluations commonly require application of ground motion models beyond the range of available data or in regions with limited data. This extended application requires extrapolation of models and data that is best informed through physics-based models. A powerful technique involves using point-source seismological models to characterize the source, path, and site effects based on small-magnitude datasets. While seismological models, such as the single-corner point source model, are relatively simple they can represent the ground motion over a wide range of conditions. The insights gained through these studies are then used to adjust ground-motion models to fit the observed behavior. This process relies on the robust scaling of the seismological models, defined in the frequency domain, as well as the compatibility of the ground motion model with the seismological model, defined in the oscillator period domain.

Three examples of insights gained through point-source models are provided. In the first, inversions are used to estimate the stress parameter for events with ranging magnitudes. These events are then used to estimate magnitude-scaling of the stress parameter and its uncertainty, as well as attenuation parameters. In the second example, a cell-based attenuation model is used to examine the boundary between the Western and Central United States based on regional differences in Q_0. In the final example, data from aftershocks are used to evaluate a site-specific site adjustment factor, which then can be applied to larger magnitude events.

Ground Motion Model Extrapolated to Large Magnitudes by Combining Local and International Records

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Region specific empirical ground motion models (GMMs) are often developed using seismic records within the target region. However, in a mid-seismicity region, large magnitude records are rare. This limitation makes difficult to develop a GMM predicting intensity measures (IMs) of large magnitude events. In South Korea, the largest recorded event is the 2016 M_W 5.4 Gyeongju earthquake, but the national seismic design criteria require engineers to use ground motions with $M_W > 6$ for seismic design analysis. This needs a GMM predicting IMs for $M_W > 6$. This study presents a development procedure for an empirical GMM using hybrid records: local records with $M_W < 5.5$ and international records with $M_W > 5.5$. The local records are used to constrain a source effect for low M_W, and the source effect for high M_W is constrained using international records. Then, local records are solely used to develop a path effect to reflect the local geologic feature. The target site condition is a bedrock layer in depth, so site effect is not considered at this stage. The developed GMM predicts the recorded IMs well, and resultant IMs for $M_W > 5.5$ are reasonable compared to other GMMs with an applicable range greater than 5.5.

Regional Ground Motion Models for Western Canada: British Columbia

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We develop ground motion models (GMMs) to characterize the Fourier amplitude spectra (FAS) for earthquakes in British Columbia (B.C.), Canada. GMMs developed for FAS are useful to understand the underlying seismological parameters and can be converted to response spectral acceleration GMMs for future applications. The GMMs are calibrated using a compiled FAS database, referenced to a B.C. generic hard rock site condition (time-averaged shear-wave velocity in the top 30 m ~2285 m/s). The GMMs are developed separately for crustal, in-slab, transition, offshore, and Haida Gwaii events. Due to a lack of observational data, we could not develop a model for Cascadia interface earthquakes. The developed GMMs are calibrated using data from ~M2.5–5.5 earthquakes recorded at rupture distances of ~50 to 500 km. Outside this range, the models are constrained by a seismological model and limited observational data. The amplitude decay rate for crustal earthquakes in B.C. is very similar to that given by the empirical model of Bayless and Abrahamson (2018; BA18), developed from California earthquake data recorded on soil sites. However, we observe magnitude and frequency dependent differences between the models for ground motion amplitude levels. We attribute these to: (i) the different reference site conditions of the models, with the B.C. GMMs being referenced to hard rock; and (ii) steeper magnitude scaling at small-to-moderate magnitudes for crustal events in B.C. in comparison to the BA18 model.

Ground-Motion Models in Earthquake Early Warning: Performance Assessment Considerations

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We examine ground-motion-based earthquake early warning (EEW) performance evaluations for the FinDer algorithm as implemented in the ShakeAlert system for the West Coast of the United States, considering the effects of different input source estimates, ground-motion models (GMMs), and ground-truth types (station observations and ShakeMaps). Empirical GMMs are present in multiple parts of the ShakeAlert process. For FinDer, GMMs are used to create the peak ground acceleration (PGA) templates that determine source parameter estimates. These source parameters are then converted to alert regions using GMMs. Finally, GMMs may be involved in EEW performance evaluations if alert regions are compared against ShakeMaps, which use a weighted average of observations and a background GMM. Understanding how these different elements affect both the alert behavior as well as the alert performance assessment is key for optimizing ShakeAlert.

We find the station-based and ShakeMap-based ground-motion performance comparisons show slight differences in their results, however, these differences correlate with expected differences between the station observations and ShakeMap values due to ShakeMap's averaging procedures that lead to smoothed amplitudes. This indicates that ShakeMaps could be considered acceptable ground truths for EEW alert evaluations. We find that while FinDer's magnitude estimates may differ in some earthquakes from catalog values (e.g., high stress drop events), the ground-motion distributions computed using FinDer's source estimates correspond well with observations (particularly PGA) when the GMMs used for the FinDer templates are consistent with the GMMs used to create the alert regions. The current ShakeAlert GMMs appear to underpredict ground motions for smaller events (M<~5.5) and overpredict ground motions for larger events. This suggests that updating the GMMs used for the alert regions will improve the ground-motion prediction accuracy of ShakeAlert.

The MyShake GM Database: Initial Observations and Utility to Ground Motion Modeling

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MyShake is a free citizen seismology smartphone app with over 2 million global downloads. In the US states of California, Oregon, and Washington, MyShake has been delivering ShakeAlert earthquake early warning messages to the public since October 2019. The app offers earthquake notifications, an interface for users to submit rapid shaking experience reports, and most importantly, offers users the capability to allow use of their smartphone's accelerometer to record earthquake shaking for research purposes. Waveform collection in MyShake is triggered by either an STA/LTA algorithm and verified by a machine-learning-based classifier, or via the receipt of an early warning message. Here, we report on the MyShake GM Database, a database of earthquake peak acceleration observations compiled from seismologist-verified waveforms collected by MyShake-powered devices from 2019 to 2023. We show how these observations more closely match peak floor accelerations expected in low-rise buildings, rather than free-field peak ground acceleration, via comparisons to median GMM-predicted response spectra and a structural response predictive model. We also discuss potential opportunities and challenges for utilizing these data for rapid response ground motion modeling (e.g., ShakeMap), as well as complementing ground motion databases (e.g., NGA-W2) in data-poor ranges such as the extreme near-source (0-20 km) and small to moderate magnitude (M3-5) range.

Using Offshore Geophones for PGA and PGV Analysis of the 21 March 2022 (Mw=5.1) Earthquake on the Norwegian Continental Shelf

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The Norwegian Continental Shelf (NCS) is an area with one of the highest rates of seismicity in Northern Europe, with earthquakes of low to moderate magnitudes. Oil and gas infrastructure and plans for large-scale industrial CO2 storage heighten the need for better seismic hazard assessment for site characterization and seismic risk management in the NCS. Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) of the earthquakes recorded by offshore geophones offer important data for constraining the Ground Motion Prediction Equation for the North Sea.

Some major oil and gas fields in the NCS have deployed Permanent Reservoir Monitoring (PRM) systems to monitor the dynamics of the reservoirs. The PRM systems also serve for passive seismic monitoring. On 21 March 2022, a Mw 5.1 earthquake occurred ca 12 km to the North of the Snorre field, with its PRM system of 10700 geophones (GS- ONE 15 Hz OMNI). This event was also recorded on the Grane PRM system about 280 km towards the south, where 3400 geophones (with the same type of instrument as the Snorre field) are deployed.

For this study, we removed the system response from the recordings to extract PGA and PGV data. The highest PGA recorded along the 25 km length on the Snorre field is about 0.24 g, while the average value is approximately 0.1 g. The PGV varies from about 20 mm/s to less than 5 mm/s across the Snorre field. The seismic waves are attenuated significantly on their travel path to Grane, where the PGA shows a maximum value of about 0.002g, which is distributed uniformly along the 14km length of the field. Maximum PGV on Grane does not exceed 0.3 mm/s. The obtained PGA data, for different distances from the source have been evaluated against the existing Ground Motion Prediction Equations (GMPEs) with similar tectonic settings, to find the best GMPE match for this region of the NCS. These insights should lead to significantly improved seismic hazard assessment for the NCS.

Overall Prediction Accuracy and Simulation Validation for Real-World Applications

Oral Session • Friday, 13 October • 11 AM Pacific

Integrated Geoscience - Engineering Earthquake Simulations at the Exascale with Focused Application on Infrastructure Risk Assessment

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For potential future earthquakes, estimation of site-specific ground motions and the detailed manner in which the incident seismic waves interact with engineered systems continues to be a challenging problem at the nexus of geosciences and engineering. Traditionally, the fault-to-structure phenomenon associated with this problem has been subdivided and attacked piecemeal with idealized process models (e.g. one-dimensional geotechnical site response simulation). With the advancements in high-performance Exaflop computing platforms, new computational ecosystems, and advanced software workflows, high-fidelity simulations of earthquake processes at regional scale are undergoing transformational change. Regional-scale simulations with hundreds of billions of grid points and multi-dimensional coupling of the domains of geoscience and engineering are computationally achievable. With the advent of these extreme-scale simulations, the necessity of software verification and code physics validation has become central to the acceptance and reliable application of these emerging tools. Two high-value applications of such models include the ability to gain new simulation-informed insight into coupled earthquake processes, and the quantification of earthquake risk to engineered systems in terms of the median and distribution of earthquake induced demand on infrastructure systems. These two applications can have overlapping but also distinct requirements for ensuring the realism and usefulness of simulation results.

In this presentation, the EarthQuake SIMulation (EQSIM) HPC simulation framework developed under the U.S. Department of Energy Exascale Computing Project is described, and example applications to earthquake process understanding and risk quantification are presented. For each application, supporting efforts for understanding prediction accuracy and simulation validation are described along with future needs to continue confidence building in regional-scale simulations.

The Next Generation of 3D Ground Motion Simulations of Cascadia Subduction Zone Megathrust Earthquakes

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The Cascadia Subduction Zone (CSZ) has the potential to rupture in large (~M8-9) megathrust earthquakes, with the last great event occurring in 1700. Without direct observations of ground shaking from these earthquakes, simulations of potential earthquake scenarios are required for hazard assessment in the Pacific Northwest. Here, we present preliminary results from the next generation of 3D broadband (0–10 Hz) ground motion simulations for the CSZ. We calculate broadband synthetic seismograms using a hybrid approach, combining waveforms generated using a 3D spectral element method (<1 Hz) implemented in SPECFEM3D with stochastic waveforms (1–10 Hz). To generate 72 different source scenarios, we use a logic tree approach, varying the magnitude, up-dip and down-dip rupture limits, and the slip distribution. Updates from previous work include using a range of magnitudes (M8.7-9.3), different up-dip geometries informed by 3D offshore seismic surveys, and both random and geodetic locking-based slip distributions. These sources are characterized as compound rupture models that combine long period background slip with five M~8 high stress drop, high frequency radiating subevents, an approach informed by observations from other large magnitude subduction zone earthquakes (e.g., M9.1 2011 Tohoku-Oki, Japan, M8.8 2010 Maule, Chile). These results are benchmarked against previous Cascadia earthquake simulations and empirically-derived ground motion models. Using these 72 simulations, we will investigate basin effects, derive ensemble ShakeMaps for hazard assessment, and couple the results with tsunami simulations to get a time-dependent understanding of ground motions and tsunami inundation in coastal communities. Ultimately, these ground motions will also be used to quantify impacts to infrastructure and cascading hazards (e.g., landslides, liquefaction, land-level change) with a focus on increasing seismic resilience and adaptive capacity in the Pacific Northwest.

Variability of Simulated Earthquake Ground Motions in Thessaloniki (Greece) from a Suite of Fault Rupture Realizations

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An accurate characterization of earthquake ground motion and its variability is crucial in assessing seismic hazard and risk for spatially distributed portfolios in large urban areas. In this work, 3D physics-based numerical simulations (PBS) by means of the high-performance spectral element code SPEED (http://speed.mox.polimi.it/) are adopted to generate a suite of fault rupture realizations of severe shocks in the Thessaloniki urban area (Northern Greece). Broadband ground shaking scenarios are produced using a regional-scale 3D numerical model accounting for an extended kinematic source model and a 3D velocity model, coupled with an Artificial Neural Network technique for the high-frequency part. As a first step, the numerical model is validated on the recordings of a small-magnitude earthquake (Mw4.4 2005 Sept.12). Then, the numerical predictions obtained from historical Mw6.5 June 20, 1978 earthquake are compared with empirical Ground Motion Models (GMMs) to check the overall consistency of the results. The variability of different ground motion intensity measures and of the corresponding spatial correlation for a suite of 60 fault rupture scenarios with magnitude Mw=6.5-7.0 breaking the Gerakarou-Langadhas and Anthemountas fault systems is analyzed to shed light on its implications for seismic risk assessment.

Keyword: Earthquake ground motion, 3D physics-based numerical simulations, fault rupture realizations, spatial correlation, seismic risk assessment

Validation of Hybrid Ground Motion Simulation for Engineering Application in South Korea

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Being in a stable continental region (SCR) with a limited history of instrumentation, South Korea lacks sufficient instrumental data for data-driven ground motion models. To address this limitation, we examined the applicability of the hybrid ground motion simulation method proposed by Graves and Pitarka (2010, 2015) for simulating ground motions in South Korea.

The hybrid method relies on region-specific parameters to accurately represent the seismic source and the wave propagation. As a practical approach, we employed relevant models and parameters available in the literature. We incorporated velocity models developed by Kim et al. (2017) and Kim et al. (2011) to account for the crustal structure of South Korea. We adopted Graves and Pitarka's rupture generator algorithm along with an SCR-specific magnitude-area scaling relationship by Leonard (2014). Additionally, we assumed the stress parameter and the attenuation constants based on studies of regional seismicity.

Our study integrates the most recent data and models currently available for South Korea. Nonetheless, we anticipated certain limitations due to the following reasons: 1) the magnitude-area relationship is based on limited global data, 2) the resolution of the velocity models is limited in the near-surface region, 3) the parameters related to source and path effects from the literature varied, and 4) the empirical site effect model needs validation.

We simulated the 2016 M5.5 Gyeongju earthquake, the 2017 M5.4 Pohang earthquake, and some recent more minor earthquakes. Subsequently, we compared the results with recorded accelerations. Overall, our study suggests the potential of employing the hybrid simulation method in South Korea. However, the current findings also highlight certain shortcomings, such as the underestimation of long-period ground motions during the 2017 Pohang earthquake. We attribute the identified shortcomings to the limitations of the adopted models, and we are currently engaged in refining region-specific models and parameters for the practical implementation of the simulation method.

Validation of Sedimentary Basin Models Through Comparison of Real and Simulated Resonance Frequencies: Application to the Fucino Intramountain Basin (Apennines, Italy)

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Urban areas are often built on sedimentary basins that can greatly amplify seismic motion. Accurate ground motion modeling in sedimentary basins is therefore essential and needs realistic 3D basin models. Evaluating model accuracy involves comparing simulated and real seismograms, although distinguishing source, path, and site uncertainties is challenging. The site term in physics-based simulations depends on detailed shallow geological/geophysical information and mesh resolution.

A good proxy of the seismic response of small- to moderate-scale sedimentary basins is their resonance frequencies, often investigated by experimental measurement of the Horizontal to Vertical spectral ratio (H/V) or Standard Spectral Ratios (SSR) computed on ambient seismic vibrations or earthquake records. The values of the resonance frequencies depend on the geometry and mechanical properties of the sediment fill, and realistic 3D models should ideally reproduce them. Comparing resonance frequencies calculated from real and simulated waveforms can therefore help identifying inconsistencies in 3D models, aiding in their improvement. In the absence of earthquake data from permanent or temporary seismic stations, short-duration seismic noise acquisitions can be used for this comparison.

We conduct 3D seismic wave propagation simulations in the Fucino intermountain basin (Central Apennines, Italy) for which several stratigraphic models, exploration and geophysical data are available in the literature. We integrate the basin's stratigraphic models with regional crustal models to create suitable 3D velocity models for testing. We evaluate the models' performances by comparing simulated and experimental seismograms and H/V curves for various basin models and earthquakes. We observe in general a good match between H/V curves computed on synthetic and real waveforms. H/V curves are similar for different earthquakes and can help evaluate the site effect component of the ground-motion modeling.

What's Shaking in the Adriatic Sea? - Implications of Ground Motion Simulation of the 2021 Central Adriatic Earthquake

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For a long time the Adriatic Sea was seen as an almost aseismic intracontinental region with sporadic occurrence of small earthquakes. However, in the last few decades, with growth in the number of seismic stations, significant seismic activity has been observed in the central Adriatic Sea with strongest earthquakes having magnitudes larger than Mw = 5.0. The most recent earthquake series from 2021 and its effects on nearby populated Central Adriatic islands again stressed the importance of investigating the source of this seismic activity. Furthermore, more detailed studies are crucial in order to identify active faults and their seismic potential, which has possibly been highly underestimated.

In this work we make use of physics-based waveform modeling as an approach to obtain information about earthquake hazards in the Central Adriatic Sea. More precisely, we focus on the ML = 5.5 March 27, 2021 event which occurred in the Central Adriatic Sea between Italy and Croatia. First, due to the scarceness and uncertainties of the available data, we build several 3D crustal models which reflect and capture the geological features and physical properties of the studied area. We test the performance of these 3D models in simulation of the low-frequency (LF) content of the waveforms using the same single point source solution. We also include topography, bathymetry and attenuation effects as an input for the simulations. We then compare the simulated waveforms against the recorded data and validate the reliability of the LF simulations by assessing the goodness of fit scores for several different ground-motion metrics. Based on this we choose the most representative model for the studied region and focus on simulating the waveforms using different source descriptions to investigate how source parametrization influences waveform shape and the fit between the recorded and simulated data. This enables us to gain a more nuanced understanding of the physical properties associated with the mechanisms responsible for the seismicity in this region.

Implications of the Use of Physics-Based Simulations in the (Re)insurance Sector

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The (re)insurance industry dealing with natural disasters aims to provide effective and risk-adequate protection against this type of risk. In the specific case of earthquake protection, in order to accomplish this difficult task, it is of paramount importance producing a reliable prediction of the consequences of strong earthquakes on urban areas and civil infrastructures. The spatially extended and interconnected nature of an urban environment makes a proper description of the spatial correlation of the ground motion crucial for any reliable damage and loss estimation, especially in the so-called "near-source" region where typically ground motion models (GMMs) are poorly constrained.

In the last decades significant progress have been made worldwide in predicting the strong motion shaking using 3D physics-based numerical simulations (PBSs). Earthquake ground motion simulations based on this methodology have gained increasing consensus through different verification and validation exercises, and they are becoming a valuable complementary tool for GMMs to provide realistic ground motion estimations.

The present work focuses on the recipe, referred to as "footprint-based", that was developed to take advantage of physics-based approaches, on the one hand, within a classical Probabilistic Seismic Hazard Assessment (PSHA) framework and, on the other, in order to accomplish reliable Probabilistic Risk Assessment (PRA), especially suited for large urban areas.

The *footprint*-based PSHA adopts directly the PBSs, without postulating any specific probability distribution by simply taking all the realizations of the scenario earthquake within a logic-tree framework, as multiple branches, each equally weighted.

The scope of this work is to compare the results obtained against the more classical approach based on GMMs. To this end the city of Istanbul has been selected as pilot case study due to (i) the proximity to a well-known mapped fault capable to trigger a severe earthquake and (ii) a good description of the geotechnical characterization of the soil.

Moving Numerical Simulations of Ground Motions from Research to Practice

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Numerical simulation methods have been used to generate suites of ground motions for the last two decades, but their application to seismic hazard practice has been limited. To date, the main use of numerical simulations has been to constrain the relative scaling of the ground motion outside the empirical data range (e.g., for large magnitudes at short distances or for geometries not well sampled in the empirical data sets). For example, the NGA-W2 GMM used numerical simulations to constrain magnitude, dip, and depth dependence of the hanging-wall scaling. 3-D simulations have also been used to set scale factors for long-period basin effects in the Los Angeles and Seattle regions that are applied to the GMMs.

To move 3-D simulations from research to practice and use the amplitudes and variability of the simulated ground motions rather than just scale factors applied to empirical GMMs, four tasks need to be addressed. (1) Quantitative demonstration that the simulations are an improvement (or no worse) compared to empirical GMMs though validation of the simulations with recorded ground motions for the bias in the median. (2) Classification of what is aleatory variability and what is epistemic uncertainty for simulations. (3) Quantitative estimation of the epistemic uncertainty in the site and path terms from 3-D simulations that reflects the uncertainty in the 3-D velocity structure. This includes a method to treat sites and sources outside the region covered by the simulations, but still account for large uncertainty in the 3-D effects due to lack of data. (4) Estimation and calibration of the aleatory variability from the simulations. For the quantification of the aleatory variability, for simulated ground motions, the aleatory term can be separated into a term due to simplifications in the simulation methodology (model aleatory from comparisons of simulations and data) and a term due to the variability of the input parameters used in the simulations (parametric aleatory from forward simulations) but which are not part of the source characterization.

Poster Presentation Abstracts

Presenting author is in bold.

Complex Kinematic Source Modeling [Poster]

Poster Session • Tuesday, 10 October and Wednesday, 11 October

Source Parameterization on Complex Faults Represented by Unstructured Meshes

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To describe the source, planar surfaces or a limited set of planar subfaults are generally used with a regular discretization. The distribution of the slip for instance on these surfaces is usually achieved with Fourier's transform based techniques or with the assumption of a composite source model. For the rupture history, usually the velocity of the rupture front is assumed constant on the different planar subfaults.

Today however, improvements in observations allow scientists to look at fault surfaces in more detail with respect to their size. Many recent earthquakes, independently of their magnitude or their faulting style, exhibit complex faulting geometries. In such cases, the use of planar faults becomes a limiting factor. This has led to the current trend of using multiple planar segments with variable dip and strike to model this complexity.

This approach may be sufficient in true segmented events but if the geometrical complexity of the fault increases and/or its shape varies continuously (e.g. listric faults, subduction zone environments) the number of segments increases, potentially to the level of linear strips of cells. In such cases, all the parameters of the single sources have to be defined nearly by hand for each cell. Thus applying a particular parameter distribution on a complex fault, formed by thousands of independent segments becomes challenging. The computation of the rupture time with heterogeneous rupture velocity on complex fault shapes is even more difficult.

In the end, the problem linked to the estimation of all these parameters on a complex fault have in common the resolution of the Eikonal's equation on a 2D manifold . Even the estimation of a distance between two points on a complex fault may be seen as the path with the shortest travel time between two points in an homogeneous unitary velocity field on the fault.

Through examples, we present a strategy to produce self affine slip distributions with variable rupture velocity on unstructured faults. We also explain what are the actual limits of the technique and demonstrate its advantages.

Simulated and Observed Ground Motions from Earthquakes on the Central Calaveras Fault, Northern California

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We use 3D finite-difference simulations and recorded ground motions to study the rupture process and resulting ground motions from M_w4.0–6.4 earthquakes on the central Calaveras Fault in Northern California. Three of these are $M_w > 5.0$ events whose kinematic ruptures have been studied in detail: the 1984 M_w6.4 Morgan Hill, 2007 M_w5.4 Alum Rock, and 2022 M_w5.1 Alum Rock earthquakes. All three of these showed almost completely unilateral rupture to the southeast (Beroza and Spudich, 1989; Oppenheimer et al., 2010; Hirakawa et al., 2023). While the 1984 Morgan Hill earthquake was notably energetic and caused some structural damage, the other two were relatively weak and caused no damage; we consider these events to have had a low stress drop.

We study these earthquakes by combined analysis of residuals from empirical ground motion models (GMM's) and computer simulations using SW4, a 4th-order finite-difference seismic wave propagation code. For the 1984 Morgan Hill earthquake, we start with the slip inversion of Beroza and Spudich (1989) and implement it in the simulations as a kinematic rupture source. For the other two M_w>5.0 earthquakes we develop simple kinematic rupture models by assuming an elliptical slip patch and determining rupture characteristics by fitting an analytical directivity function to the GMM residuals (Boatwright and Boore, 1982; Hirakawa et al., 2023). We also model 4 M_w4.0–4.5 earthquakes as point sources to help constrain the relative contribution from source, site, and path effects on seismic motions. We find that in all cases, simulated motions are amplified in the Santa Clara Valley basins (the Cupertino, Evergreen, and Hollister basins), but to different degrees depending on rupture area and directivity. The results of this study provide useful information for further understanding the seismic hazard in this region, particularly the highly populated Santa Clara Valley.

Slip Distribution in Shallow Areas Above Seismogenic Zone for the Inland Crustal Earthquakes

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Recently strong ground motion data in near-fault area have been accumulated (e.g., 2016 Kumamoto, Japan, earthquake; 2022 Taitung, Taiwan, earthquake; 2023 Kahramanmaras, Turkey, earthquake). These records at extremely-near-fault stations have long-period motion pulses over around 3 s and permanent displacements larger than around 2 m. For the recipe of strong ground motion prediction by Irikura and Miyake (2011), the characteristic source model consists of the asperity area and within the rupture area, which assumes a rectangular shape inside the seismogenic zone. However, this conventional recipe does not always succeed in reproduction of long-period ground motions with permanent displacements, especially fling-step just above surface fault. To reproduce these observed long-period ground motions with permanent displacements at near-fault stations, large slips with long durations in shallow area (LMGA; Long-period Motion Generation Area) between the surface and top of the seismogenic zone are needed for simulations of ground motions. Miyakoshi et al. (2022) proposed a rectangular LMGA in shallow area, whose LMGA length is about 50-60% of the rupture length and the homogeneous slip distribution with about twice the average slip in rupture area. Although a rectangular LMGA with homogeneous slip is proposed, many studies have reported the asymmetric sin-type slip distribution (e.g., Manighetti et al., 2005; Wesnousky, 2008). In this study, by comparing the simulated fault displacements with those observed, we discuss the asymmetric sin-type slip distribution in LMGA.

The Interpretation of Double-corner-frequency Source Spectral Model Considering the Heterogeneous Slip Distribution for Crustal Earthquakes in Japan

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Source spectra for large (Mw: 5.5-7.1) crustal earthquakes occurring in Japan in 1995-2018 have been accumulated by applying the S-wave coda spectral ratio method to observed strong motion data (Somei et al., 2014). The corner frequencies from these observed source spectra were determined assuming the omega-squared source spectral model. Then, they found that the crack sizes calculated from the single corner frequencies coincide with the total rupture area from the heterogeneous slip distribution by the waveform inversion analysis. On the other hand, the Irikura recipe realizes to reproduce the broadband ground motions based on a concept of the characterized source model consisting of the total rupture area and asperity area, which are extracted from the heterogeneous slip model. The spectrum of this synthesized ground motion is expected to have double corner frequencies, corresponding to those two characterized sizes of total rupture area and asperity area. When we consider the double-corner-frequency source spectral model, the first corner frequency corresponding to the total rupture area is clearly seen from the observed source spectrum. Whereas the second corner frequency corresponding to the asperity area is not always as clear as the first corner frequency. In this study, we discussed the physical implications of the corner frequencies of the observed source spectrum considering the double-corner-frequency source spectral model.

Rupture Process of the 2021 and 2022 Fukushima-Oki, Japan, Intra-Slab Earthquakes (Mw7.1, Mw7.4) Inferred from Broadband Strong Motion Records

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The 2021 Mw7.1 and 2022 Mw7.4 Fukushima-oki, northeastern Japan, intra-slab earthquakes occurred on 13 February 2021 and on 16 March 2022, respectively. Several stations recorded strong shaking with PGA larger than 1g during these earthquakes. Large PGVs were also observed in the South-West region from the epicenter of the 2021 earthquake and North-West region from the epicenter of the 2022 earthquake. In order to understand the ground motion generation processes of two earthquakes, realiable source models need to be estimated for broad band period range. We firstly tuned the seismic velocity structure model for each station using aftershock records (Mw 5.0), and secondly obtained final slip distributions based on the finite-fault inversion method (Ji *et al*., 2002) for period range longer than 2 s. We also constructed the SMGA models (Strong Motion Generation Area; Miyake *et al.*,2003) using the empirical Green's function method (Irikura,1986) for period range from 0.1 s to 5 s. Our inverted result of finite-fault inversion showed that the fault rupture of the 2021 earthquake mainly propagated toward to the south-west direction from the hypocenter. On the other hand, the fault rupture of the 2022 earthquake mainly propagated toward to north-east direction. These rupture processes were consistent with different in spatial distribution of observed PGVs. The location of the SMGAs agreed with the large slip area estimated by the finite fault inversion. The estimated stress parameters for SMGAs were between 60-90MPa, which is consistent with observed large PGAs. These high stress parameters also agree with the previous results of the 2003 and 2011 Miyagi-oki intra-slab earthquakes (e.g.,Asano et al.,2004; Harada and Kamae, 2011). We confirmed that the combined area of SMGAs and the flat level of acceleration source spectrum (Dan et al., 2001) of these earthquakes were consistent with the previous empirical scaling relationships for intra-slab earthquakes (Sasatani *et al.*2006).

Dynamic Rupture Propagation Analysis [Poster]

Poster Session • Tuesday, 10 October and Wednesday, 11 October

From Dynamic Source Inversions to Broadband Ground Motion Modeling, With Applications

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Broadband earthquake ground motion modeling based on low-frequency dynamic source inversions is becoming possible with increasing computational power and development of tailor-made efficient numerical codes. We present our recently developed techniques for dynamic rupture inversions and strong-motion modeling utilizing the slip-weakening friction law. Examples of dynamic inversion of local low-frequency strong-motion waveforms for coseismic rupture include the 2016 Mw6.2 Amatrice, Italy, the twin Mw5.8 earthquakes of 2011 and 2016 on the Mochiyama fault, Ibaraki prefecture, Japan, and the 2020 Mw6.8 Elazig, Türkiye, earthquakes. The latter event exhibits an initial Mw 5.8 stage followed by a reversal of rupture direction, and cascading rupture episodes featuring local supershear speeds. We also present a preliminary dynamic inversion based on apparent source time functions of the 2010 Mw6.9 600-km deep earthquake in China (in cooperation with J. Liu, V. Plicka, and J. Zahradník).

Modeling high-frequency radiation in dynamic rupture models to simulate broadband data (0-10Hz) is challenging because smooth planar dynamic rupture models result in ground motions depleted in high-frequency content. To remedy this issue, we propose a method to enrich the dynamic models with small-scale random fractal perturbations in fracture energy and initial stress. We demonstrate the performance of our approach on a generic elliptical Mw6.3 dynamic model and the inverted dynamic models of the 2016 Mw6.2 Amatrice and the twin Mw5.8 Ibaraki earthquakes. The random perturbations preserve large-scale characteristics of the original model and introduce small-scale abrupt changes in rupture velocity, including locally supershear propagation. We show that the models improve the fit to the recordings of the Amatrice earthquake and Central Italy GMM up to 10Hz. The technique can be readily implemented in physics-based earthquake rupture modeling for seismic hazard applications.

A New Method for Dissipating Energy in Dynamic Earthquake Rupture Simulations: Nonlinear Radiation Damping

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We introduce 'nonlinear radiation damping,' a new mechanism that dissipates energy in elastic dynamic rupture simulations and results in more realistic ground motions and slip velocities, while not requiring the large number of assumed variables in viscoplastic methods. Computational simulations of dynamic earthquake rupture help us learn about earthquake source behavior and the resulting ground motions. A challenge with these types of simulations is that they require many assumptions, including the fault geometry, the fault friction constitutive laws, the rock properties, and the initial stress conditions. Although we have some information about these parameters, much of the information is unknown. This requires modelers to make many assumptions, with one of the most common assumptions being that rocks respond elastically to sudden changes in stress and strain. An elastic rock response is helpful in that it allows for a simplification of the initial stress conditions. However, an elastic rock response can also lead to simulated on-fault slip rates and off-fault ground motions that are faster than those inferred from earthquake observations. Our work provides a solution to this problem. We propose a new method, which we call 'non-linear radiation damping'. The implementation is simple, and just requires adding the non-linear radiation damping term to the friction formulation. The result is slower on-fault peak slip rates and ground motions, similar to what might be achieved by incorporating a complex viscoplastic framework, but without the need to assume values for a variety of unknown features such as the initial stress conditions and rock yielding parameters at all locations in an earthquake region.

s="MsoNormal">Barall, M., and R.A. Harris (2023) Nonlinear Radiation Damping: A New Method for Dissipating Energy in Dynamic Earthquake Rupture Simulations, The Seismic Record. 3(2), 69–76, doi: 10.1785/0320230001.

Testing the Impact on Surface Rupture of Dynamic Rupture Parameters: An Example from the Shallow 2019 Mw4.9 Le Teil (France) Event

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We investigated the impact of several dynamic rupture parameters such as friction, stress drop and fault geometry on surface fault rupture amount and patterns. Based on a shallow reverse surface rupturing Mw4.9 earthquake which occurred in southeastern France in November 2019, and models derived from data collected (InSAR, waveforms), we set up a rupture scenario that is consistent with the observations. From this kinematic scenario we fixed the dynamic parameters of the deeper part of the rupture (300-2 km depth), while we test the shallower part parameters (<300m). The surface rupture produced by the different models are then compared to the surface deformation patterns and amplitude.

Simulation results show how the frictional behavior (Dc, Stress drop, weakening or strengthening) directly modulates the amount of surface rupture, but also show the sensitivity of the deep rupture process to shallow properties. From the data comparison, the shallow surface layers are likely slip-strengthening in the Le Teil event. Adding a secondary structure in the northern part improves significantly the surface rupture fit to data, as well as the rupture history. Finally, we discuss some questions brought by the occurrence of such a shallow reverse fault earthquake as seen through its dynamics.

Quantifying the Effects of Absolute Friction and Geometrical Symmetry on Thrust Fault Rupture

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Absolute friction has been theorized to have a measurable influence on thrust fault rupture, though its effects have not been well documented. For a purely symmetric fault, absolute friction does not influence slip because the normal stress does not change during rupture; it is only the drop in friction that matters. However, once a fault's symmetry is broken, slip is affected by absolute friction. We aim to better understand the relationship between the geometrical symmetry, absolution friction and slip.

Our approach uses dynamic finite element modeling to simulate rupture propagation and slip during a thrust earthquake. We model a 2-D, 40 km-long, 15º dipping thrust fault within a homogenous solid using the finite element code FaultMod. For each condition of absolute friction, three models are conducted: (1) a strongly asymmetric case where the upper fault tip terminates at the free surface, and is allowed to slip; (2) a moderately asymmetric case where the upper fault tip is buried 9 km (a blind thrust in a half-space); and (3) a purely symmetric case where the upper fault tip is buried 120 km (a blind thrust effectively in a whole-space). Only for models (1) and (2) is seismic radiation from the free surface allowed to interact with the fault as rupture propagates, thereby causing changes in the normal stress and influencing slip.

Preliminary results for a purely symmetric fault in a whole-space demonstrate that different frictional and stress parameterizations produce identical final slip results. Thus, only the drop in friction contributes to slip for our model (3) case. For the models that approach the free surface, where the free surface boundary condition is apparent, we find that the evolution of fault rupture and slip do depend on the absolute level of friction. The effect on slip is dominated by the dynamic friction. The influence from static friction is limited to causing differences in the temporal evolution of rupture rather than the final slip.

Physics-Based Ground Motion Simulation for the 2017 Mw 6.5 Botswana Intraplate Earthquake

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The 2017 Mw 6.5 Botswana earthquake was a rare intraplate earthquake with the potential to cause catastrophic damage. One remarkable aspect of this event was its significant depth, estimated to be around 24 to 31 km. In our research, we utilized the open-source code SeisSol, which is one of the flagship codes of the EU ChEESE project, to perform a physics-based dynamic rupture model for this event. Specifically, we solved fault slip and 3D elastic wave propagation as a coupled problem on unstructured tetrahedron grids, incorporating complex fault geometry and applying theoretical stress analysis under a laboratory-driven rate-and-state friction law. This approach allowed us to capture self-arresting slip behavior.

Our main focus was on developing a physics-based dynamic rupture model specifically for the Mw 6.5 Botswana intraplate earthquake. This model enabled us to accurately simulate fault slip and 3D elastic seismic wave propagation, resulting in the generation of synthetic seismograms and displacement on the free surface. It is crucial to develop numerical simulation approaches for earthquakes with limited recorded data, particularly in stable continental regions where earthquakes can occur on previously unknown faults. The 2017 Botswana earthquake serves as an example of such a scenario.

Our study successfully integrated data-driven inversion results with physics-based modeling methods, providing a comprehensive framework for assessing the ground motion associated with deep intraplate earthquakes. To validate the accuracy of our findings, we compared the synthetic data generated by our model with observational seismological and geodetic data.

Overall, our work offers valuable insights into understanding the behavior and impact of deep intraplate earthquakes, paving the way for improved intraplate earthquake risk assessment in similar geological settings in the future.

Asperity Location Identification of the 2016 Kumamoto Earthquake Mainshock by Dynamic Rupture Modeling with 3D Basin Structure

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3D simulation of the Mw 7 2016 Kumamoto earthquake with 3D velocity structure is adopted using the dynamic fault rupture model with a simple slip weakening law. Stress drop variation was assumed to be increased with depth. The assumed 3D velocity structure is constructed by referring to the Japan Integrated Velocity Structure Model of the Headquarters for Earthquake Research Promotion of Japan. The recorded near-fault ground motions at 26 strong motion stations installed by a couple of Japanese institutions are compared to the synthetic motions. Two strategies to generate three asperity locations for the mainshock are proposed. 1476 of 1520 randomly generated scenarios are found to be mature simulations. A hybrid goodness-of-fit function that includes peak ground velocity (PGV) and cross-correlation coefficient is used to evaluate the optimal scenario among 1476 simulations. The rake angle of the mainshock is analyzed and found to be between 20 and 40 degrees, which is consistent with the values from kinematic source inversions. The shallow and deep asperities beneath the Futagawa fault zone with the size of 5 to 8 km in length by 5 km in depth are located close to the hypocenter. Among 26 sites, 16 were found to have a good similarity between observation and synthetic waveforms. Large fault slips are mainly located in the shallow Futagawa asperity, as large as 4 m. Large fault slip rates are mostly concentrated in the deeper Futagawa asperity, as high as 6 m/s. The Kostrov shape fault slip function is found in three asperity areas on the fault plane, while the triangle shape slip function appears in the other areas or background areas. The forward directivity of rupture propagation produces strong seismic motions at Mount Aso and the surrounding Aso City areas, producing large PGVs in the EW and NS directions in these areas.

Supershear Cascading Ruptures Envelopes

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Faults are weak, geometrically complex, strongly interacting interfaces of crustal volumes dissipating tectonic stress. Earthquake ruptures propagate throughout them following uneven multiple paths, taking jumps and bends producing spatially heterogeneous slip amounts and stress drops. Nevertheless, routinely implemented dynamic and kinematic simulations model ruptures as uniform fronts travelling along smooth or slightly rough surfaces. How far can this assumption impact our view of coseismic dynamics? Super-shear earthquakes are seismic events whose apparent rupture speed exceeds the shear wave velocity. The possibility of ruptures propagating faster than shear waves was predicted theoretically and reproduced in the laboratory (Xia et al., 2004); while just a dozen of tectonic "supershear" earthquakes have been convincingly reported so far (Bao et al., 2022). Because of the small number of observations, their dynamics is still poorly understood. Moreover, super-shear speeds have been unambiguously detected only along faults with dominant strike-slip component. Here we propose a new interpretation of super-shear events: we speculate that apparent super-shear velocities should not be attributed to continuously propagating single fronts, but instead to envelopes of dynamically triggered multifocal ruptures within rough fault zones allowing a faster motion of the two fault walls along strike. We also show that ruptures speed up in the presence of competent rock rheology and low local stress drops. On the other hand, the patches of sub-shear velocity can be interpreted as related to synthetic step overs. Our model, although more complex than the classical one, is more physics-based assuming intricated and wavy fault zones and geometry; moreover, it can reproduce the Mach cone. In addition, it allows to overcome some inconsistencies due to the anomalously intense high-frequency content in the power frequency spectrum expected whenever ruptures travel at super-shear speed (Bizzarri & Spudich, 2008), which is incompatible with observational evidence (e.g., Bouchon et al., 2010).

Empirically Modeling Source Effects as Inputs to Models [Poster]

Poster Session • Tuesday, 10 October and Wednesday, 11 October

The Effect of Azmiuthal Variation on Measured Stress Drop: A Case Study of the 2019 Ridgecrest Sequence

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A longstanding issue in source seismology is whether or not the variation in measured "stress drop" is due to methodological differences or physical assumptions, which leads to confounding results about predicted ground motion in regional earthquake hazards and source physics. The spectrum of seismic radiation is commonly used to derive the stress drop for earthquakes, which relates an earthquake's source dimension to its ground motion. The first step in using the spectrum to estimate the stress parameter is to separate out source contributions in the raw data from site- and path- effects, which may be performed in various ways. In this study, we compare two common methods of deconvolving source spectra from waveform records: using a nonparametric matrix inversion (spectral decomposition) and using an empirical Green's function (eGf) method. Using the example case of the 2019 Ridgecrest sequence, we classify source spectra into types based on observed spectral complexity, noting that complex spectral shapes (at both the event and station level) are more likely to yield variable estimates of the stress parameter when the deconvolution method differs. We show that source directivity can account for some amount of discrepancy in source parameter estimates between the two methods. Typically, azimuthal heterogeneity in path is not accounted for in a spectral decomposition, while eGf methods specifically account for specific paths. We present an alternative sampling algorithm to improve the ability of spectral decomposition to resolve azimuthal variability.

Slip Pulses and PSHA

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The observation that average stress drops (3 MPa) are scale independent over an enormous range of earthquake sizes has been the primary motivation for modeling earthquakes as expanding cracks. However, constant stress drop expanding cracks can only be arrested by introducing a zone of high fracture energy at the crack tip. Furthermore, the fracture energy increases linearly with the scale of the rupture. In that sense, crack models are not independent of scale. Slip pulses are fundamentally different; a propagating slip pulse knows nothing about the ultimate dimension of the rupture. How can slip pulses match the observation of scale-free stress drops? I show that slip pulses are inherently unstable and that they are dynamically chaotic. I show a simple spring-block slider model that has a prestress that evolves into a complex state that results in events that have scale independent stress drop; heterogeneous prestress from self organization is the mechanism of rupture arrest. Chaotic dynamic systems are typically described by power-law statistics (aka, fractals), which implies that current PSHA can severely underestimate the probabilities of very large long-period ground motion.

Quantitative Assessing the Variability of Earthquake-source Models to Ground Motion Prediction for an M8 Scenario Earthquake in the Ryukyu Subduction Zone

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In 1920, an M8 earthquake occurred in the Ryukyu subduction zone in eastern offshore Taiwan. To estimate the possible ground motions in eastern-inland Taiwan if earthquakes with similar magnitudes happen again, we assume an M8 scenario earthquake in the same region accounting for a series of characteristic source models (CSMs) generated according to the procedure of Recipe (e.g., Irikura and Miyake, 2010) for ground motion modeling. Kinematic fault-rupture parameters are modeled, including rupture directivity, rupture speed, and asperity distribution. Therefore, a 3-D finite-difference method (FDM) is utilized to perform full-waveform ground motion simulations to test the variability of ground motions from the given CSMs. Tomographic velocity models and topographic relief are accounted for in these simulations. A total of 24,755 fictitious stations with an inter-station spacing of 500 m are deployed to output 3-component synthetic waveforms. We adopt the RotD50 approach to calculate spectral acceleration and pick 1-, 3- and 5-s PSAs for ground motion model (GMM) analysis. The results show that the effects of rupture speed and directivity are the most critical factors affecting ground motion distribution. By comparing with the GMM of Chao et al. (2020), simulated ground motion distributions from source models with a rupture speed of 3 km/s have good agreements with the 1-s PSA curve of GMM prediction; on the contrary, the ground motions from source models with a rupture speed of 2.4 km/s fit 3- and 5-s PSA curves. We also performed the sensitivity analysis among source parameters using three fictitious stations. The sensitivity analysis suggests that the ground motions in different dipping directions of the rupture plane are sensitive to different segmentation settings of asperity. Our simulation dataset has also been used to calculate non-ergodic terms based on the GMM of Chao et al. (2020). It shows that the simulations could indicate long-period ground motions and be further incorporated into non-ergodic GMMs and seismic hazard assessments.

Near-source Ground Motions During the 2008 Wenchuan Earthquake

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Strong ground motions were observed at dozens of stations within 100 km from the ruptured Longmen Shan Fault during the 2008 Wenchuan earthquake. Many studies have been made of the source of this earthquake using datasets, strong motion, teleseismic, geodetic, and InSAR data.

Strong ground motions of this earthquake were successfully simulated based on the characterized source model with two strong motion generation areas (SMGAs) except very-near-fault stations using the empirical Green's function method (Kurahashi and Irikura, 2010; Xia et al., 2015). However, the pulsive motions obtained at very-near-fault stations such as MZQ and SFB cannot be reproduced using the conventional characterized source model with only SMGAs.

We parameterized more complex faulting of the Wenchuan earthquake to reproduce near-source ground motions with pulsive velocity motions and permanent displacements at very-near-fault stations. We apply an extended characterized source model with the strong-motion generation areas (SMGAs) inside the seismogeneic zone adding long-period-motion generation area (LMGAs) in surface layers above the seismogenic zone used for the 2016 Kumamoto, Japan, earthquake (Irikura et al., 2020).

Slip velocity time functions inside the SMGAs and LMGAs are assumed to have a Kostrov-type function and a smoothed ramp function, respectively. The velocity motions simulated from five SMGAs can reproduce the observed motions well at stations except very-near-fault stations, MZQ and SFB. The pulsive motions with permanent displacement at MZQ and SFB can be reproduced by ground motions from the SMGAs adding those from the LMGAs.

Finally, we compare simulated surface displacements for the SMGA-LMGA model with the observed surface displacements from InSAR (Feng et al, 2017) to determine the length, width and displacement of the LMGA. In the model we assumed that the SMGAs and LMGAs are on the strike-slip right lateral fault planes. We need to introduce normal fault movements on some parts of the LMGAs to explain complex fault-movements of the observed surface displacements.

Simple Source Modeling and Strong Ground Motion Simulations of the 2023 Mw 7.8 Türkiye-Syria Earthquake

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Investigating strong motion generation mechanisms of past large earthquakes is important for predicting ground motions of future earthquakes. In this study, source modeling and strong ground motion simulations of the 2023 M_w 7.8 Türkiye-Syria earthquake were conducted. Southwestern part of the fault was considered due to the data availability. The main focus was put on the generation mechanisms of near-fault large velocity pulses, which are important for earthquake engineering. Many strong ground motions were recorded near the surface ruptures during the earthquake and they showed large velocities in both fault normal and parallel components with PGVs over 100 cm/s and durations of several seconds. Deep asperities and shallow slip areas were considered to appropriately explain these features of observed strong ground motions. A semi-empirical method called the corrected empirical Green's function method, which combines the omega-square source spectrum and the empirical path and site amplitude/phase characteristics, was used for asperities. Empirical path and site characteristics were evaluated from aftershock data. The discrete wave number method was used for shallow slip areas. Source parameters were determined to generate observed near-fault large velocity pulses and overall Fourier amplitudes. As a result, seven asperities and shallow slip areas with slips of 4-6 m and rise times of 2-3 s were identified. Observed near-fault large velocity pulses were mostly explained by near surface slips. Long and large shallow slips generated both fault parallel and normal velocity pulses. Although large fault normal components were often modeled by deep asperities with the directivity effect, long shallow slip areas generated fault normal directivity pulses for this earthquake. In addition, detailed comparisons implied complex source effects, such as multiple subevents on shallow slip area, hierarchical slip structure, and nonuniform rupture speed.

Assessing the Accuracy of Earthquake Stress Drop Estimation Methods for Complex Ruptures Using Synthetic Earthquakes

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We evaluate how well simple, commonly used stress drop estimation methods are able to recover the known stress drop of synthetic, complex ruptures, constructed by combining multiple simple kinematic source models. Earthquake stress drop is a commonly estimated parameter that can provide insight into both earthquake source physics and the resulting ground motion. Stress drop methods usually assume that earthquakes are a symmetric circular crack which release their energy in a single pulse with a simple source time function (STF). Real earthquakes, however, often have complex STFs with multiple pulses of seismic moment release, and studies have shown that stress drop estimates contain significant uncertainties, which maps into uncertainties in ground motion predictions.

Therefore, in this study, we seek to investigate systematically how the complexity of real earthquakes can bias stress drop estimates. To do so, we utilize synthetic earthquakes. We create a synthetic catalog of complex rupture earthquakes by combining multiple simple, circular-crack spectral models to create complex STFs with known static stress drops. We then apply time-domain methods (i.e., rupture duration) and frequency-domain methods (such as corner frequency) to estimate stress drop. The different stress drop estimates differ systematically by simple parameterizations of STF complexity. Our results suggest that neither the frequency-domain nor the time-domain methods are particularly good estimators of stress drop when applied to complex earthquakes. However, frequency-domain stress drop estimates more strongly correlate with the stress drop of the largest moment pulse rather than the average stress drop of the entire rupture area. Discrepancies between stress drop estimates have significant implications for expected ground motions. Identifying which stress drop estimation methods (or combination of methods) perform best under which circumstances can lead to more accurate assessments of future earthquake hazards.

Long-range Fiber-optic Earthquake Sensing by Active Phase Noise Cancellation

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We present a long-range fiber-optic environmental deformation sensor based on active phase noise cancellation (PNC) in metrological frequency dissemination. PNC sensing exploits recordings of a compensation frequency that is commonly discarded. Without the need for dedicated measurement devices, it operates synchronously with metrological services, suggesting that existing phase-stabilized metrological networks can be co-used effortlessly as environmental sensors. The compatibility of PNC sensing with inline amplification enables the interrogation of cables with lengths beyond 1000 km, making it a potential contributor to earthquake detection and early warning in the oceans. Using spectral-element wavefield simulations that accurately account for complex cable geometry, we compare observed and computed recordings of the compensation frequency for a magnitude 3.9 earthquake in south-eastern France and a 123 km fiber link between Bern and Basel, Switzerland. The match in both phase and amplitude indicates that PNC sensing can be used quantitatively, for example, in earthquake detection and characterization.

Break in Self-similar Source Parameter Scaling for Shallow Crustal Earthquakes

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Reveling the scaling laws of source parameters and the physical mechanism underlying the scaling laws is important for improving physics-based ground motion prediction. This study estimated the source parameters of shallow crustal earthquakes (M_w 3.2 to 6.0) in Japan by the spectral ratio approach. Then, the scaling relations of stress drop, apparent stress, radiation efficiency, and fracture energy were investigated for a wide magnitude range by combining the source parameter results of small ($M_w < 3.0$) and large earthquakes ($M_w > 6.0$) obtained in previous studies. This study calculated the stress drop using a simple heterogeneous source model. The stress drops for small earthquakes were estimated from corner frequency, while those for large earthquakes were obtained from finite fault inversion results. Thus, this study calibrated the value of the constant to relate stress drop and corner frequency (the k_S value) based on the spectral ratio analysis results and confirmed that the corner-frequency-based stress drops calculated using the calibrated k_S value for earthquakes with $M_w > 5.1$ are consistent with the typical stress drop values for large earthquakes, 1 to 20 MPa. It was found that the stress drop and the apparent stress increase with the magnitude for $M_w < 5.1$ and become magnitude-independent for $M_w > 5.1$. The radiation efficiency is magnitude-independent relatively. The radiation efficiency estimates are typically within 0.1 to 1.0, energetically consistent with crack-like rather than self-healing pulse-like rupture. This study also found that the observed slip-dependencies of the stress drop, the apparent stress, the radiation efficiency, and the fracture energy can be explained consistently by the slip-dependencies of these source parameters predicted from the slip-weakening model considering the thermal pressurization effect. Although other mechanisms are possible, thermal pressurization may be a dominant mechanism underlying the non-self-similar source scaling.

Quantifying Earthquake Rupture Complexity from Theory and Observations: A Review

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The dynamics of earthquake rupture is inherently complex due to the non-linearity of processes related to fracture and friction of rocks in geological heterogenous and geometrically complicated fault zones. While the seismological community has made great advances in recent years to understand and model the intricacies of the dynamics of earthquake rupture, large-scale multi-scenario simulations for potential future events for a site/area of interest for the purpose of ground-motion prediction are still limited. As an alternative, we may employ kinematic rupture simulations in which the earthquake rupture complexity is prescribed using stochastic yet physics-based approaches. Being computationally less demanding and conceptually simpler, such a kinematic ground-motion simulations may augment standard PSHA approach, as for example in the CyberShake method (Graves et al, 2010).

In this presentation, I attempt a review of empirical and theoretical models developed over the last ~40 years that quantify on-fault heterogeneity in stress and displacement (slip). These methods and models form the foundation for modern physics-based kinematic rupture simulations. Using concepts of rupture dynamics, as well as recent laboratory and field observations, allows then to constrain the temporal evolution of earthquake source kinematics by constructing physically plausible and self-consistent realizations of the rupture process. Because these "pseudo-dynamic" source models successfully reproduce past observations and replicate key characteristics of spontaneous dynamic rupture models, they are now almost routinely applied in physics-based ground-motion motion simulations for earthquake-engineering applications.

Physical Modeling Issues of Site Effects [Poster]

Poster Session • Tuesday, 10 October and Wednesday, 11 October

Effect of Liquefiable Double Sand Lenses Position on Surface Settlement of Clayey Soil: Numerical Simulation

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The existence of discontinuous layers of sand, known as sand lenses, causes notable settlement of clay and silt deposit during earthquakes. This paper presents the effect of liquefiable double sand lenses of the surface settlement of clayey soil with numerical analysis. The lenses have been placed in different depths (5, 7, 9, and 11m from the surface) to evaluate the effect of lenses placement on the surface settlement of saturated clayey soil. Moreover, the influence of clayey soil cohesion and input acceleration on the settlement has been studied. It has been observed that increasing the depth of sand lenses and clay cohesion reduced the ground surface settlement. However, the effect of clay cohesion on the settlement reduction was up to 18 kPa. Finally, increasing the input acceleration applied to the base of the model causes an increase in settlements.

3D Simulations of Strong Ground Motion and Site Effects in the Pohang Basin, Korea

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The accurate evaluation of site effects is significant in understanding the behaviour of ground motion during earthquakes thereby ensuring the safety and reliability of infrastructure. This study presents physics-based ground motion simulation of multiple events from the 2017 Pohang aftershock sequence. The 2017 Pohang earthquake (Mw 5.5) has been known to be a triggered event related to the development of the enhanced geothermal system resulting in a shallow hypocentral depth (4km). The present study reveals compelling evidence of surface wave generation around the epicentral region (10km) which was successfully reproduced using 3D numerical simulations. The impact of site effects on seismic wave modification was examined using an exhaustive modelling process that incorporates the site effect characteristics. A 3D velocity model of the region was developed based on a 1D velocity profile at a reference site and the geological map of the study area. The process involved fine tuning the model based on comparison of simulated and recorded waveforms up to a maximum frequency of 5Hz for multiple events from the Pohang aftershock sequence. The analysis exhibited lateral heterogeneities incorporated in the model played a critical role in the generation of surface waves in the study area. By emphasizing the impact of site effects on the seismic wave behavior, the findings contribute to a deeper understanding of the complex interaction between geological structure and ground motion as well as in quantification of important engineering parameters for the case of Pohang basin.

Effects of Input Ground Motion Selection Techniques on Site Response Analyses: Insights from Different Tectonic Settings

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In this study, we investigate how input ground motion selection techniques influence the results of site response analyses. Site response analyses are used to estimate site-specific ground motions as a function of the properties of the soil profile, the assumed constitutive models for dynamic soil behavior, and the input (bedrock) motion applied at the base of the soil profile. We perform analyses at two locations, Seattle, Wash., and Boston, Mass., in order to evaluate the influence of different site conditions, target spectrum definitions, spectral periods of interest, seismic source scenarios, and ground motion databases. When directly incorporated into target spectrum definitions, different types of seismic sources and the corresponding databases have a significant impact on site response, as captured by spectral amplification factors and non-spectral intensity measures (e.g., significant duration and Arias intensity), particularly in subduction zones. We find that the conditional spectrum is a suitable target spectrum for sites having hazard contributions from multiple seismic sources (such as crustal sources and subduction zones), but the conditional spectrum exhibits limitations in stable continental regions. In addition, we conclude that the variability in site response estimates is highly dependent on site conditions (e.g., soft vs. stiff sites). When the soil behavior is strongly nonlinear, we find that the influence of input motion selection protocols on site-response uncertainty decreases significantly, and that nonlinear soil behavior can suppress the variability (associated with the input selection process) in surface ground motions. Analyses using alternative profiles indicate that ground motions at stiffer sites are more greatly influenced by input motion selection protocols relative to softer sites. Finally, we provide recommendations on the suitability and limitations of different target spectrum definitions with respect to seismotectonic settings.

Physical Modeling of the Influence of Vertical Drain Length on Mitigating Liquefaction-induced Tunnel Uplift

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Due to the risk of liquefaction causing the uplift of tunnels at shallow depths, such as the subway tunnel, it is vital to pay attention to the uplift phenomenon. Several methods of confronting this issue have been researched. One of the conventional methods for mitigating the impacts of liquefaction-induced uplift is to use a drainage system and rapid dissipation of the excess pore water pressure. The precise design of drains is critical and beneficial during dynamic loading. In this regard, the appropriate depth to achieve acceptable performance of the vertical drains has been studied in this research. Physical modeling employing a shaking table was used in the investigations. According to the results, the tunnel uplift is greatly reduced when the drains reach a depth deeper than the tunnel's bottom level.

Numerical Simulations for Site Effect Estimation in a Complex Sedimentary Basin: A Comparison Between Different Approaches for Designing 3D Seismic Models of the Subsurface

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Estimating site effects is important for seismic hazard assessment but can be difficult due to the scarcity of data in time and space, especially in low-to-moderate seismicity regions. Numerical simulations are helpful for understanding the physical parameters controlling site effects and for modelling their spatial variability, but simulations need detailed seismic models of the subsurface in input, as well as empirical measurements of amplification for calibrating their outputs. In this study, we perform 3D numerical simulations of seismic wave propagation and amplification in the Tricastin basin (Rhône valley, France) based on a range of models built with different sources of information. A first type of models consists of layers separated by interfaces interpreted from active seismic profiles and interpolated over the area of interest. A second type of models is obtained by Ambient Noise Surface-Wave Tomography (ANSWT) applied on a dense array of 400 3C sensors and resulting in a 3D model of shear-wave velocities. Array analysis of the

seismic noise recorded by this network also provides us with an estimation of attenuation parameters (Qs) within the basin. We compare our numerical results with empirical amplification measurements based on earthquake and ambient noise recordings. Our results highlight the characteristics of the input models in terms of seismic amplification. Layered models generate significant 3D wave propagation effects consistent with the observations but, if over-simplified (e.g. sediments vs. bedrock), do not fully explain the measurements in complex areas of the basin. On the other hand, preliminary models based on purely data-driven ANSWT suffer from the resolution limits of the tomographic process, especially in terms of lateral variations, and do not reproduce expected 3D wave propagation effects, but seem to provide a satisfying estimation of the subsurface velocity structure in complex areas of the basin. This study sheds light into how to acquire and combine information to design and calibrate numerical simulations for site effect estimation.

Soil Seismic Response Modeling of KiK-net Downhole Array Site Based on a Multi-input Neural Network

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Accurate prediction of soil seismic response is necessary for geotechnical engineering. The conventional physics-based models such as the finite element method (FEM) usually fail to obtain accurate predictions due to the model assumption and parameter uncertainties. And the physics-based models are computationally expensive, especially for simulating the seismic response of large numbers of soil sites. This study proposed a multi-input neural network to predict soil seismic response based on the recorded ground motions from more than 500 KiK-net downhole array sites. The input variables were divided into three groups: Ground motion, Site conditions, and Source. Since the site conditions (S- and P-wave velocity profiles) are considered in the neural network, the accurate prediction of the seismic response for new sites can be obtained by the trained model. Compared with the state-of-art FEM models, the proposed models could achieve better prediction performance with higher efficiency.

Hessian Preconditioners for Sensitivity Kernels Calculation and Uncertainty Quantification in Full Waveform Tomography Application for the Upper South Island Region, New Zealand.

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For adjoint waveform tomography, the adjoint source calculated for each event were injected simultaneously at all station locations and for all 3 components. The sensitive kernels (Tromp et al., 2005) for model parameters: Bulk modulus and shear modulus which in turn allow the determination of P- wave velocity and S-wave velocity. From this, we have sensitive kernels for Vs, and Vp calculated. After the calculation of the sensitivity kernels for all events, we combine them and precondition by the sum of the approximate Hessians (Zhu et al., 2015) to compute the gradient. This precondition technique was based on the geometrical spreading factor to reduce the large sensitivity near the sources and stations (Fichtner et al., 2009; Lee et al., 2014).

In the real data application for full waveform tomography for the upper South Island region, New Zealand, the gradient was smoothed by a convolution with a 3-D spatial Gaussian function (Tape et al., 2007). The horizontal and vertical widths of the Gaussian function are different (wider Gaussian in horizontal directions) to speed up the misfit reduction as well as preserve the high variation with depth.

3D Wave Propagation Simulations of M6.5+ Earthquakes on the Southern Whidbey Island Fault, WA, Considering Surface Topography and a Geotechnical Gradient

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The southern Whidbey Island fault (SWIF) is a large crustal fault in Washington State capable of producing large (M6.5-7.2) earthquakes. Despite its proximity to the Seattle, Everett, and Bellevue metropolitan regions, past simulations of earthquakes on this fault have focused only on a small number of rupture scenarios, resulting in a limited understanding of the ground shaking potential from a large SWIF event. Here, we present directly simulated ground motions from SWIF earthquakes to expand on the set of previous simulations and better characterize regional seismic hazard. We conduct a suite of high-frequency (<=3 Hz), local-scale simulations, as well as lower frequency (~1 Hz), region-scale simulations of large magnitude earthquakes on the SWIF. Simulations are run in 3D using a spectral element method code (SPECFEM3D) on a mesh with a 30m-sampled topographic surface. The seismic velocity structure is constrained using a 3D velocity model considering local geology and implementing a region-specific geotechnical gradient in the upper ~100m. We test a variety of kinematic source scenarios considering different hypocenter locations and slip distributions. Additionally, we compare simulated ground motions between different iterations of the model (topography/flat, local-scale/region-scale) and validate them against the empirically predicted peak ground motions from the 2014 NGA-West2 ground motion models (GMMs). These simulated ground motions allow us to characterize complex source, path, and site effects that could only be approximated using empirical GMMs, including basin effects, rupture directivity, and topographic amplification. The results from this work provide a framework for updated seismic hazard analysis and direct earthquake simulation in the Pacific Northwest.

Calculation of Full Nearfield Motion on and Above the Sea Bottom Due to Seismic and Tsunami Waves Excited by an Offshore Earthquake with the Discrete Wavenumber Method

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For design of seismic resistant offshore structures the evaluation of full motions in the sea-water layer including ocean acoustic waves and tsunami waves might also be necessary as well as the seafloor motion from sub-oceanic earthquakes. Around near-fault area under the sea the seawater motion associated with tsunami generation immediately follows the sea-bottom seismic motion, permanent sea-bottom deformation and ocean acoustic waves. In this study we develop a quasi-analytical method for calculating full motion on and above the sea bottom due to nearfield seismic wave propagation and tsunami wave generation and propagation for horizontally stratified media with compressible water layers on top of a multi-layered solid half-space from a submarine earthquake. We introduce the gravitational effect into the water layer in a similar way to Watada (2009, 2013) and An and Liu (2016) to excite tsunami waves. The solution method is based on the Kennett and Kerry's (1979) reflection/transmission matrices and Bouchon's (1980) discrete wavenumber summation method. We derive the Aki-and-Richards (1980, 2002)-like layer matrix for a fluid layer under compression of gravity, and the reflection coefficient for the free surface of a gravitational fluid, the reflection/transmission matrices for the fluid-fluid interface and the interface between a gravitational fluid layer and a non-gravitational solid layer. For accurate computation of tsunami waveheight the exploitation of complex frequency might be essential as well as for that of static displacement shown by Zhu and Rivera (2002) and Wu et al. (2021). The effect of the imaginary part of the complex frequency is removed from the calculation time window of an appropriate length after numerical conversion from the frequency-domain solution to the time-domain one, which is equivalent to a numerical inverse Laplace transform for the Laplace-domain solution.

Effect of Water Saturation on Ground Motion from a Fault Rupture and an Underground Explosion

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This work presents a sensitivity study for the ground motion caused by two sources (an explosion and a fault rupture) in dry and wet rock masses using a thermo-mechanical model for porous partly saturated rock for the numerical modeling in the near-field. The model describes effects of nonlinear poroelasticity, porous compaction, dilation and shock-induced liquefaction. The fault is modeled as an embedded discontinuity with a Mohr-Coulomb failure effective stress model activated by a sudden stress drop. Various assumptions were made about the in-situ stress in the vicinity of the source. The modeling was done using LLNL non-linear hydrodynamic code Geodyn-L. We compare the calculated ground motions for various levels of fluid saturation at various in-situ stress conditions. The ground motion calculated in the near-field using Geodyn-L can be coupled to an elastic wave propagation code, WPP, applied to the far-field in a consistent way, where both codes use the same mechanical material models.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-679820

Site Response Analysis for the Istanbul Region Using Simulated Ground Motions

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1D site response analysis (SRA), which simulates the seismic waves vertically propagated from the bedrock to surface, has been a popular approach for geotechnical engineers to investigate the site-specific ground shaking levels subjected to earthquakes. However, upon numerous evidence from past earthquakes and theoretical studies, it has been noticed that the accuracy of 1D SRA can be dramatically affected by many factors, such as the spatially variability of soil properties, surface topography, basin effects, earthquake directivity, etc. The 3D ground motion simulation (GMS), on the other hand, can intrinsically incorporate these factors and hence yield more reliable predictions. In this study, we will utilize the simulated ground motions from 57 physics-based broadband (8~12 Hz) GMS for the Istanbul region. A total of 2,912 sites over a 30 km by 12.5 km area with measured soil profiles will be modeled as 1D soil columns and then analyzed by performing 1D SRA on OpenSees. The ground responses from 1D SRA will be compared with ones from 3D GMS for all 57 earthquake scenarios. Overall, such systematic comparisons can significantly help us quantitatively understand the relative importance of each factor controlling the performance of 1D SRA, uncertainty of 1D SRA for different intensity measures, including PGA, PGV and spectral acceleration, and the conditions in which 1D SRA can deliver accurate results and vice versa.

Regional Differences in Quantification of Path Effects [Poster]

Poster Session • Tuesday, 10 October and Wednesday, 11 October

Understanding the Impact of Anelastic Attenuation on Ground Motion Parameter Estimation in Central Italy

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In recent decades, Central Italy has experienced seismic sequences that caused significant casualties and extensive damage to buildings, as the one started in August 2016 with the Amatrice mainshock (Mw6.2), followed by Visso (Mw5.9) and Norcia (Mw6.5) events two months later. Given the recurring seismic activity in this region, it is crucial to employ physically-based ground-motion (GM) simulations to assess seismic risk and support earthquake engineering endeavors. Previously studies have investigated the GM characteristics of Amatrice and Norcia earthquakes using stochastic and numerical approaches. In addition, there has been a significant emphasis on enhancing attenuation relationships and GM models used for predicting GM from postulated events, fundamental to ensure the overall accuracy of seismic assessments. Recent studies have focused on reducing uncertainties in these models through non-ergodic approaches, which consider various physical parameters associated with the seismic source, wave propagation, and path-specific heterogeneities. Here, we first aim to calculate the anelastic attenuation due to the crust using the Coda Normalization method, which measures direct and coda-wave energies and divides them to obtain a quantity that only depends on Q (Quality Factor). We calculate the total attenuation Q as a function of frequency for the 2016-2017 seismic sequence and employ a regionalization approach to map it in a three-dimensional space. Once the frequency dependence of Q-total is determined, we use this value in conjunction with other specific input parameters (e.g., magnitude, stress drop, rupture model) to perform the strong-GM simulations. We simulate earthquake-induced GMs based on a stochastic model to explore the impact of the seismic wave attenuation variability on the GM hazard in the Central Apennines. Finally, we compare and validate our estimates against the observed peak ground accelerations, velocities, and spectral acceleration at several frequencies for the Amatrice and Norcia mainshock with the GM prediction equations adopted for the region.

Constraining Large Magnitude Earthquake Source and Path Effects Using Ground Motion Simulations

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The most promising way to improve the accuracy of hazard curve calculation is through the separation of epistemic and aleatory uncertainties. For example, wave propagation path effects should be considered as repeatable, with their possible variability constituting epistemic uncertainty. However, path effects represented by Ground Motion Models (GMMs) often include unmodeled source effects, such as radiation pattern and directivity, which may lead to bias in seismic hazard assessment. Moreover, the path effects from an event to a site are often represented by a single path between one point on the fault and the site, regardless of the magnitude and extent of the rupture. For a large magnitude earthquake, seismic waves travel from any point along the rupture plane that extends hundreds of kilometers. Hence the single travel path assumption for large magnitude earthquakes is potentially flawed. Theoretically, we need to include an infinite number of paths from the entire rupture plane when estimating the path effects of large magnitude earthquakes. In reality, we may make simplifications, such as aggregating path effects from small magnitude earthquakes that sample the larger rupture plane.

The purpose of this study is to use ground motion simulations to investigate ways in which source and path effects for large magnitude events can be represented in non-ergodic GMMs. We designed a new ground motion simulation study, which includes earthquakes occurring on a fault plane with a large range of magnitudes, and sites covering a large range of rupture distances and azimuths. We first develop a non-ergodic GMM, in which radiation pattern and directivity effects are modeled using existing relationships. Then, we compare the mean path effects among different magnitude groups of events and examine any difference dependence on distance and azimuth. Our ultimate goal is to develop guidelines for how large magnitude ruptures can be adequately represented within non-ergodic GMMs.

Separation of Intrinsic and Scattering Seismic Attenuation in the Crust of Alaska

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Seismic hazard analysis is a crucial aspect of assessing potential earthquake damage and loss of life in an area, particularly in areas like Alaska, which are prone to frequent seismic activity. The accuracy of seismic hazard assessments depends on the reliability of ground motion prediction equations, which are used to predict the expected ground shaking at a given location. However, in regions with significant variations in crustal attenuation, such as Alaska, the accuracy of these equations may be compromised. The average Lg Q in Alaska is significantly higher than in the western U.S. and Canada, affecting seismic hazard assessments as it affects the magnitude and duration of ground shaking. Failure to account for these regional variations in crustal attenuation can result in inaccurate hazard assessments.

In order to better understand the reasons for this issue, this study proposes the use of Coda Q analysis to investigate the role of scattering and intrinsic crustal attenuation in Alaska. The study will focus on earthquakes with magnitudes between 2-6.5 and an epicentral distance of 20km - 200km occurring between December 2014 and December 2020, with focal depths of less than 30km. The Multiple Lapse Time Window (MLTW) method with the center frequencies of 0.75 to 12.0 Hz will be used to distinguish between intrinsic and scattering crustal attenuation using seismic energy of three-time windows of 0-15 s, 15-30 s, and 30-45 s, measured from the S arrival. The results of this study will provide important insights into the regional variations in seismic attenuation in Alaska. By analyzing the regionalized values of intrinsic and scattering attenuation and their frequency dependencies, the study aims to interpret the causes for regional variations of crustal attenuation of Alaska. This knowledge can help improve geological and tectonic interpretations, leading to better ground-motion prediction equations that can be used in seismic hazard assessments.

Challenges for Model Extrapolations Outside of the Data Range [Poster]

Poster Session • Thursday, 12 October and Friday, 13 October

Can Non-linear Degradation Curves Be Extrapolated to Large Depth? Insights From the Observed Response of Thick Sedimentary Deposits in Japan

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Numerical simulations of the non-linear response of thick sedimentary deposits give extremely variable results depending on the maximum depth considered for a non-linear behavior of soils. For (non-exceptional) cases where the deep bedrock is hard enough to generate to significant (≥ 2) velocity contrast with the deepest sediments, the application of widely accepted degradation curves to the entire soil column generally leads to a significant reduction of high frequency ground motion even for relatively moderate shaking levels, because deformation levels are high enough to result in significant damping increase over the whole sediment thickness. Nevertheless, as most of these degradation curves have been developed from lab measurements performed under limited confinement pressure, their extrapolation to large depths (exceeding a few hundred meters) can be questioned.

This contribution will present a statistical analysis of strong motion recordings obtained on thick Japanese sedimentary sites from the KiK-net, K-NET and JMA (Shindokei) networks. From a qualitative viewpoint first, the distribution of velocity profiles for sites with very large pga (above 0.4 g) is similar to the distribution for all strong motion sites in Japan, without any bias towards rock or shallow, stiff sites. Second, the non-linear effects are quantified by comparing various kinds of site-response characteristics (surface-to-borehole spectral ratios, H/V spectral ratios or site-specific terms resulting from generalized inversion techniques) for moderate to large motion to their weak motion counterparts. While a non-linear behavior can be detected on thick and shallow sites as well, even for relatively moderate loading levels, thick sites do not exhibit any peculiar high-frequency reduction. The inconsistency of such results with the high frequency decrease predicted by most non-linear simulations warns on the caution to extrapolate non-linear degradation curves at large depths, or to use frequency-independent damping in linar equivalent computations.

Deterministic Ground Motions from an Earthquake Simulator Are Consistent With NGA-West2 Ground Motion Models

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We use the deterministic earthquake simulator RSQSim to generate complex sequences of ruptures on fault systems used for hazard assessment. We show that the source motions combined with a wave-propagation code create surface ground motions that fall within the range of epistemic uncertainties for the NGA-West2 set of empirical models. The deterministic physics-based approach provides an opportunity for better understanding the physical origins of ground motions. For example, we find that reduced stress drops in shallow layers lead to peak ground velocities in the near field that better match those from empirical models. The simulators may also provide better extrapolations into regimes that are poorly empirically constrained by data, because physics, rather than data parameterizations, is underlying the extrapolations. Examples include ground motion radiation patterns and directivity for complex multi-fault ruptures, each relevant to modern hazard assessments.

Perfecting Ground Motion Model for Induced Seismicity in Groningen, the Netherlands

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Induced seismicity due to the extraction of gas has been recorded in the Groningen field in the north-east of the Netherlands during the last 30 year. Low magnitude events occur at reservoir level (3 km). An accurate ground motion model (GMM) has been developed in 8 sprints (from version v0 to v7) from 2014 under the guidance of Julian Bommer. GMM v0 and v1 were based on Akkar et al. (2014) with coefficients modified for magnitudes below M4. GMM v2 was rebuild using only local data recorded in the target area. In this version, non-linear site amplification functions were included. GMM v3 and v4 were improved by selecting a deeper reference horizon rock and redoing the wave propagation modelling from source to stations. GMM v5 and v6 had additional improvements leading to the final GMM v7. To include most epistemic uncertainties, GMM v7 has 72 branches. The GMM has PGA, PGV and PSA (to 3 s) components.

The database of local data consists of a 3D structural model, 2 deep wells with Vs profiles, near-surface Vs measurements over most of the area, waveform data for magnitudes to M3.6, a hypocenter list for M+2 events from 2016 and stress drop measurements. For higher magnitude events to M7, finite-difference waveform and Exsim simulations were carried out. The rupture distance definition is used from the GMM v4. Style of faulting was determined by moment tensor analysis.

PGA maps were calculated side by side with each GMM version. To include both induced earthquakes and plausible larger triggered events in the PSHA, a Mmax distribution was proposed. The max PGA value was 43 %g for GMM v0 and was reduced to the value around 12 %g from GMM v4. The activity rate and b-value distribution do not change significantly over the period even though the production of gas has been reduced in previous years. The reduction of the hazard level is due to the admittance of local seismological and geological data and better modelling which improved the accuracy of the GMM for Groningen considerably.

Ground Motion Modeling in Tectonically Active and Complex Geological Region – Israel and the Dead Sea Transform

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The Dead Sea Transform (DST) dominates the seismicity of the Eastern Mediterranean. The slow slip rate, 5 mm/y, results in low seismicity. The Israel seismic catalog (1983-present) includes more than 23,000 events, but only 15 are M > 5, without M > 6 events. The regional, pre-instrumental record spans over 3000 years and includes up to fourteen M > 7 events in the past two millennia. The 105 km motion along the DST forms a series of deep and narrow pull-apart basins, with depths similar to their width, reaching >10 km in the Dead Sea. The sedimentary filling of the basins is mainly low-density and -velocity (V_S < 1200 m/s) sediments, bounded by stiff walls (V_S > 2000 m/s).

The geological structure of Israel exhibits considerable spatial heterogeneity over short scales: deep pull-apart basins along the DST and the Zevulun (ZV), Harod, and Jezreel Valleys along the Carmel fault zone. The vulnerability of ZV, underlain by a deep sedimentary basin, is particularly crucial because of its dense population and high concentration of industrial infrastructure. The Israeli coastal plain is underlain by a westward thickening sedimentary wedge (SW). The majority of Israel's population resides atop the SW in densely populated cities (up to 29,000 people/km^2), with many residential and public buildings built before the implementation of the seismic design code.

Currently, ground motion models in the code are imported from different geological and tectonic settings, e.g., Campbell and Bozorgnia 2008. We study the effects of DST on regional ground motions using forward 3D numerical modeling. We show that ground motions and amplifications atop the sedimentary structures are products of the complex interactions between the inter-basin sources of the DST and the sedimentary structures along the CFZ and SW. We developed ground motions attenuation model (AM) for M 6 and M 7 earthquakes in Israel based on the numerical modeling. The proposed AM bridges the Israel seismic catalog's M > 6 data gap and provides valuable insights for understanding the seismic hazard in Israel.

Empirical Modeling of Site Effects [Poster]

Poster Session • Thursday, 12 October and Friday, 13 October

On the Empirical Assessment of Ground Motions in Sedimentary Basins and Testing Regional Site Response Models across Tectonic Regimes

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We test the hypothesis that site-response models are independent of earthquake source parameters by analyzing ground-motion records in the Portland, Oregon, region. We assess whether empirical site-response models developed for subduction-zone ground-motion models (GMMs), regionalized for the Pacific Northwest (PNW), perform as well as the site-response model developed for crustal earthquakes in California. This study builds upon our previous regional empirical analyses of basin response for the California Great Valley, the Reno-Sparks basins in Nevada, and the Portland-Tualatin basins in Oregon. Those analyses showed that the Boore et al. (2014) and Campbell and Bozorgnia (2014) NGA-West2 GMMs improved predictions of basin response in the California Great Valley but did not perform as well in the shallow Reno-Sparks basins or the more geologically complex Portland-Tualatin basins.

We first analyze basin response by compiling and processing regional ground-motion data and performing residuals analyses and mixed-effects regressions. We build upon the study in Portland by (1) improving V_{S30} characterization of stations that recorded ground motions by using measured V_{S30} values where available or alternative proxy-based V_{S30} prediction models other than topographic slope and (2) computing GMM estimates with both an NGA-Subduction empirical site-response model for the PNW and the site-response model built into the NGA-West2 GMMs for shallow crustal events. If the site-response models are shown to be independent of earthquake source type, we can reduce uncertainty in ground-motion predictions by replacing site-response models in ergodic GMMs with region-specific site-response models developed using a subset of potential earthquake sources. This would result in improved ground-motion estimation in regions within national-scale seismic hazard studies that generally employ global ergodic site-response models at all locations within a tectonic regime.

Site Response and a New Empirical Ground-Motion Prediction Equation for the Korean Peninsula

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Site effects amplify or weaken ground motions propagated to the surface according to site conditions. Because the site effect is unique site-by-site, it complicates the analysis of actual attenuation of ground motions with distance. We estimated the site response function of the surface seismic stations operated in the southern Korean Peninsula. Ambient noise data at each station were used to derive the function based on the horizontal-to-vertical spectral ratio method. To deconvolve the site response from ground motions, we first designed a linear zero-phase finite impulse response (FIR) filter corresponding to the site response function. Then we divided the amplitudes of observed spectra by the frequency response of the FIR filter. Surface ground motions of 75 surface stations for 229 events that occurred around the Korean Peninsula were corrected, and then peak ground accelerations (PGAs) of surface stations and borehole stations were measured. The attenuation pattern of surface PGAs after the correction was changed to be similar to that of borehole PGAs. Ten double-equipped stations, which have two accelerometers at the free surface and specific depths of about 30-60 m, are used for verifying the ground motion correction. The PGA ratios of surface-to-borehole records were approximately 2, except for two stations. This could be attributed to the free-surface effect in ground motions which was not completely removed during the site response correction. We used a ground-motion dataset consisting of corrected surface PGAs and uncorrected borehole PGAs to develop an empirical ground-motion prediction equation (GMPE) for the Korean Peninsula. The nonlinear mixed-effect model was applied in regression analysis for developing a GMPE. Initial values of regression coefficients were chosen from the existing studies, while the pseudo-depth parameter was fixed at 10 km. The regression analysis showed an underestimation of the GMPE in the hypocentral distance range of about 100 and 200 km, which could be caused by constructive interference of the direct waves with Moho reflections.

Stiffness Wave Propagation 1D Numerical Modeling and Experimental Transfer Function Using Cross- and Auto-Power PSD Functions from Earthquakes Recorded in Tri-Axial Accelerometers Vertical Array, and Ambient Vibration Measurements at Ground Surface

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Transfer functions were estimated by means of spectral ratios of cross- and auto-power PSD functions for different depth intervals of the accelerometers vertical array at the CDAO seismic station of Mexico City, and compared with numerical simulations using 1-D wave propagation stiffness matrix method. From their amplitude and frequency distribution the layers geotechnical properties were clearly associated in terms of their individual contribution to the site fundamental vibration frequency. Fundamental vibration frequency is dominated by shallow layers with low shear wave velocities, while high order vibration frequencies are associated due to the deep rigid layers with relative high shear wave velocities. The estimated transfer function using the ground surface ambient vibration measurements provided a better resolution than the traditional spectral ratio methods, and correlated quite well with earthquake records.

Evaluation of the Site Amplification Factors on the Severely Damaged Sites During the 1923 Kanto Earthquake for Delineating the Complex Source Process

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For precise prediction of future megathrust earthquakes along the Philippine Sea Plate in western Japan, it is necessary to understand the source rupture process of the past earthquakes without strong-motion data, which happened before the deployment of strong-motion observation networks as well as those with unsaturated short-period seismograms. For those old earthquakes, we have already performed a parametric study for understanding the source characteristic of the 1944 Tonankai earthquake (M8.0) by using the observed structural damage ratios (SDR) as a substitute for strong-motion seismometers in the heavily-damaged areas (Ito et al., SSA meeting, 2021). We constructed the complex source process based on Sekiguchi and Yoshimi (2011) and Green's function from the fault to the sites obtained from the generalized inversion technique (Nakano et al., BSSA, 2015).

Applying the method described above to the 1923 Kanto Earthquake, with the goal of delineating the source rupture process, we first estimated the site amplification factors in the area severely damaged by the 1923 Kanto Earthquake. To that end, microtremor observations were conducted at the sites with high SDRs to calculate the horizontal-to-vertical spectral ratio of microtremors (MHVR). Then, the EMR method proposed by Kawase et al. (2018) was used to obtain the pseudo horizontal-to-vertical spectral ratio of earthquakes (pEHVR), and the VACF method of Ito et al. (2020) was used to obtain the pseudo site-amplification factors (pHSAF).

As a result, the pHSAF at the site with the greatest SDR had a large amplification near the 1 second, which may explain the occurrence of major structural damage, but the contribution of the source characteristic must also be taken into account. On the other hand, there are several sites where the site amplification factor is small but the SDR is relatively large. At such sites, it is necessary to explain the damage by the local source characteristic.

Five Fundamental Rules for Successful Implementation of Spectral Site Amplification Evaluation

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Despite the efforts of seismologists and earthquake engineers in these one hundred years, we have not yet reached common conclusions on how to quantitatively predict site amplification factors (SAFs) over a broad frequency band of engineering interest, namely 0.1 Hz to 20 Hz, for moderate to strong input from different types of earthquakes in different tectonic settings. However, we found five basic rules useful for successfully modeling ground motions as a common approach to site effect studies. First, we introduce various emerging techniques for broadband quantitative evaluations of SAF based on the vast amount of observed ground motions, primarily from dense Japanese strong-motion networks. Based on the findings of our investigation and the physical relationships behind the parameters, we would like to recommend that researchers on the quantitative evaluation of SAFs and related topics would refer to the following five basic rules for the successful implementation of SAF evaluation in a specific region of interest, namely, 1) Use Fourier spectra, not response spectra, because only the former gives us a direct connection with the physical process behind; 2) Use the seismological bedrock outcrop as a reference, rather than just a hard-rock outcrop, because the only former shows no site effects; 3) Use the observed spectra or their ratios in the target frequency range, rather than their scalar proxies such as Vs30 or Z1.0, because we will loose important information in the extraction process; 4) Use relative ratios between strong motion and weak motion, rather than strong motion spectra directly in nonlinearity evaluations, because nonlinearity is the phenomena of deviation from the linear response; 5) Use extracted outcrop motions or spectra, rather than the borehole motions or spectra directly as a reference, because of cancellation effects of downgoing waves and amplification effects below the borehole sensors.

Development of Taiwan Generic Rock Seismic Velocity Profile

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Based on the concept of evaluating site amplification for generic rock sites, a generic rock condition was defined for Taiwan as V_{S30} (time-average S-wave velocity of top 30 m strata from the surface) = 754 m/s. The measured V_S profiles from PS-logging at strong motion stations with V_{S30} between 610 m/s and 930 m/s were selected to develop the shallow part of the profile. The velocity profiles obtained from multiple existing geophysical studies were then used to extend the V_S profile to seismic bedrock and construct a generic rock V_S model for Taiwan. A corresponding generic rock P-wave velocity (V_P) profile was also developed using V_P from PS-logging measurements and an empirical relationship between V_P and V_S. The proposed Taiwan Generic Rock (TWGR) velocity model has V_{S30} of 754 m/s, $Z_{1.0}$ (thickness of sediments with V_S < 1.0 km/s) of 29 m, $Z_{2.5}$ (thickness of sediments with V_S < 2.5 km/s) of 2.1 km, and $_0$ (spectral decay slop) of 0.052 sec. The V_S values of the TWGR profile at depths of 50 m - 8 km are smaller than from the generic rock profile with V_{S30} = 760 m/s for California, which may lead to very different site responses between Taiwan and California soft rock sites.

Site Database for the Strong Motion Stations of NCREE in Taiwan

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The site database for the free-field TSMIP (Taiwan Strong Motion Instrumentation Program) has been renewed by Kuo et al. (2017). The database is generally applied to seismology and earthquake engineering studies in Taiwan. However, the National Center for Research on Earthquake Engineering (NCREE) also operates two strong motion networks all over Taiwan Island. They are the Seismic Array of NCREE in Taiwan (SANTA; http://santa.ncree.org) and NCREE Earthquake Early Warning System (NCREE EEWS). The SANTA is a multipurpose seismograph network with 37 seismograph stations to support the research both on seismology and earthquake engineering. Most SANTA stations consist of a strong-motion accelerometer and a broadband seismometer installed at the same site. The NCREE EEWS contains about 100 strong-motion stations installed in schools around Taiwan to provide nearby schools with on-site earthquake early warning service. Because the two networks also provide high-quality real-time strong motion records for analyzing the ground motion characteristics of earthquakes in Taiwan, it is essential to construct the site database for the stations of the two networks. This study collected the historical earthquake and the microtremor records of the stations to estimate the site parameters, including the V_{s30}, $Z_{1.0}$, κ_0, and F_0, by various analyses. The estimated site parameters are compared and discussed with that of the TSMIP to evaluate the site characteristics of Taiwan. It is proved that the comprehensive site parameters of the TSMIP and NCREE stations would be reliable for the studies of strong motion prediction and simulation, and site effect evaluation, etc in Taiwan.

Estimation of Kappa Within a Low Seismicity Region in Northern New Mexico

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Traditional methods to estimate the high-frequency attenuation parameter Kappa generally rely on the abundance of well-recorded, large-magnitude earthquakes (greater than 3.5) to estimate the decay of spectra beyond the source corner frequency. However, seismic hazards also pose a risk to facilities in regions with low historic seismicity, necessitating approaches that can be adapted to lower-magnitude earthquakes where corner frequency and attenuation effects are often convolved. Here, we present ongoing progress in our work to estimate Kappa at different sites located along the margin of the Rio Grande Rift in Northern New Mexico. The region is historically characterized by low seismicity, but evidence suggest larger surface-rupture events have occurred in the past. Using data recorded by the Los Alamos Seismic Network, we apply previously used methods that have been shown successful in estimating Kappa for low magnitude earthquakes and seek to test new approaches that leverage borehole seismometers and methods previously applied to estimate stress drop.

Velocity Structure Identification and Site Amplification Estimation at Rock Sites in Japan

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Site amplification factor (SAF) is a crucial parameter for ground motion estimation. It has been investigated especially for sediment sites because sediment sites are critical from the viewpoint of disaster prevention and amplifying ground motions more than rock sites. SAF at rock sites is small, and it is difficult to estimate SAF from observed motions such as microtremors due to weak fluctuations of SAF at rock sites. However, SAF at rock sites also has an impact on ground motions and should be investigated as quantitatively as those at sediment sites.

We investigated velocity structures and SAFs at 7 sites in Japan, which were located in mountainous area or close to the edge of basin and considered as rock sites from borehole data, using Diffuse Field Concept for earthquake (Kawase et al., 2011). We first calculated Horizontal-to-Vertical spectral ratio of earthquake (EHVR). Earthquakes with epicentrtal distance < 200 km, PGA < 50 Gal to avoid nonlinearity of SAF, and MJMA > 5 to get high signal-to-noise ratio in the low frequency range were selected. Waveforms of 40 seconds after S-wave arrival were retrieved, transformed to the frequency domain, and smoothed by the Parzen window of 0.1 Hz band width. Geometrical means of EHVR were finally obtained. EHVRs at the sites located in mountainous area were generally flat but had small peaks in the low and high frequency ranges. The EHVRs were inverted to estimate the subsurface velocity structures lying on the seismic bedrock and the SAFs from the seismic bedrock to the ground surface based on DFCe. SAFs inverted from the EHVRs with the generally flat shape have small peaks at the frequencies corresponding to the peaks of EHVRs. This results indicate the importance of considering SAFs not only at sediment sites but also at rock sites.

Evaluation of the Characteristics of Group Delay Time as a Phase Property and the Whole-Duration to S-wave Spectral Ratio based on Generalized Inversion Technique with Subsequent Application to the Ground Motion Prediction

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For requirements of engineering purpose, we need a method that can predict strong ground motions with sufficient accuracy at any target sites for quantitative evaluation of the hazard and subsequent risk by large earthquakes. However, our knowledge on the source, path, and site factors of the observed strong motions has not been fully utilized.

In this study, at first, we performed the analysis to investigate the properties of these factors mentioned above based on a generalized inversion technique on Fourier spectra of strong motion networks deployed in Japan. We investigated the long period components of site amplification reflected by subsequent potions after S-wave portion as the Whole-duration to S-wave spectral Ratio (WSR). WSR is modeled as the correction function of the site amplification with S-wave converting to the site amplification with full-wave contributions. Next, we tried to model not only spectral amplitude but also phase information in frequency domain, using the group delay time (Tgr) which corresponds to the non-stationary characteristics of ground motions. We introduced these characteristics in this presentation in detail.

Once we obtain statistical properties of the amplitude and group delay time, we can produce ground motions at an arbitrary site from an elemental source at an arbitrary location on the fault surface, which can be used as a Green's function in the statistical Green's function method. We also constructed a procedure for predicting the strong motions considering both the spectral difference between the whole duration of motion and the S-wave portion and the effects of soil nonlinearity.

As a validation exercise, we confirmed that the proposed method can work well for the reproduction of ground motions generated by the 2011 Ibaraki-Oki earthquake, which was the largest aftershock (Mw7.8) of the 2011 Tohoku earthquake sequence. As a result, we obtained waveforms with realistic characteristics in the spectra and envelop shapes.

Geometric Parameters for Seismic Site Response in Sedimentary Basins

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Site response in sedimentary basins is governed by mechanisms associated with three-dimensional features. This includes the generation of propagating surface waves due to trapped (reflected and refracted) seismic waves, focusing of seismic energy due to basin shape and size, and resonance of the entire basin sediment structure. These mechanisms are referred to as basin effects and they lead to a significant increase in the amplitude and duration of the observed ground motions from earthquake events. Currently, ground motion models (GMMs) incorporate basin effects using the time-averaged shear-wave velocity in the upper 30 m ($_{S30}$), and the isosurface depths (depth to a particular shear wave velocity horizon, $_{x}$). This approach captures site response features associated with the basins but uses parameters that are one-dimensional in nature and therefore are limited in their description of the lateral and other three-dimensional (3D) contributing effects. This work explores geometric features as predictive parameters in the development of site-specific models to improve the characterization of site response in sedimentary basins. In this work basin shape is constrained using depth to subsurface geologic formation interfaces associated with the oldest sedimentary deposits (depth to a particular shear wave velocity horizon i.e., $_{1.5}$ and $z_{2.3}$) and depth to crystalline basement (z_{cb}) which are derived and validated using a systematic exploration of geological cross sections and Community Velocity Model (CVM) profiles in the Los Angeles Basin (LAB). Finally geometric parameters such as basin centroid, area of basin, distance from basin margin, and basin eccentricity are computed based on finalized shape. Residual analysis is employed to evaluate these derived geometric parameters for their ability to reduce bias and uncertainty in basin site response analysis.

Classification Algorithms for Sedimentary Basins in Southern California

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Seismic site response is influenced by a variety of physical mechanisms in which amplification due to topography and three-dimensional features from sedimentary basins plays a crucial role. Contributions from sedimentary basins to site response is referred to as basin effects which includes the generation of propagating surface waves due to trapped (reflected and refracted) seismic waves, focusing of seismic energy due to basin shape, and resonance of the entire basin sediment structure. Current ground motion models (GMMs) consider basin effects in their estimates of ground motion hazard but this requires an indication of if the location of interest is within or outside a basin. This is relatively straightforward for a few sites but non-trivial for a regional study. As such, there is a need to systematically classify sites as basins or non-basin. In this study a quantitative classification algorithm is developed for southern California that estimates the probability of a site residing within a basin. This was accomplished by exploring the relationship between geomorphological features such as elevation, slope, curvature, and surface texture, with unambiguous classifications of basin and non-basin sites using a suite of machine learning methods. Feature engineering analysis involving Principal Component Analysis revealed surface texture as the optimal identifier for the classification model development. Performance analysis unveiled three models as the best classifiers of basin and non-basin sites. These three models are derived from logistic regression, support vector machine, and extreme gradient boosting, and as such their combined estimates capture the epistemic uncertainty associated with varying modeling approaches. The resulting basin/non-basin classification algorithm suite provides probability maps that will serve as a necessary tool for forward application of seismic hazard assessments that incorporates region specific basin effects (i.e., the U.S Geologic Survey National Seismic Hazard Model).

Empirical Functions for Obtaining Horizontal Site Amplification Factors Considering Soil Nonlinearity

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The horizontal-to-vertical spectral ratio of earthquakes ($HVSR_E$) is the ratio of the horizontal Fourier amplitude spectrum (FAS) with respect to the vertical FAS, both on the Earth's surface. In this study, more than 140,000 weak motion recordings with a peak ground acceleration (PGA) of less than 100 cm/s^2 and more than 5,300 strong motion recordings with a PGA of greater than 100 cm/s^2, which are detected across K-NET and KiK-net, are utilized to calculate $HVSR_E$; the difference between the $HVSR_E$ of weak and strong motions are defined and quantified using a shift both on the frequency and amplitude axes in the logarithmic system. A series of empirical functions, proposed based on the shifts between the $HVSR_E$ of weak and strong motions, can be used to transform the $HVSR_E$ of weak motions into that of strong motions. Subsequently, the vertical amplification correction function (VACF), which is the ratio of vertical FAS on the Earth's surface with respect to the horizontal FAS on the seismological bedrock, is utilized to transform the $HVSR_E$ into the horizontal site amplification factors (HSAF). Herein, the obtained HSAF already considered soil nonlinearity because the abovementioned empirical functions involved the consideration of nonlinear soil behaviors.

Estimation of Subsurface Wavefields from Surface Ground Motion Records: A Method Without Conventional Assumption of Plane-wave Incidence

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Seismic motion or incident wavefield at the subsurface bedrock level is needed to evaluate the response of buildings through the numerical simulation of seismic wave propagation. It is conventional that the subsurface motion is estimated from a seismic record at a free surface position assuming a vertical plane-wave incidence, which means that the vertical and horizontal components of the seismic waves independently propagate as P- and S-waves, respectively. This assumption is theoretically incorrect. In this study we propose a new method to evaluate subsurface wavefields from a surface record without the assumption of plane-wave incidence. Our method exploits the effective source time functions (ESTFs) for P- and S-waves, which are extracted from the surface record, to evaluate the subsurface motion. Our method employs a horizontally layered model including both the station and the source to calculate theoretically separated P- and S-wave portions of the waveforms at the surface and subsurface positions assuming the focal mechanism and impulsive source. At the surface position, we deconvolve S-wave part of the observed record with the S-wave synthetic seismogram after synchronizing them by matching the S-wave first arrivals each other to get the S-wave ESTF. P-wave deconvolved waveform is calculated in the similar way of the S-wave one to obtain the P-wave ESTF. Both ESTFs mainly include the actual source time function around 0 sec and the effects due to the difference between the model and real structures. We then apply the special window functions, which depend on the depth of the evaluation point and the wave type, to the ESTFs. We convolve the windowed ESTFs with the synthetic P- and S-wave-portion seismograms to estimate the target motion. By comparing the actual subsurface records observed in boreholes with the estimated ones quantitatively, it is found that our method gives much better estimated waveforms at deeper bed rock level than the conventional one.

Using Multiple HVSR Shape Parameters for Non-Ergodic Site Effects Modeling

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Horizontal-to-vertical spectral ratios (HVSRs) are a widely used on-site technique for assessing site effects without the need for a reference station. HVSRs are commonly summarized by two site parameters: the fundamental frequency (f_{peak}) and its corresponding amplitude (A_{peak}). While HVSRs are generally regarded as providing a reasonable estimation of the fundamental frequency, their amplitudes are less accurate compared to other empirical transfer functions. Conventional ergodic ground-motion models heavily rely on unified site proxies, such as the time-averaged shear-wave velocity in the upper 30 m (V_{S30}) and basin depth, to determine site terms. However, these proxies have been shown to introduce significant uncertainties at specific sites.

In this study, we demonstrate the advantages of utilizing multiple site parameters derived from HVSR data, including frequency, shape, and amplitude information, in non-ergodic ground-motion modeling, which better captures site-to-site variability. Specifically, we compile time series data for a large subset of stations in subduction-zone regions. We establish a comprehensive database of various HVSR shape parameters, such as the number of peaks, peak frequency, peak amplitude, prominence, half-power bandwidth, and interevent variability of significant peaks at each site. To quantify the site effects, we perform mixed-effects regression on residuals from existing ground-motion models for subduction-zone regions. We develop two sets of models: one utilizing only f_{peak}, and the other incorporating multiple HVSR shape parameters. Subsequently, we compare the aleatory variabilities of the two new site-effects models with existing ergodic site-effects models that rely on V_{S30} and basin depth. The primary objective of this research is to enhance the accuracy of site terms in ground motion models by integrating frequency, shape, and amplitude HVSR statistics derived from observed ground motion data.

Overall Prediction Accuracy and Simulation Validation for Real-World Applications [Poster]

Poster Session • Thursday, 12 October and Friday, 13 October

Developing International Standards and Guidelines for Curating, Disseminating and Validating Simulated Earthquake Ground-Motion Data

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We are leading an effort to develop international standards and guidelines for curating, disseminating, and validating simulated ground-motion data. This effort is organized as a working group within the Consortium of Organizations for Strong Motion Observation Systems (COSMOS). In 2022 we held two virtual workshops to gather information about earthquake ground-motion simulation efforts around the world, including validation and dissemination of ground-motion waveforms and metrics for earthquake engineering applications. Key points from the workshops include: (1) numerous groups are generating simulated earthquake ground motions and making them openly available; however, there is very little coordination among groups to provide consistent interfaces for searching and retrieving data; (2) participants advocated for a distributed architecture that would allow institutions to host and manage their own data while broadcasting their metadata to a combined catalog; and (3) validation results should provide a clear, transparent, and quantitative assessment of the simulated ground motions.

We are currently building on ideas from the online workshops and refining our vision for drafting and implementing the international standards and guidelines. We anticipate that the general architecture will be similar to the one used by the International Federation of Digital Seismograph Networks (FDSN), which provides a central catalog of metadata from many data centers that curate datasets. In our case, much of the simulated ground-motion data are archived at high-performance computing centers. The standards will need to specify interfaces for metadata and data access that can adapt to changing capabilities and user needs, including storage schemes, file formats, and validation procedures. We plan to offer guidelines with best practices for curating simulated data that facilitate adoption of the standard interfaces. Additionally, we want to build upon previous validation efforts to expand best practices for validating simulated data to a broad range of engineering applications.

NDSHA Scenario Seismic Hazard Map, Vancouver, B.C. Area – Xeris Methodology

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Neo-Deterministic Seismic Hazard Assessment NDSHA is the new multi-disciplinary scenario- and physics-based approach for the evaluation of seismic hazard and safety—with demonstrated "Overall Prediction Accuracy and Simulation Validation For Real-World Applications". Building upon a long experience of successful practice with DSHA, NDSHA now convolves a comprehensive physical knowledge of: (i) seismic source process; (ii) propagation of earthquake waves; (iii) combined interactions with site conditions—and thus effectively accounts for the tensor nature of earthquake ground motions.

Standard NDSHA, using geological and geophysical data, computationally estimates an envelope of scenario ground-shaking characteristics from both: (1) the largest historically observed earthquake within a region; and (2) also from the Maximum Credible Earthquake MCE. Because each scenario is always "a real earthquake", it therefore does not require considerations of either probabilistic hazard model temporal representations of earthquake "likelihood", or scalar empirical GMPEs.

Some NDSHA applications performed at an international level will be presented, together with some preliminary results for ground shaking scenarios in the Vancouver Island and mainland areas https://www.xeris.it/Methodology/index.html

Earthquakes and Sustainable Infrastructure (Panza et al 2021) presents a new NDSHA paradigm for seismic safety—detailing in one volume the 'state-of-the-art' scientific knowledge on earthquakes and their related seismic risks, and the actions that can be taken to reliably ensure greater safety and sustainability. Thirty chapters of the book provide comprehensive reviews and updates of NDSHA research and applications so far in Africa, America, Asia and Europe—evidences and case histories illustrating the overall prediction accuracy of NDSHA and its robust validation for real-world applications leading to more reliable procedures for seismic hazard assessment evaluations.

Verification and Validation of Physics-Based CyberShake PSHA Simulations

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SCEC's CyberShake platform was designed to utilize earthquake rupture forecasts and ground motions simulated with 3D velocity models to produce low-frequency (0-1 Hz) physics-based probabilistic seismic hazard models. A CyberShake hazard model provides multiple layers of data products including hazard maps, hazard curves, event slip time histories, seismograms, and intensity measures.

In 2022, we began an effort to update the CyberShake modeling codes, develop broadband (0-50 Hz) hazard model capabilities, and calculate a broadband hazard model for southern California. This included updating the CyberShake platform with stochastic broadband modules, a refined velocity model to reduce high-velocity sub-surface Vs values outside of defined basins, and an improved rupture generation process to reduce shallow slip rates, reduce correlation of temporal rupture parameters with slip, and sample variability in average rupture speed. Throughout this process, we performed verification and validation testing to ensure the usefulness of CyberShake PSHA models to the broader community. Some tests used the CyberShake platform to simulate a collection of historic California earthquakes and compare 3D CyberShake results to both 1D SCEC Broadband Platform results and to ground motion observations for these earthquakes. We also performed additional tests in which we compared CyberShake platform results with standard ground motion model estimates, considering regional and site-specific hazards, median ground motions, ground motion variability, and residuals.

After performing these tests, we initiated a broadband CyberShake simulation campaign, Study 22.12, for 335 sites in Southern California that was completed in April 2023. In this talk, we will describe the verification and validation tests and results used to prepare for CyberShake Study 22.12, present the resulting CyberShake 22.12 hazard models, and discuss more generally the challenges in performing verification and validation for physics-based PSHA moving forward.

Potential Strong Ground Motions and Seismic Hazards in Seoul, South Korea

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There is public concern about possible occurrence of devastating earthquakes in Seoul, the capital city of South Korea, where historical seismic damage was reported. Strike-slip earthquakes with NNE-SSW fault-plane orientations dominantly occur in Seoul, clustering in the northwestern region. Microearthquakes occur episodically near the Chugaryeong fault system that runs across Seoul in a N-S direction. Seismic damages are recorded in historical literatures. The historical seismic damage is reproduced by numerical modeling of strong ground motions of earthquakes in Seoul, confirming the occurrence of historical earthquakes. The seismicity distributions, focal mechanism solutions, surface geology, topography, and seismic and geophysical properties suggest the possible presence of earthquake-spawning blind faults in Seoul. We consider scenario earthquakes for assessment of seismic hazard potentials in Seoul. We conduct numerical modeling of strong ground motions for a Mw5.4 earthquake at a depth of 7 km, which corresponds to a plausible event in Seoul. We observe the peak ground accelerations to reach ~11 m/s^2. The seismic damage by a moderate-size earthquake may be high in most areas of Seoul, particularly along the Han River that is covered by alluvium. The information may be useful for prevention of seismic damages by a plausible earthquake in Seoul.

Influence of Site Effect in Evaluation of Near-fault Velocity Pulses Simulated by a Stochastic Finite-fault Derived Method - Validation Cases from Recent Worldwide Large Earthquakes

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We developed a stochastic finite-fault derived method to evaluate near-fault velocity pulses (VP). The proposed method was validated by near-fault observations in recent worldwide large earthquakes (Huang et al., 2022) such as 2016 Kumamoto, Japan, 2022 Taitung, Taiwan, and 2023 Turkey earthquakes. The extracted VPs for validation cases were based on Shahi and Baker (2014)'s method. When localized source and path effects of each region and an empirical transfer function (ETF, Huang et al., 2017) based method which represents linear site response were used, and a moving asperity model was applied. The proposed procedure derived on stochastic finite-fault ground motion simulation technique were proved to have good ability to predict pulse periods Tp and main portion of VP in velocity time history. Although the restriction of the stochastic point-source simulation technique in predicting acceleration time history is clear due to the random phase. Good agreements in velocity time history for the validated cases suggests that near-fault VPs are mainly controlled by the locations of asperities and the hypocenter on the fault from the finite-fault procedure but are not sensitive to random phase of each point-source simulations. In addition, as reported by Rodriguez-Marek and Bray (2006), local site response will influence Tp calculations, in particular in shorter period (i.e., shorter than 2.5 s) from the results of synthetic ground motions. In this study, because ETFs were adopted as a representative of linear site response of each station and have good agreement between simulated and observed VPs. Several simulated ground motions without applied on-site ETFs as evaluation cases in rock site condition are made to compare simulated Tp and peak ground velocities (PGVs) between rock and soil site conditions. The results indicated that PGVs are significant influenced by local site response and Tp will shift in some of the evaluation cases. These sensitivity testes than highlight the importance of site response when considering near-fault VPs in the future.

Investigating Ground Motion Bias in Finite-fault Simulations of Moderate Magnitude Earthquakes in Southern California

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Simulation-based platforms have become a valuable tool for predicting earthquake ground motion intensities especially in data-limited regions. Recent studies utilizing simulations to examine potential ground motions from significant historical or anticipated earthquakes include the 1886 Charleston and 1906 San Francisco earthquakes, and the HayWired and Great Southern California ShakeOut scenarios. Simulated ground motions use advanced computational platforms that can include sophisticated representations of fault slip distributions, crustal structure, and near surface geological features. However, the information available to constrain those model inputs are limited, and thus the computed ground motions have large uncertainties. Hence, for a given set of input parameter selection protocols, it is essential to validate outputs against observations. One approach for validating simulated ground motions is to conduct simulations for events with ample recordings, examine any discrepancies, and refine the simulation models to eliminate biases. Our study builds on work of Nweke et al. (2020) who found a significant positive bias in long-period (T>1s) ground motion levels for finite-fault simulations of moderate magnitude (Mw 4-5) events in the Los Angeles region. Initially, simulations were done for 13 events using standard magnitude-rupture area scaling model, which we have now expanded to 27 well-recorded events. Preliminary findings suggest that the observed bias is primarily due to the magnitude-area scaling. Adjustments to the source attributes are currently being made on an event-by-event basis to reduce the bias. The research aims to enhance simulation methodology and improve the accuracy of ground motion estimation for moderate and large earthquakes, thereby bolstering confidence in the application of simulations for high impact scenarios.

Short Period Full Waveform Inversion for Seismic Hazard Analysis in the Aegean

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We present a Full seismic Waveform Inversion (FWI) model of the Aegean region in the context of exploring numerical simulations for seismic hazard assessment. Greece and Western Turkey are subject to intense seismic activity, due to the extrusion of the Anatolian plate, primarily accommodated by the North and East Anatolian Fault Zones. Considering the geological context and the vicinity of large cities such as Istanbul, Izmir and Athens, the Aegean region presents a large seismic risk.

Using the latest FWI developments and high-performance computing, we model and fit waveforms at this regional scale (on the order of 1000 km) at periods down to 5 s. These 'short periods' are sensitive to small-scale structure and will allow us to build high-resolution FWI models. However, for seismic hazard assessment, the estimation of ground motion parameters such as peak ground acceleration (PGA), peak ground velocity (PGV), or spectral acceleration (SA), require simulations with a significantly shorter minimum period (~ 0.1 s) than our FWI model. It is therefore challenging to assess how uncertainties in the FWI model affect synthetic ground motion parameters at shorter periods.

Our objective is to study the effect of unresolvable small-scale structures on physics-based ground motion estimates at shorter periods. To this end, we aim to quantify the sub-resolution uncertainties by generating multiple data-consistent models of the Aegean region and to study the impact of these uncertainties on synthetic earthquake ground motion modeling.To generate this ensemble of models, we use Hamiltonian Nullspace Shuttling to perturb an FWI output without compromising the fit to the longer-period data (> 5s). Since forward simulations are significantly less expensive than inversions, we can afford wave propagation simulation at short periods for alternative models to obtain uncertainties on ground motion parameters.

Comprehensive Validation of Physics-Based Ground Motion Simulations in New Zealand Using Historical Data

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Studies validating physics-based ground motion simulations in New Zealand using historical ground motion data have been numerous over the last decade. Through comparison of observed and predicted ground motion intensity measures, the performance of simulations were assessed to understand their biases and uncertainty in a New Zealand context. Detailed analyses of the results highlighted the strengths and limitations of the simulations, and informed aspects where improvements can be made.

Initial efforts focussed on the 2010 Mw 7.1 Darfield, 2011 Mw 6.2 Christchurch and 2016 Mw 7.8 Kaikoura earthquakes due to their engineering significance. Comparisons between prediction and observation were on an individual scenario basis and the simulations showed promise relative to empirical ground motion models.

Subsequent focus shifted to small Mw earthquakes (3.5 - 5.0) as larger ground motion datasets were available and the simpler point source rupture models allowed for a greater focus on wave propagation path and linear site response aspects. This provided an opportunity to partition the intensity measure residuals and assess systematic biases and trends. California-based parametrizations were adopted for crustal earthquakes while subduction parametrizations were specifically developed for the NZ tectonic environment. Though biases remained and standard deviations were similar to empirical ground motion models, improvements were made to increase ground motion duration, advance crustal velocity modelling and modify empirical site amplification. Region-specific trends were highlighted in both systematic site-to-site and between-event residuals which indicated the need to improve regional input models like Vs30 and adopt regionally-varying stress parameter.

Ongoing validation of moderate Mw earthquakes (5 - 6.6) seeks to bridge the gap between past studies. However, additional challenges are present in modelling kinematic ruptures as finite faults from widely available source descriptions (i.e. centroid moment tensor solutions) in the absence of rigorously inverted finite fault models.

Aleatory Variability and Epistemic Uncertainty for Real-world Application of Ground-Motion Simulations in Physics-Based PSHA

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As numerical simulations gain wider use in developing Ground-Motion Models (GMMs) used in PSHA, the aleatory and epistemic components need to be quantified. Currently, there is confusion regarding classifications of aleatory and epistemic components in numerical simulations. We provide a clarifying framework of aleatory variability about the median, epistemic uncertainty of the median, and epistemic uncertainty of the aleatory variability for GMMs based on numerical simulations. Aleatory variability is variability of ground-motion due to unmodeled effects in the simulations (model aleatory) or variability of simulated ground-motion due to variable source inputs that are not modeled in the source characterization (parametric aleatory). An example of an unmodeled effect would be use of a 1-D velocity structure. This leads to an inability of the simulations to capture the full 3-D path effects. An example of a parametric aleatory variability is variability in the ground-motion due to alternative slip distributions that are inputs to the simulations but not part of the source characterization used in the PSHA. Epistemic uncertainty is scientific uncertainty in the simulation methodology and scientific uncertainty in the inputs to the methodology. An example of the first part would be the use of different numerical methods (model epistemic). For the second part, an example includes the different probability density function distributions of input parameters, in the form of the median and standard deviation a slip distribution (parametric epistemic epistemic). For these two parts, these can both be epistemic uncertainty of the median and epistemic uncertainty of the aleatory variability. For model components, ground-motion estimates using optimized input parameters are compared to observed ground-motions. For parametric components, forward realizations are generated from samples of defined distributions. We provide classifications for aleatory variability and epistemic uncertainty for a complete set of example calculations relevant to standard simulation modeling.

Realistic 3D Simulations and Ground Motion Prediction in the Offshore Area near Crotone, Ionian Calabria

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Ground motion prediction is crucial for seismic hazard assessment. While empirical equations may fail to capture the complexity of ground shaking, full waveform modeling in 3D media is increasingly utilized. We present our workflow for realistic simulations of 3D seismic shaking scenarios, focusing on the offshore area near Crotone, along the Ionian Calabria (Southern Italy).

We start by collecting all available geological and geophysical data for the region.

We analyzed multichannel 2D and high-quality 3D seismic data, morpho-bathymetric data, instrumental seismicity, and wells data, to characterize both shallow and deep tectonic features and active faults in this sector of the Calabrian accretionary prism. We then built a 3D geological and velocity model at crustal scale, as a comprehensive understanding of the geometry of major discontinuities and velocities is essential to accurately model wave propagation.

Finally, we proceed with the shaking simulation associated with the identified faults.

We implement our model in the spectral-element code SPECFEM3D_Cartesian to reconstruct the waveforms up to 1 Hz. We combine these low-frequency signals with high-frequency seismograms generated by a stochastic method, following the hybrid broadband approach by Graves and Pitarka (2010).

The model accuracy is checked by simulating real earthquakes and comparing the synthetics with recorded data. Furthermore, we also test a local tomography model and a European crust model (Molinari & Morelli, 2010). Additionally, we compute the ground shaking that would occur if some of the identified larger faults were to slip completely. The ground motion maps derived from the broadband simulations are compared with empirical ShakeMaps, using a new VS30 map that covers the offshore area.

Advancements in 3D Seismic Wave Propagation Simulations of Scenario Earthquakes in Southwest British Columbia

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Physics-based earthquake ground motion prediction in southwest British Columbia (SW BC) is challenging due to the active and complex Cascadia seismotectonic setting and resulting three earthquake source types (crustal, inslab, interface), and the great variability in regional seismic velocities (unconsolidated sediments to glaciated igneous plutonic rocks), their associated depth scales (rock at a max. depth of 800 m), and their associated (sub)surface elevations (Fraser River delta basin within the Late-Cretaceous Georgia sedimentary rock basin, Coast Mountains of > 1000 m elevation). We present our multi-year research efforts towards advancing physics-based earthquake ground motion prediction in SW BC. We have found significant variability in amplification throughout Greater Vancouver due to rupture characteristics and location of large, shallow crustal earthquakes, and that peak ground velocity increases with topography for most crustal scenario simulations with frequencies ≤ 2 Hz, particularly at mountainous sites. Examination of low-frequency (≤ 1 Hz) synthetics for a suite of magnitude (M) 7 crustal scenarios of the Leech River Valley fault zone (LRVFZ) demonstrates that ground motions vary between 1 cm/s (weak) and 25 cm/s (very strong). For Victoria, the highest motions are generated by an eastward-rupturing M7 LRVFZ earthquake where the maximum slip is at a shallow ~10 km depth near the city. We have also found that the average Georgia basin amplification factors from the suite of 30 M9 project's Cascadia interface scenarios are as high as 2.2 (basin-edge reference) and 6.3 (outside-basin reference) at 2 s. We have achieved the capacity to generate region-specific suites of ground motions to improve reliability of seismic hazard prediction in SW BC and incorporate outcomes from physics-based simulations into region-specific hazard mapping in parallel with efforts in communicating state-of-the-art physics-based simulations to the Canadian earthquake engineering community.

Machine Learning Based Estimator for Ground Shaking Maps

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Large earthquakes are among the most destructive natural phenomena. Fast estimation of the ground shaking intensities is a crucial task for impact assessment after a large earthquake occurs.

The Machine Learning Estimator for Ground Shaking Maps (MLESmap) is proposed as a novel methodology that exploits the predictive power of Machine-Learning (ML) algorithms fed by high-quality physics-based seismic scenarios. MLESmap aims at providing ground intensity measures a few seconds after a large earthquake occurs. The inferred information can produce shaking maps of the ground providing quasi-real-time affectation information to help us explore uncertainties quickly and reliably.

To set up the MLESmap technology, we used ground-motion simulations generated from the CyberShake platform, which is a physics-based Probabilistic Seismic Hazard modeler developed for Southern California, and recently migrated for the first time to South Iceland.

Our approach (i.e. simulate, train, deploy) can help to produce the next generation of ground shake maps, capturing physical information from wave propagation (e.g. directivity, topography, site effects) with evaluation times similar to the empirical Ground Motion Models. In this work, we present the MLESmap methodology applied at two different tectonic regions, the Los Angeles basin, and the Southern Iceland region. Moreover, we demonstrate the validation of the technology with new samples available from records of real events in these regions of interest.

Joint Distribution of Input Source Parameters for Physics-Based Ground Motion Modeling Obtained from Simple Dynamic Cycle Simulations

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Any predictive or hazard-related application of physics-based ground motion models requires the combination of a physics-based simulation method and a probabilistic description of the joint distribution of all model parameters. With increasing number of source parameters, the latter multivariate distributions become increasingly complex and difficult to constrain solely from finite fault inversions of strong motion recordings. In this regard, an expression of the joint distribution of source parameters is computed from earthquake rupture sequences simulated with a physics-based seismic cycle model. This model utilizes basic knowledge on the coupling of rupture and recurrence processes to provide additional constraints in the derivation of suitable source properties. The resulting distributions $f(Y_{rup} \mid X_{rec},\theta)$ provide a joint description of source-specific kinematic rupture properties Y_{rup} (e.g. slip, T_{rise} and $V_{rupture}$) for a given set of recurrence or scaling properties X_{rec} and fault geometry θ. The natural variability of simulated rupture properties, arising from differing initial stress conditions throughout the seismic cycle, further informs on the aleatoric parametric uncertainty. The above concepts are presented for a two-dimensional fault description of the Parkfield section on the San Andreas fault, using a simple dynamic cycle model with rate-and-state friction. The joint distributions of source parameters obtained from local expressions of X_{rec} are compared with those obtained from generic recurrence and scaling properties. Finally, the description of parametric uncertainty at Parkfield is discussed in relation to the explicit treatment of uncertainties within predictive applications and with respect to advanced validation studies that assess both mean and variance of simulated and observed strong ground motions.

Physics-Based Broadband Ground Motion Simulations of M6.5 Scenario Earthquakes in Central and Eastern US, Including Surface Topography: Ground Motion Variability Related to Earthquake Rupture Characteristics

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We have developed a computationally efficient simulation platform that can provide representative synthetic ground motions from crustal earthquakes in the Stable Continental Regions of Central and Eastern US (CEUS), using 3D modeling and high-performance computing. The main objective is to use synthetic ground motion to provide constrains to refinements of existing ergodic Ground Motion Models (GMMs), for large magnitude earthquakes and near-fault distances, for which these models are less reliable. We used physics-based broadband (0-5Hz) ground motion simulations to estimate the near-fault ground motion amplitude and within event and between-event variabilities associated with fault rupture characteristics. First, as part of a strategy for selecting a regional velocity model, we simulated ground motion from two recorded small magnitude earthquakes. The successful simulations of both earthquakes demonstrated the reliability of our deterministic simulation approach while emphasizing the importance of including small-scale variability in the regional velocity model. Additional validation analysis, based on comparisons with different GMMs for CEUS region and for a Mw6.5 earthquake, resulted in a very good match between the simulated and empirical ground motion models.

Our initial investigation of within-event and between-event ground motion variabilities for M6.5 scenario earthquakes on a strike-slip fault, suggests that they are strongly related to spatial slip and slip rate variations, average rupture velocity, rupture area and rupture initiation location. Regardless of the rupture scenario, the simulated ground motions tend to fully saturate at short distances and for all periods. The near-fault saturation has to do with the attenuation of waves propagating along the fault and local rupture radiation pattern that also contribute to stronger ground motion variation at such distances. Analysis of the effects of rupture initiation location suggest that the ground motion PGV and SA can be quite variable due to rupture directivity effects.

Physics-Based Probabilistic Seismic Hazard Analysis of Mumbai City, India

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Traditionally, hazard analysis for data deficit regions such as India is conducted using Ground Motion Models (GMMs) derived for other regions, in a logic tree framework. However, these foreign GMMs cannot depict the non-ergodicity associated with station-to-station and inter-site variabilities of the local region. On the other hand, derivation of such non-ergodic models for data-deficit regions is not practical due to sparse local data. Therefore, an alternative method involving Probabilistic Seismic Hazard Analysis (PSHA) using ground motions simulated from a physics-based method is desirable. In this study, numerical simulations are performed to generate seismic ground motions in a spectral finite element domain, with possible rupture scenarios generated from an established random slip model. The output of the Physics Based Simulations (PBS) thus obtained is then integrated with high frequency simulations derived from a stochastic model in the same domain to generate a broad frequency range of ground motions. The uniform hazard response spectra thus obtained from PBS-PSHA of Mumbai city are then compared with the traditional PSHA results.

Instant Physics-Based Ground Motion Time Series Using Reduced-order Modeling of 3D Wave Propagation Simulations

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Physics-based ground motion estimates obtained by numerical simulation of wave propagation are increasingly being considered for seismic hazard assessment. However, this approach is computationally expensive especially when considering ensembles of earthquake sources. We investigate reduced-order modeling (ROM) for obtaining synthetic seismograms that could be used for on-demand simulation of seismic wave propagation and ground motion prediction. To generate the data that inform our ROM, we perform 2D and 3D wave propagation simulations using SPECFEM2D and SeisSol, respectively, for velocity models with heterogeneous elastic media and varying earthquake source locations. We build the ROM using radial basis function interpolation combined with proper orthogonal decomposition and examine the time-domain and frequency-domain errors for modeling ≤ 1.0 Hz elastic wave propagation for earthquake sources in a 30,000 km^3 volume. Due to the high computational cost of the simulations, we explore multiple sampling strategies of the source locations to develop a high-accuracy ROM for a fixed computational budget. We compare uniform sampling, depth-aware, velocity-aware, and an adaptive sampling approach using a Voronoi neighborhood algorithm. We find that the accuracy of the ROM can be controlled by the number of forward simulations, and we find the number of simulations required to achieve a user-specified tolerance. We also quantify the change in error when we vary the simulation domain size, the highest resolved frequency, and the lowest S-wave speed considered in the velocity model. We highlight that once constructed, the ROMs can be made easily accessible to the community to enable instant computation of ground motion time series. For the Los Angeles region where high resolution community velocity models are available, we present a ROM based on the CVM-H velocity model that accurately matches simulated seismograms.

Adjusting Cascadia Ground Motion Models based on M9 Cascadia Earthquake Simulations

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Seismic hazard in the Cascadia Subduction Zone (CSZ) is in part due to the potential for a future megathrust earthquake. However, no instrumental recordings are available to evaluate subduction zone earthquake ground motion models for such a scenario. Therefore, we evaluate the behavior of the "M9 Project" simulated ground motions, including the estimated basin effects for the Seattle basin (Frankel et al., 2018). The M9 Project amplification factors of 2-5 for reference basin depths of 3-5 km at periods of 1.5-10 s in the Seattle basin are higher than the empirically derived basin terms for Cascadia for two of the NGA-Subduction GMMs (KBCG20 and PSBAH20). This suggests a need for simulation-based basin-depth scaling that can be incorporated into empirical ground motion models to account for the high epistemic uncertainty in basin amplification in this region. We expand the methodology used to develop the M9 basin-depth scaling model presented in Sung and Abrahamson (2022) to the other two NGA-Subduction Cascadia GMMs and consider the effect of the functions chosen to represent the Vs_{30}-$Z_{2.5}$ correlation in the GMMs. We also evaluate the effect of incorporating site-specific Vs_{30} into the residuals. We propose an M9 adjustment factor for Cascadia interface events based on the difference in the source term between the simulations and the empirical GMMs (C_{sim}). This centering adjustment is meant to apply to all sites in Cascadia, whereas the basin-depth scaling only applies for sites located on sedimentary basins. We compare the C_{sim} adjustment to alternative ways of adjusting the empirical GMMs to the simulation results, such as using the bias. These adjustments, in general, lead to higher ground motions when used in hazard applications and are one way to incorporate physics-based simulation results into empirical GMMs.

A Framework for Incorporating 3D Simulation Data into Non-ergodic Ground Motion Models

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We present a framework for incorporating results from 3D simulations into non-ergodic ground-motion models (NGMMs) that can be used in seismic hazard calculations and show results from two recent examples of incorporating results of 3D simulations into NGMMs for long-periods from the M9 project and CyberShake. The M9 simulations are for multiple realizations of a single scenario, whereas the CyberShake simulations are for a large number of different scenarios. The framework requires four modifications to ergodic GMMs to incorporate 3D simulation results: (1) modify the average basin scaling to be consistent the average basin scaling from 3D simulations; (2) use the varying coefficient model (VCM) to estimate the spatial distribution of the non-ergodic adjustment for the path and site effects in the region covered by the 3D velocity model; (3) reduce the aleatory variability to account for the more accurate modeling of site and path effects from the 3D simulations; and (4) estimate the epistemic uncertainty for non-ergodic terms. The currently available simulations can be used to address the first three items, but not the full epistemic uncertainty in non-ergodic terms. The epistemic uncertainty is due to the uncertainty in the 3D velocity model; however, 3D simulation results from multiple alternative 3D velocity models are not available. We know that the uncertainty is not zero, but without suites of 3D velocity structure to sample the uncertainty, we currently assume that the epistemic uncertainty due to the 3D velocity model is one-half of the standard deviation of the path+site terms as a reasonable value. An alternative would be to use comparisons of simulations with observe values as a proxy for uncertainty in the 3D velocity model. The proposed approach can also be used with empirical ground-motion data, which would allow a comparison of non-ergodic terms from simulations with non-ergodic terms from observed data. We expect that hybrid GMMs based on the combination of simulation data and empirical data will be the direction of future NGMM development.

Some Views on the Physics Based Ground Motion Synthesis

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The main future direction of ground motion modeling must be the physics-based motion synthesis, since strong motion mostly interested for engineering seismic fortification must from large earthquake and in near fault field, thus governed by the source mechanism. The ground motion prediction equations commonly adopted in seismic hazard assessment are from point source, then could not take into account the near source effect, only if the attenuations in orthogonal four directions are defined. The knowledge on source mechanism up to now is mainly from inversions of past strong quakes, therefore the finite fault source model with just one rupture plane is compatible. The depth and attitude of the plane could be estimated from the fault exploration. The scaling laws of area, width and length of the plane, and the average slip on the rupture plane are available from global statistics in groups of strike or dip slips, and in active crust or subduction zone. The most difficulty is to estimate the slip distribution on the plane, the effort at present should be on the main asperity. The distribution of asperity(s) could be combined with a random slip distribution by two dimensional wave-number spectrum model. The effect of the regional crust structure on the motion is not negligible, so the simple random synthesis approach is just a semi-physics based. The numerical Green function approach is flexible for the complex crust structure, but could not describe the high frequency motion properly, if the size of the discrete elements are not small enough. Analytical Green function is perfect, and could consider the regional crust model with horizontal layered structure, by simplification in frequency-wave number domain. By this method, the rupture velocity and the rise time of rupture time function of each subsource are the two key parameters to be estimated carefully. The ground motion time histories can show the physics-based potential large velocity pulse and the coherence between motions at two locations.

A case of the synthesis is presented in this presentation for illustration.

A Simulation-based Method to Generate Spectrum-matched Ground Motions Considering Spectral Variability

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Ground motions tightly matching the target spectrum are widely adopted in performance-based seismic design. However, a suite of multiple ground motions that sample the realistic spectral variability are also used in the dynamic analysis of structures. This study proposes a novel simulation-based method for generating spectrum-matched ground motions considering their spectral variability. In this method, ground motions at the target site are generated using deterministic broadband numerical simulations considering the source process, propagation path, and local site conditions. A suite of multiple ground motions that averagely match the target spectrum while considering realistic spectral variability are then selected from the simulation results of numerous earthquake scenarios with different source process. Compared with the conventional methods, the spectrum-matched ground motions generated by this method have not only the realistic spectral variability but also the deterministic physical backgrounds. Therefore, this study has great potentials in performance-based seismic design and analysis.

Near Source High-frequency Ground Motions from Physics-Based Dynamic Rupture Simulations

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In this project, we form a modeling group targeting improving methods of simulating earthquake ground motions for seismic hazard applications using dynamic rupture simulations. We aim to determine conditions that make broadband synthetic ground motions more reliable in a broader effort towards supplementing empirical models with simulation-derived information. Each modeler within our group uses their preferred simulation code to generate ruptures across a range of magnitudes and computes the resulting ground motions at a selection of spectral acceleration periods. We focus on near-source distances, where observed ground motion data is lacking, and generate a suite of dynamic rupture simulations at periods relevant to engineering applications. We generate ruptures along strike-slip faults, but we anticipate the approach being extended to other styles of faulting moving forward.

Within this group's study, we evaluate how earthquake rupture characteristics effect the rupture process, and ultimately influence ground motion behavior. The resulting broadband ground motions are pooled and compared with trends of period and distance with leading empirical ground motion models (GMMs). We analyze characteristics from each modeler individually, as well as with reference to the entire group's average synthetic trends, comparing both the synthetic median and ground motion variability terms, isolated in terms of both intra- and inter-event standard deviations. We find that the aggregate level of ground motion for an active tectonic region compares well using GMMs in terms of both distance decay and median ground motion at long and intermediate periods (e.g., 0.3-1 s). We observe that intra-event variability fluctuates widely with distance, resulting from azimuthal changes in ground motion amplification. As part of this work, we have initiated the creation of a synthetic ground motion database, compiling the ground motion metrics generated here into a uniform format, to provide access and straight-forward selection of records from synthetic events.

Comparative Analysis of Physics- and Empirical-Based Ground Motion Predictions: A Case Study of Hanaore Fault in Kyoto, Japan

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Ground motion prediction is vital for seismic hazard assessment. In the field of ground motion prediction, two primary approaches, physics-based and empirical-based ground motion predictions, have been widely employed for different earthquake scenarios. The physics-based approach involves modeling source rupture process and seismic wave propagation, so it requires detailed fault geometry and subsurface soil structure. On the other hand, the empirical-based approach utilizes ground motion models based on regression of observed data to calculate expectative intensity of ground motion for the earthquake. We anticipate combining physics-based and empirical-based ground motion predictions to a novel approach for probabilistic ground motion prediction. By comparing the average and uncertainty of the results from two different prediction methods, it can help to highlight the area with inconsistency based on different approaches. The aim of this study is to evaluate the difference of predicted ground motion intensities by using the two different major approaches in Japan. First, we calculate the ground motion intensities on engineering bedrock based on different approaches and scenarios, then we compare the results of two difference approaches to identify the discrepancy between them. For the physics-based approach, we utilize the earthquake scenario provided by Japan Seismic Hazard Information System and follow the recipe for ground motion prediction published by The Headquarters for Earthquake Research Promotion to simulate seismic waveform. Long-period waveform and short-period waveform are calculated by using 3D finite difference method and stochastic green's function method, respectively. On the other hand, for the empirical approach, we utilize the ground motion model to calculate the seismic intensity. We expect this analysis could provide the preliminary result for the integration of physics-based and empirical-based approaches for more robust probabilistic seismic hazard assessment.

Index of Authors

Aagaard, B. T. 32, 35
Abercrombie, R. 26
Abrahamson, N. A. 17, 22, 33, 37, 39
Adhikari, S. R. 18
Aguar, A. 38
Ahdi, S. K. 32, 35
Ahn, B. 32
Akçiz, S. 13
Akinci, A. 25, 30
Allen, R. M. 20
Allmann, A. 22
Ampuero, J. 15, 40
Arduino, P. 30
Arriola, S. 30
Asano, K. 11
Asimaki, D. 15, 40
Askan, A. 35
Atkinson, G. M. 19
Bae, S. 21
Bagayoko, N. 28
Baise, L. G. 35
Baltay, A. 16, 23, 26, 27
Barall, M. 24
Bard, P. 17, 31
Bayat, F. 13
Beauprêtre, S. 28
Bela, J. 35
Ben-Zion, Y. 36
Besharatinezhad, A. 27, 28
Bindi, D. 18
Blanco, R. 38
Boese, M. 20
Bonilla, L. 15
Boué, P. 28
Boyd, O. S. 32
Bradley, B. 21, 37
Cabas, A. 18, 28
Cabrera, E. 14
Callaghan, S. A. 31, 35, 38
Carpenter, S. 16
Casarotti, E. 11
Chaljub, E. 28
Chao, S. 17, 33, 36
Chatterjee, A. 14
Chavez, M. 14
Chou, Y. 40
Chowdhury, I. N. 28
Chu, S. 26
Cotton, F. 18
Cramer, C. H. 30
Cushing, E. M. 28
Daluger, L. 40
Dehghan Niri, R. 20
de la Puente, J. 38
Delouis, B. 24
De Martin, F. 28
Derras, B. 31
di Giulio, G. 21
Do Couto, D. 28
Doglioni, C. 25
Duan, B. 40
Dunham, A. 21
Dupuis, M. 37
El Khoury, C. 15
Esfahani, R. 18
Ezzedine, S. M. 16
Faenza, L. 37
Farihurst, M. 19
Fichtner, A. 27, 37
Frankel, A. 15, 21, 29
Frid, M. 16
Froment, B. 28
Fujiwara, H. 13
Gabriel, A. 12, 13, 39, 40
Gabrielli, S. 30
Gallovič, F. 24
Gao, K. 18
Gélis, C. 15, 28
Ghofrani, H. 18, 38
Gisselbrecht, L. 28
Goulet, C. A. 11, 30, 31, 36, 40
Graizer, V. 38
Grant, A. 15, 21, 29
Graves, R. 11, 30, 36, 37
Gregor, N. 28
Gutiérrez, C. 30
Haddad, A. 28
Halldorsson, B. 13
Harris, R. A. 24
Hassani, B. 19
Heaton, T. 26
Heo, G. 19
Herrero, A. 23, 25
Hirakawa, E. T. 23
Hirth, G. 14
Hok, S. 15, 24
Hong, T. 36
Hsieh, M. 26
Huang, J. 33, 36
Huerta-López, C. I. 32
Husmann, D. 27
Inoue, N. 23
Irie, K. 12
Irikura, K. 13, 23, 26
Ito, E. 17, 25, 31, 32, 33, 34
Iwaki, A. 13
Iwata, T. 11
Jafarian, Y. 28
Jeong, S. 19, 21
Ji, C. 18
Jin, F. 29
Jo, K. 28
Jomard, H. 15
Jonsson, S. 13
Jordan, T. H. 36
Joshi, L. 28
Kaeser, M. 22
Kaklamanos, J. 28, 35
Kamae, K. 23
Kamai, R. 16
Kang, T. 32
Kase, Y. 12
Kawase, H. 17, 25, 31, 32, 33, 34
K C, S. 36
Keating, S. 37
Khodabandeh, M. 27, 28
Kim, B. 36
Kim, J. 19, 21
Kim, S. 28
Klinger, Y. 13, 24
Komatsu, M. 29
Kottke, A. R. 19, 28, 36
Kowsari, M. 13
Kumamoto, T. 23
Kuo, C. 33, 36
Kurahashi, S. 26
Kwak, D. 19
Lacour, M. 39
Ladage, H. 13
Lancieri, M. 15
Lanteri, A. 37
Larmat, C. 33
Latečki, H. 22
Lavoué, F. 28
Lee, J. 14, 36
Lee, R. 37
Li, B. 13
Li, L. 29
Lin, C. 33, 36
Lin, J. 21
Liou, I. Y. 37
Lipparini, L. 37
Liu, D. 40
Locchi, M. 11
Lozos, J. 13
Lyon-Caen, H. 15
Ma, S. 40
Maechling, P. J. 35
Maeda, T. 13
Mahanama, A. 30
Mai, P. 13, 27
Maier, N. 33
Marcou, S. 20
Margolis, A. 25
Martínez-Cruzado, J. A. 32
Masoudi, M. 28
Matsumoto, Y. 23
Matsushima, S. 15, 34, 40
May, D. A. 39
Mazzieri, I. 22
McCallen, D. B. 19, 20
Melgar, D. 14
Meng, X. 30, 35
Milner, K. R. 31, 36
Miura, H. 17
Miyake, H. 13
Miyakoshi, K. 23, 24
Miyazu, Y. 17
Modesto, D. 38
Modrak, R. T. 18
Moiriat, D. 28
Molinari, I. 21, 22, 37
Molnar, S. 18, 38
Monterrubio Velasco, M. 38
Morel, J. 27
Mori, T. 17
Morikawa, N. 13
Moschetti, M. P. 12, 32, 39
Mosconi, F. 11
Müller, N. 27
Munoz Heinen, L. C. 38
Murphy, S. 23
Nagasaka, Y. 26
Nagashima, F. 25, 32, 33, 34, 40
Nakamura, T. 29
Nakano, K. 17, 32, 34
Nakata, R. 19
Neely, J. S. 27
Nguyen, T. T. D. 29
Noe, S. 27, 37
Nokande, S. 27, 28
Nozu, A. 26
Nweke, C. C. 34, 36
Nye, T. 14
Oh, J. 21
Ojeda, J. 30
Ojo, A. 18
Olsen, K. B. 36
Oral, E. 15, 40
Oshima, M. 34
Panza, G. F. 35
Paolucci, R. 22
Park, S. 27, 36
Parker, G. A. 12, 16, 23, 32, 34
Pienkowska-Cote, M. 37
Pilz, M. 16, 18, 28
Pinilla Ramos, C. 19
Pitarka, A. 13, 19, 20, 25, 38
Podili, B. 39
Razafindrakoto, H. 18
Régnier, J. 31
Rekoske, J. M. 39
Ren, X. 40
Rezaeian, S. 35
Ringrose, P. 20
Roberts, P. M. 33
Rodgers, A. 38
Ruiz, S. 30
Ryu, B. 19
Sahakian, V. J. 14
Saikia, C. K. 18
Salazar, A. 14
Salsabili, M. 18
Sassi, R. 24
Sato, T. 24
Saunders, J. K. 20
Sekiguchi, H. 11
Sgattoni, G. 21, 37
Shams, R. 34
Shaw, B. 31
Shigefuji, M. 12
Shimmoto, S. 27
Silva, F. 31, 36
Smerzini, C. 21, 22
Smith, J. 39
Solomon, M. 18
Somei, K. 23
Spetzler, J. 31
Stabile, T. 25
Stafford, P. J. 38
Stehly, L. 28
Stephenson, W. J. 15, 32
Stewart, J. P. 36
STG, R. 39
Stipčević, J. 22
Stone, I. 15, 21, 29
Stupazzini, M. 22
Su, H. 25
Suárez-Colche, L. E. 32
Sun, J. 17, 25, 31, 32, 33, 34
Sung, C. 17, 39
Taciroglu, E. 30
Takai, N. 12
Takenaka, H. 29, 34
Tao, X. 39
Tao, Z. 39
Telesca, L. 25
Thompson, E. M. 12, 39
Tinti, E. 11
Torita, H. 12
Török, Á. 28
Trugman, D. T. 14
Tsai, V. C. 14
Tsesarsky, M. 31
Tsuda, K. 24
Tvedt, E. 20
Ulrich, T. 13, 40
Valentová, Ľ. 24
Van Herwaarden, D. 37
Vorobiev, O. Y. 16, 29
Wang, J. 40
Wang, X. 40
Wang, Y. 40
Wang, Z. 16, 17, 31, 32, 33, 34
Watanabe, T. 29, 34
Wheatherill, G. 18
Wirth, E. A. 15, 21, 29
Withers, K. B. 23, 40
Yadanar, T. 40
Yan, L. 19
Yong, A. 35
Yoo, H. 32
Yoshida, S. 24
Zaccagnino, D. 25
Zarifi, Z. 20
Zeng, Q. 40
Zhan, W. 35
Zhang, W. 30
Zhang, Y. 35