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Authors
McCallen, David
Tang, Houjun
Wu, Suiwen
et al.

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Coupling of regional geophysics and local soil-structure models in the EQSIM fault-to-structure earthquake simulation framework

David McCallen[1], Houjun Tang[2], Suiwen Wu[3], Eric Eckert[4], Junfei Huang[5], N. Anders Petersson[6]

Abstract

Accurate understanding and quantification of the risk to critical infrastructure posed by future large earthquakes continues to be a very challenging problem. Earthquake phenomena are quite complex and traditional approaches to predicting ground motions for future earthquake events have historically been empirically based whereby measured ground motion data from historical earthquakes are homogenized into a common data set and the ground motions for future postulated earthquakes are probabilistically derived based on the historical observations. This procedure has recognized significant limitations, principally due to the fact that earthquake ground motions tend to be dictated by the particular earthquake fault rupture and geologic conditions at a given site and are thus very site-specific. Historical earthquakes recorded at different locations are often only marginally representative. There has been strong and increasing interest in utilizing large-scale, physics-based regional simulations to advance the ability to accurately predict ground motions and associated infrastructure response. However, the computational requirements for simulations at frequencies of engineering interest have proven a major barrier to employing regional scale simulations. In a U.S. Department of Energy Exascale Computing Initiative project, the EQSIM application development is underway to create a framework for fault-to-structure simulations. This framework is being prepared to exploit emerging exascale platforms in order to overcome computational limitations. This article presents the essential methodology and computational workflow employed in EQSIM to couple regional-scale geophysics models with local soil-structure models to achieve a fully integrated, complete fault-to-structure simulation framework. The computational workflow, accuracy and performance of the coupling methodology are illustrated through example fault-to-structure simulations.

Keywords
Regional scale simulations, code coupling, multi-scale models, interface workflow, Domain Reduction Method

1 Introduction

Earthquake processes are complex starting from the earthquake fault rupture where the earthquake source suddenly releases vast stored energy, continuing with the propagation of seismic waves through the heterogenous earth and finally to the interaction between incident seismic waves and an engineered soil-structure system as illustrated in Figure

[1] Department of Civil and Environmental Engineering, University of Nevada, Reno, Nevada, and Energy Geosciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA (corresponding author)
[2] Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA
[3] Department of Civil and Environmental Engineering, University of Nevada, Reno, Nevada, USA
[4] Energy Geosciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA
[5] Department of Civil and Environmental Engineering, University of Nevada, Reno, Nevada, USA
[6] Center for Applied Scientific Computing, Lawrence Livermore National Laboratory, Livermore, California, USA

1. With the continual advancements in high performance computing, the ability to rigorously simulate the coupled processes between the initiation of fault rupture and the ultimate response of critical infrastructure is becoming increasingly viable. The advent of exascale platforms will provide a major boost to the ability to simulate these processes at regional scales and move the frequency resolution of fault-to-structure simulations into the ~10 Hz range necessary to represent ground motions in the frequency range relevant to a breadth of engineered systems.

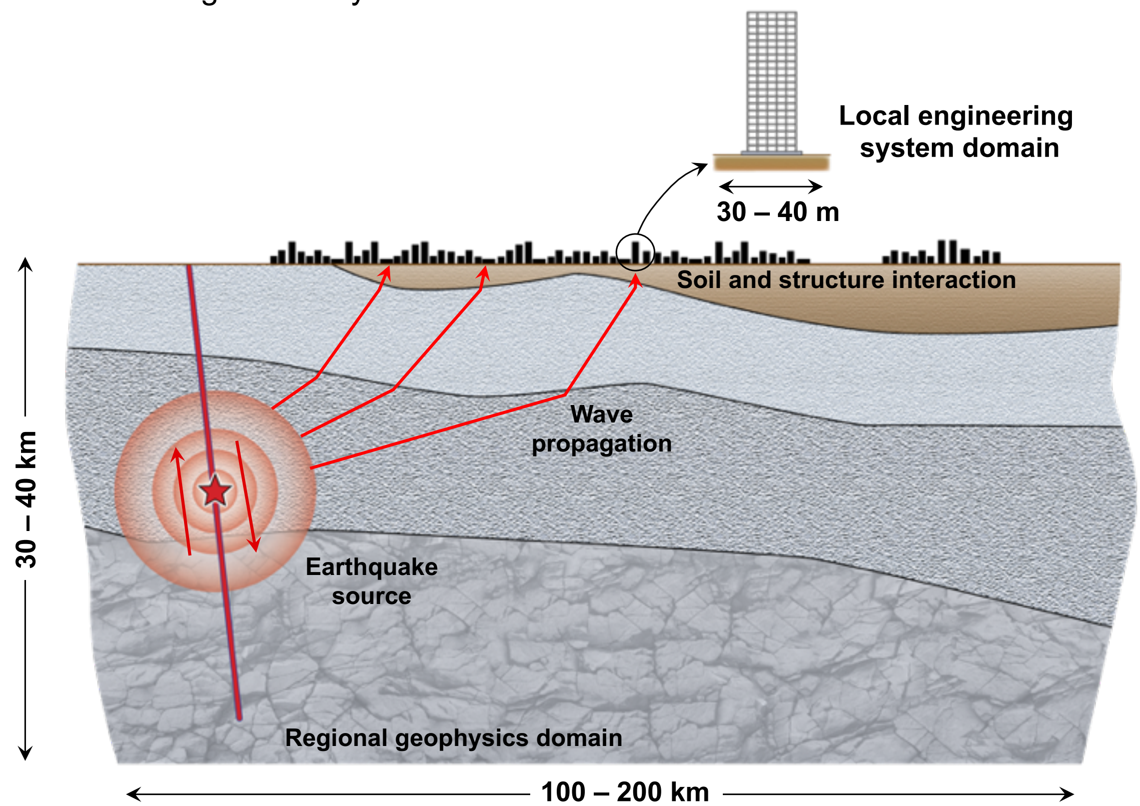

Figure 1. Regional geophysics and local engineering system domains.

The **E**arth**Q**uake **SIM**ulation (EQSIM) exascale application is creating a fault-to-structure simulation workflow to model from initial fault rupture to final structural response (McCallen et. al. 2020a, McCallen et. al. 2020b). This framework is being developed specifically in preparation for GPU-based exascale platforms under development in the DOE Exascale Computing Initiative. The approach taken in EQSIM includes the appropriate coupling between the SW4 (Seismic Waves 4th Order) summation by parts, fourth order, finite difference code for seismic wave propagation (Petersson and Sjogreen 2012, Sjogreen and Petersson, 2012, Petersson and Sjogreen 2015), with implicit nonlinear finite element models of soil-structure systems (McCallen and Larsen, 2003, McKenna et. al., 2010, Jeremic et. al., 2020). Such regional geophysics models allow the representation of the complex spatial variation of earthquake generated ground motions and coupling of geophysics and engineering infrastructure models fully represents the interaction between complex incident seismic waves and infrastructure systems.

The objective of the EQSIM framework is to model ground motions and infrastructure response across entire regions, for example in the San Francisco Bay Area (SFBA) in

California, USA as illustrated in Figure 2. This requires geophysics models representing on the order of 100's of kilometers of the earth with up to 200 - 300 billion grid points, coupled to engineering models of individual facilities on the dimension of 30 - 40 meters (Figure 1) which creates a significant multi-scale computational challenge. This article describes the methodology and workflow for coupling the regional geophysics and local engineering models as developed and implemented in the EQSIM framework.

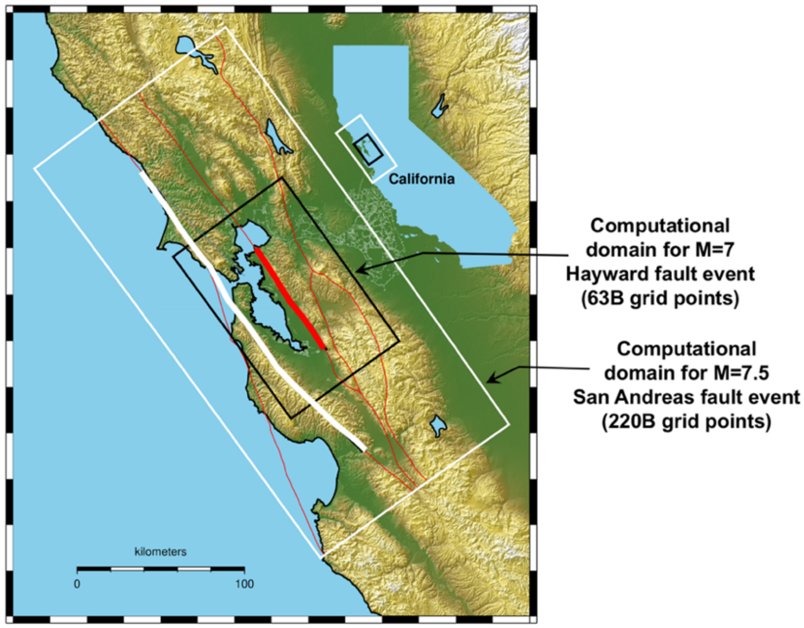

Figure 2. Regional simulation domains for a M7 Hayward fault earthquake where the thick red line shows fault rupture length, and a M7.5 San Andreas fault earthquake where the thick white line shows fault rupture length.

2 Coupling regional and local models

An important element of the EQSIM regional-scale simulations is the ability to rigorously represent the coupling between the regional geophysics model used to represent the three-dimensional wave propagation resulting from a large earthquake and a local model used for simulating the response of a soil-structure system. This includes the ability to account for the complex three-dimensional wavefield consisting of body and surface waves arriving at the location of the soil-structure system. Traditionally engineers have idealized incident seismic wavefields as consisting of pure vertically propagating shear and compressional body waves, which is not explicitly true, and the ability to represent more realistic complex wavefields is an important design feature of EQSIM.

2.1 SW4 geophysics computational grid

The SW4 finite difference program for linear wave propagation utilizes two grid types in the representation of the earth. For the near-surface region of the SW4 domain, a curvilinear grid is used to capture the topography of the earth's surface while at depth an efficient Cartesian grid is employed as shown schematically in Figure 3b. SW4 uses a distributed memory programming model that is implemented with an MPI library, which decomposes the 3D problem domain and assigns the workload to different MPI tasks for parallel computation. As part of the EQSIM project, SW4 has been significantly advanced including: improvements for massively parallel I/O using Hierarchical Data Format (HDF5) data containers (Byna et.al., 2020); implementation of advanced algorithms for mesh refinement in both the curvilinear and Cartesian grids (Wang and Petersson, 2019, Zhang, Wang and Petersson, 2020) in order to optimize simulation grids to the natural variation of geologic properties in the earth as indicated in Figure 3; and preparations for implementation on the pending U.S. Department of Energy exascale GPU-based accelerator platforms. To ensure easy transition and implementation on emerging exascale platforms, RAJA C++ library routines (Beckingsale et. al., 2019) have been implemented around SW4-inner loops. RAJA is a software abstraction that systematically encapsulates platform-specific code to enable applications to be highly portable across diverse hardware with minimal code disruption. For EQSIM, RAJA has been implemented to minimize the coding changes that are needed for multiple emerging new GPU-based hardware architectures.

The recent developments in SW4 have yielded significant improvements in the ability to simulate large regional-scale earthquakes. In the latest EQSIM annual application performance assessments, SW4 demonstrated the ability to simulate a large M7 earthquake in a regional SFBA model to 10 Hz in under 7 hours on the Summit computer at Oak Ridge National Laboratory (https://www.olcf.ornl.gov/summit/) as summarized in Table 1. This is a major advancement beyond previous regional scale simulations performed by a number of research groups at significantly lower frequency resolutions.

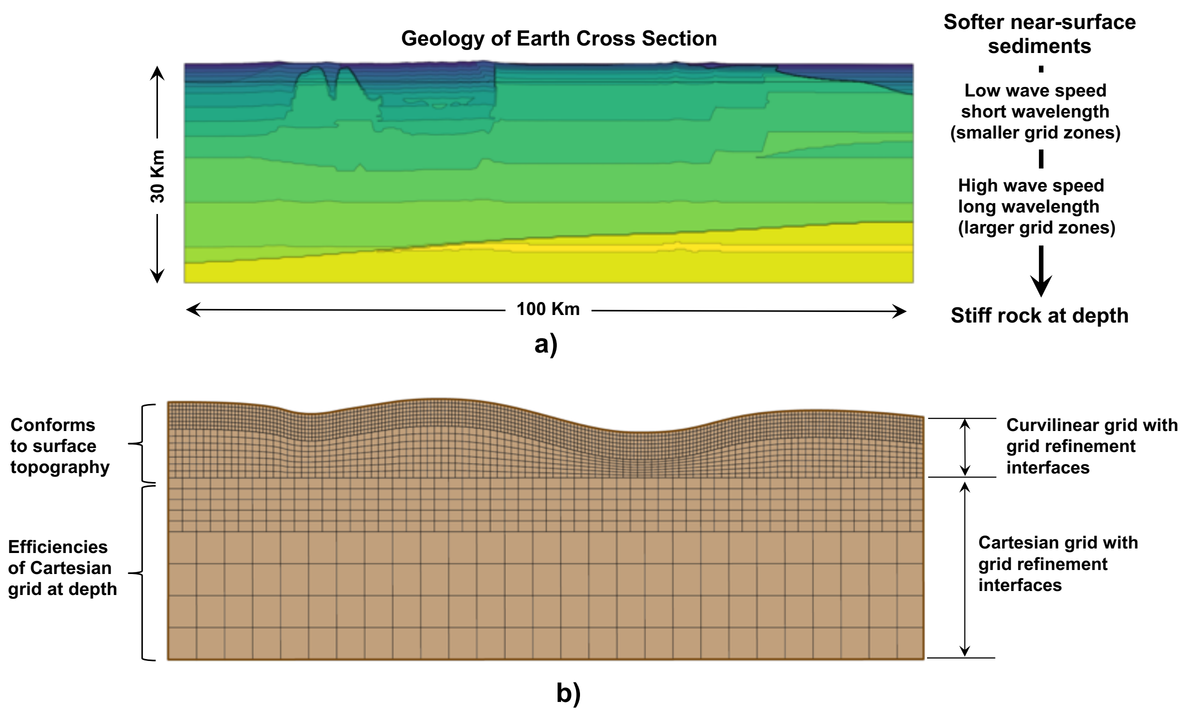

Figure 3. Mesh refinement to represent the depth-dependent properties of the earth. a) Variation of geologic properties in a cross-section of the SFBA model of Figure 2; b) schematic of SW4 curvilinear and Cartesian grids with mesh refinement boundaries.

The EQSIM workflow accounts for two alternative forms of coupling between the geophysics and local engineering models of the computational domain as shown in Figure 4. In the weak coupling case, surface ground motions computed at a point on the earth surface with a regional geophysics model are applied directly and uniformly across the base of an infrastructure model, for example to the base of a building finite element model as indicated in Figure 4a. This traditional approach to applying earthquake ground motions to a model of an engineering structure neglects any interaction between the structure and the supporting soil, and it is only explicitly consistent with an idealization that the incident seismic wavefield consists of pure vertically propagating shear and compressional waves. For this idealization, a building structure will only translate vertically and horizontally under earthquake excitation as shown in Figure 4a. In the case of strong coupling, the interaction between the structure being considered and the surrounding supporting soil is fully accounted for, and most importantly the full complexity of the three-dimensional incident seismic wavefield is appropriately applied to the soil-structure system. For the strongly coupled case the building can both translate as well as rock and rotate due to soil-structure interaction and rotations of the ground resulting from combined surface waves and inclined body waves. The focus of this article is on the EQSIM implementation and workflow for the representation of strong coupling between the geophysics and local engineering models.

Table 1. SW4 recent performance metrics on the Summit computer for a M7 Hayward fault earthquake simulation (black rectangle computational domain in Figure 2).

Earthquake Simulation Parameter	EQSIM Performance Test on Summit
Frequency resolved	10 Hz
Vsmin (minimum geologic shear wave velocity)	500 m/s
Smallest cell size	6.25 m
Number of grid points	63 Billion
Time step size	8.491e-4 sec
Total time steps	106,000
Number of compute nodes used / total	1024 / 4600
Earthquake simulation wall clock time	6 hours 58 min
Summit Hardware	**Component**
CPU	IBM Power9 (42 physical cores per node)
GPU	NVIDIA Tesla V100 (6 per node)
Memory	512 GB DDR4, 96 GB HDM2, 1.6TB NVMe per node
Storage	250PB IBM Spectrum Scale

To perform strong coupling between the global geophysics and local engineering models, the Domain Reduction Method (DRM) devised by Bialak et. al. is employed in EQSIM

(Bielak et. al., 2003). This method provides a two-step solution that appropriately preserves the interaction between the regional geophysics model and local engineering model, fully accounts for soil-structure interaction and ensures that the actual complex incident seismic wavefield is appropriately applied to the local soil-structure model. The mechanics of the DRM have been demonstrated in integrated ground motion-building simulations (Taborda and Bielak, 2011). In the DRM implementation, a DRM boundary is defined at the interface between the global geophysics model domain and the local engineering model domain as shown in Figure 5a. The DRM boundary provides spatially and temporally varying tractions on the outer boundaries of the soil island domain consistent with the stresses created by the seismic waves incident on the soil-structure domain. In practice, the DRM allows an efficient two-step solution process for coupling the regional geophysics and local engineering models as indicated in Figure 5b.

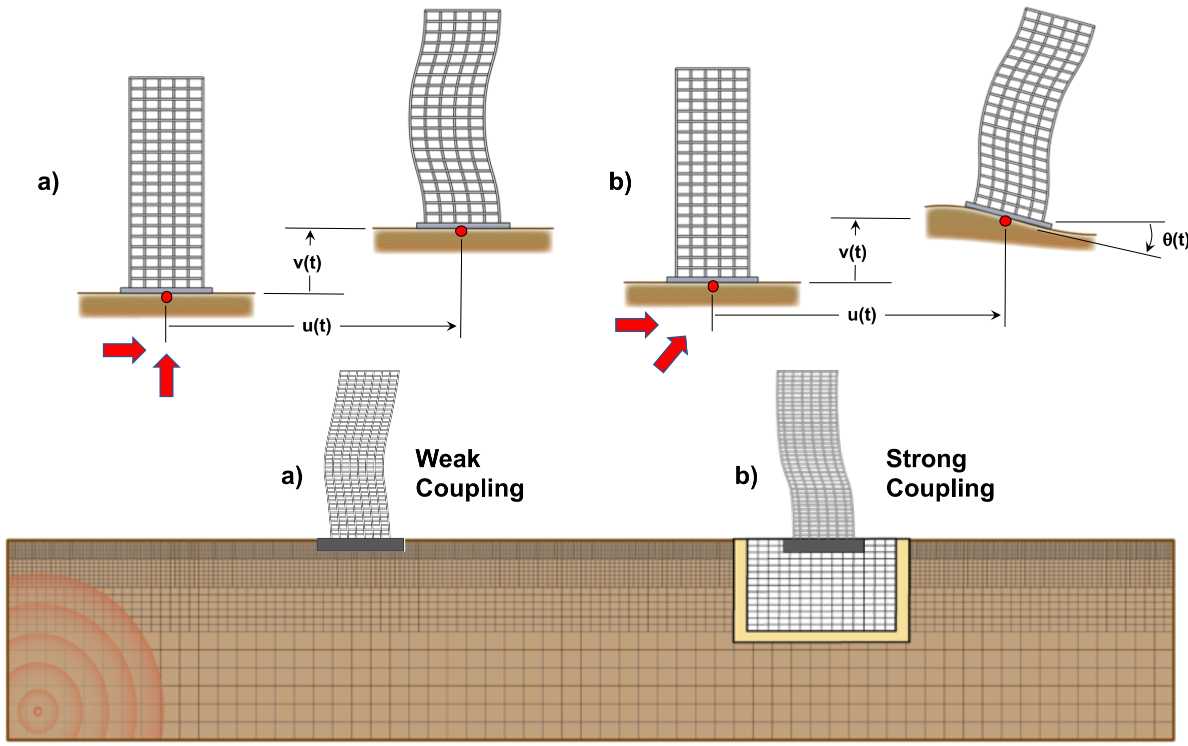

Figure 4. Options for coupling regional geophysics and local engineering system models in EQSIM. a) Weak coupling where ground motions from a point on the ground surface are applied directly to building model resulting in horizontal and vertical translations of building; b) strong coupling where soil-structure-interaction and complex incident seismic waveforms are fully represented and building translates and rocks/rotates.

In the two-step application of the DRM, first an SW4 wave propagation analysis is executed without consideration of the embedded soil-structure domain. The time varying accelerations and displacements at the location of the DRM boundary are saved from the SW4 earthquake simulation. The displacements and accelerations that occur in the ground along the DRM boundary surface are then utilized to apply the effective DRM surface tractions from the incident seismic waves to the soil-structure island in the second part of the two-step simulation. By saving and storing the DRM motions from the SW4 simulation, multiple step two analyses of the soil-structure model can be executed including different building structures or different soil models including nonlinear constitutive models. The partitioning into two steps makes the DRM approach to coupling very efficient while maintaining the rigorous characterization of the complex impinging seismic waves on the soil island domain. Examples in section 3 will illustrate the performance of the DRM method as implemented in EQSIM. As shown in Figure 6, the DRM approach can be applied to a localized soil island and structure, or it can be applied to an extended larger volume to represent the nonlinear site response associated with a horizontally distributed soft soil layer. When undergoing strong earthquake shaking, near-surface soft soils can exhibit strong nonlinear inelastic behavior, the modeling of which is beyond the scope of the linear SW4 wave propagation code. Invoking a DRM boundary encompassing the geotechnical soil layer allows a local nonlinear characterization with nonlinear geotechnical constitutive models. In both cases, the EQSIM workflow creates an HDF5 data container where the grid point displacement and acceleration responses are stored for the entire volume of the region contained within the HDF5 data container boundary for subsequent step two analyses. This allows a two-step simulation for code coupling for any DRM defined sub-volume within the HDF5 container.

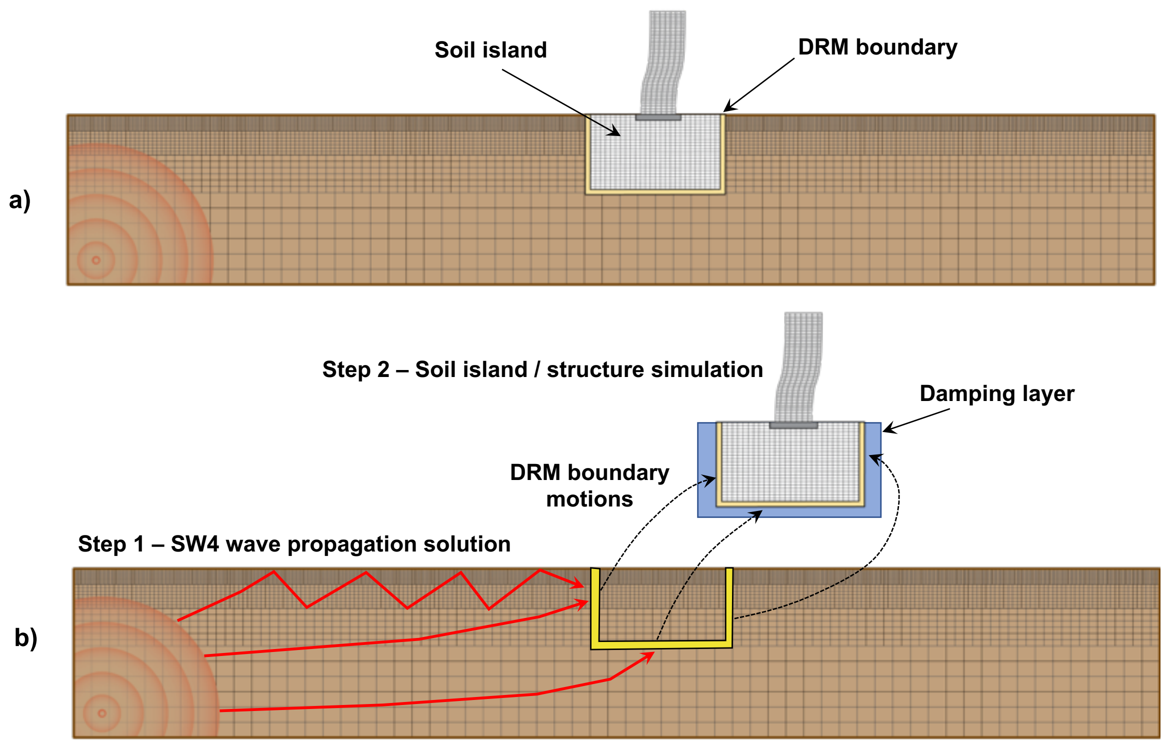

Figure 5. Global-local model coupling through the Domain Reduction Method. a) Conceptual embedment of soil-structure domain within the global geophysics grid; b) practical implementation as a two-step solution where DRM boundary motions are applied to the DRM boundary of the soil-structure domain model.

2.2 DRM data management and workflow at scale in EQSIM

The EQSIM workflow to accomplish the two-step analyses is summarized in Figure 7. In the first step, the SW4 earthquake simulation is performed and the user defines the near-surface volume for the HDF5 data container to store grid point displacements and accelerations. User defined HDF5 container volumes, which can exist for multiple user selected locations, are specified such that subsequent local engineering simulations can be executed for sites contained anywhere within the defined HDF5 container domain. As shown in Figure 7, such a volume can be arbitrarily large, including up to the entire SW4 near-surface simulation domain, and can result in tens or even hundreds of TBs of data from a single earthquake simulation. Without adoption of an effective data management schema, it can become impractical to manage such large datasets.

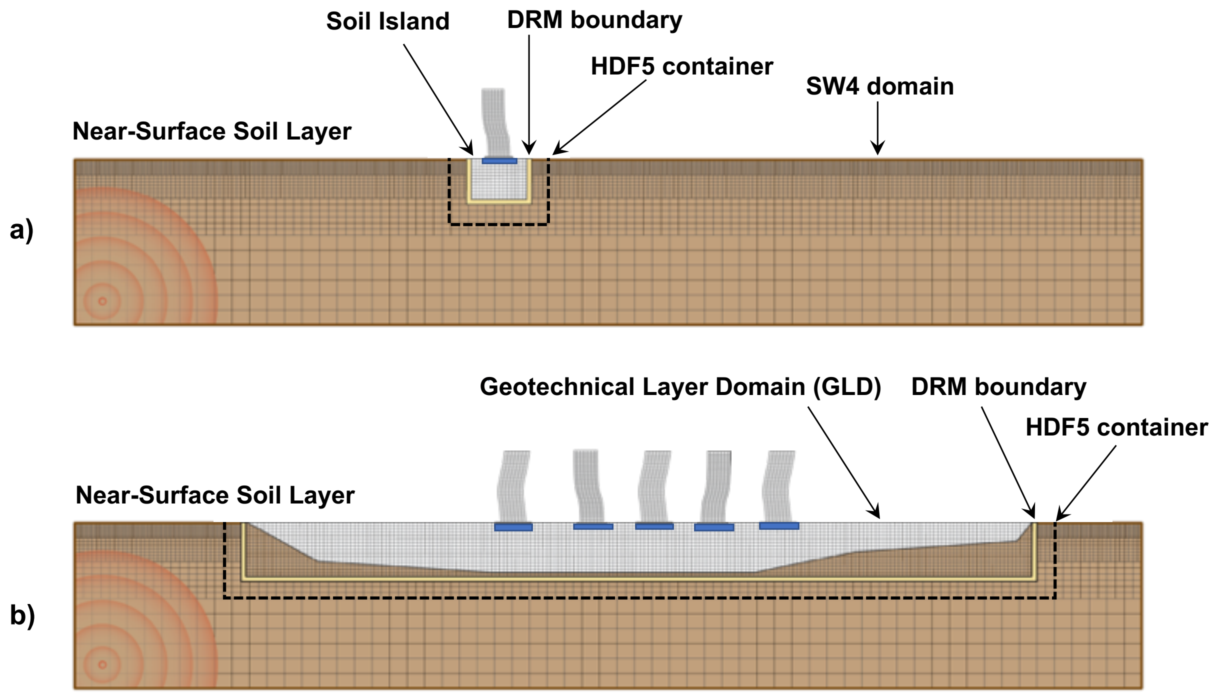

Figure 6. Applications of the DRM-based code coupling. a) Representation of soil island - building system; b) representation of an extended geotechnical soil layer.

One approach to overcome the data size issue is for the user to specify a limited number of subdomains and associated HDF5 data containers to create the data for step two engineering system simulations, and only output the simulated ground motion results corresponding to these subdomain locations. However, this approach puts a significant limitation on the data that can be employed to analyze and visualize the response of engineering systems, especially during exploratory analyses where it is not possible to pinpoint in advance the exact locations of highest interest. In this approach, to obtain data that are not previously saved, the same earthquake simulation would need to be re-run which is a significant cost of HPC compute hours for high frequency regional-scale runs and has obvious practical limitations. This approach is one option implemented in EQSIM, however, to solve the data bottleneck more effectively, EQSIM has adopted a data compression approach, using a state-of-the-art compression library ZFP (Lindstrom, 2014) that works seamlessly and transparently with the HDF5 I/O library. ZFP is designed to achieve high compression ratios for floating point data and uses lossy compression with a user-specified error tolerance. In the case of EQSIM, an error tolerance of 1e-1 was found to result in a compression ratio of up to 251 with single precision data, which makes it possible to save a sufficiently large volume of near-surface ground motion data so that the necessary grid point motions from a large-scale earthquake simulation can be fully saved for an entire regional model as illustrated in Figure 8. Performance of simulations down to the engineering system analyses have verified the ability to fetch and utilize the compressed data without loss of necessary earthquake simulation accuracy.

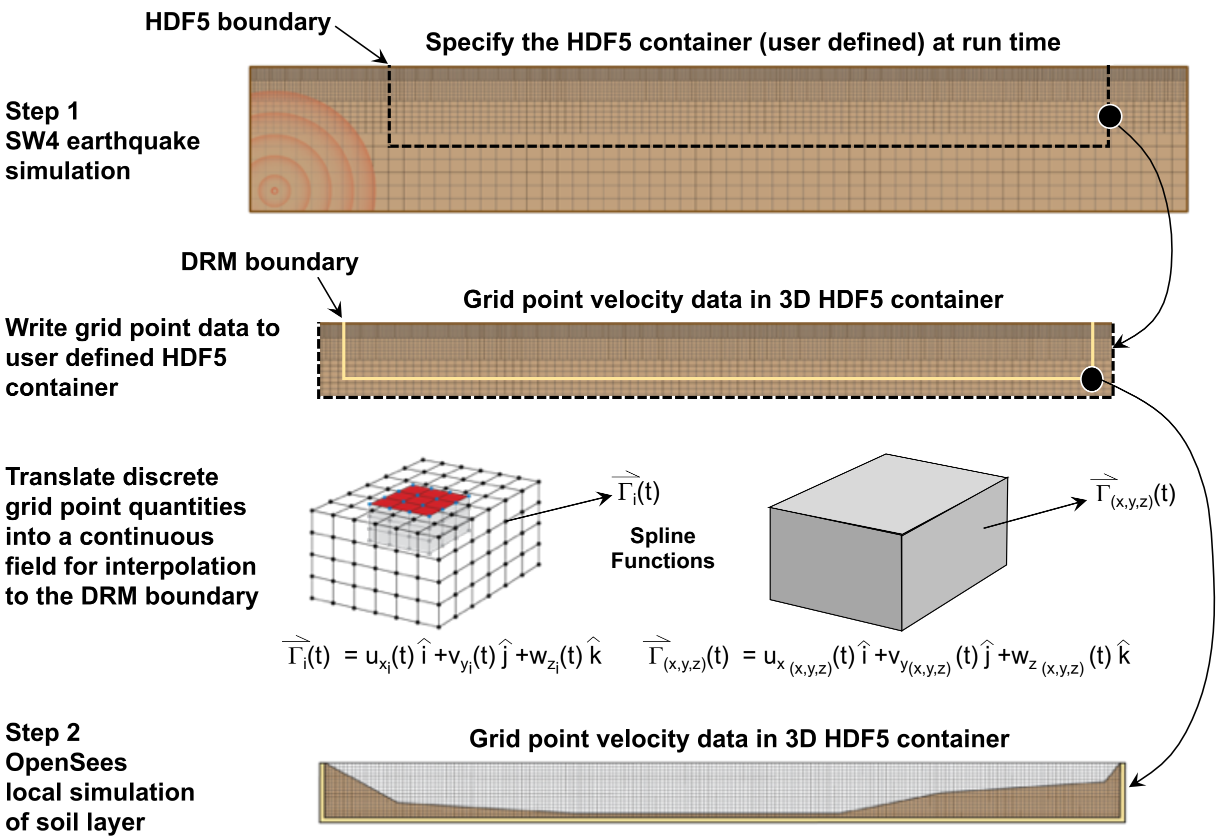

Figure 7. Computational workflow for DRM-based coupling between regional geophysics and local engineering simulation codes.

Table 2 compares the I/O performance for writing the entire near-surface volume of the simulation domain (to 150 meters depth in this example) with and without ZFP compression to the SSD-based burst buffer on the Cori supercomputer (https://www.nersc.gov/systems/cori/) at the National Energy Research Scientific Computing Center (NERSC). A total of 8192 MPI processes were executed on 1024 KNL nodes with collection of the I/O time, application total run time, and the output data sizes with different configurations. Enabling efficient compression requires setting the HDF5 chunk size parameters, which divides the multi-dimensional array into smaller chunks and allows data in each chunk to be compressed. It is recommended to use a multiple of 4 for the HDF5 chunk size for best performance and performance experimentation has occurred with three configurations, 60x60x32, 32x60x32, and 32x32x32, with a problem domain of 1961x3981x31 and 5-meter grid spacing. Larger chunk size results in a smaller number of chunks and the overall output size, but it requires additional communication time as the data of a chunk may reside in several MPI processes. A buffer of 800 steps of data before each write allows larger chunks for better I/O performance. It was found that a chunk size of 32x60x32 achieves the best performance and is in fact 3X faster than writing uncompressed data.

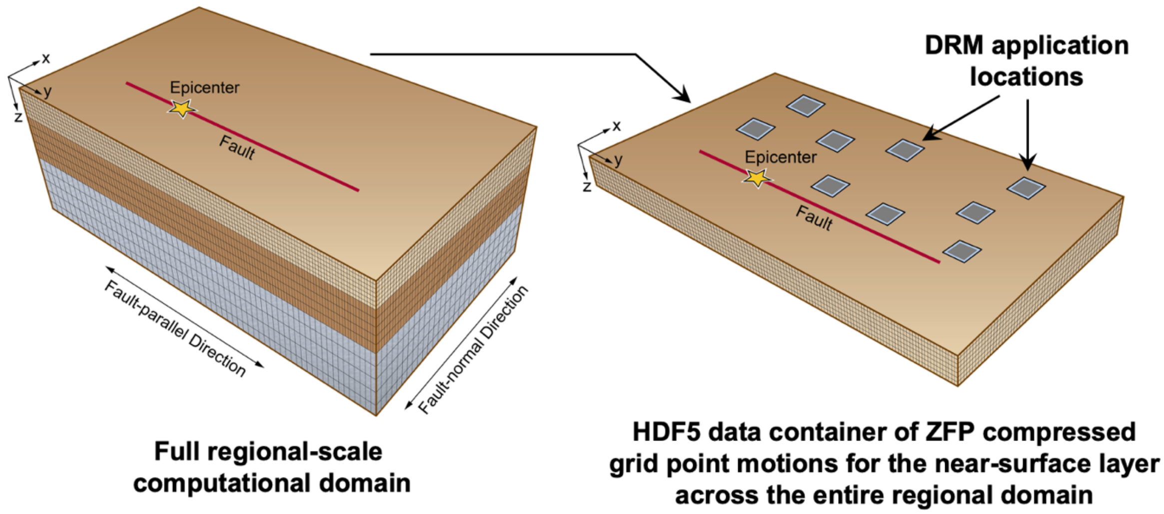

Figure 8. Compression and storage of ground motion data from a near-surface volume of a regional scale geophysics model allows DRM coupling at any selected site.

Table 2. I/O performance comparison with and without ZFP compression using 1024 nodes on the Cori supercomputer for an M7 Hayward fault earthquake simulation (tested on a subset of the domain shown in Figure 2).

Case	HDF5 chunk size	I/O Time (s)	Total Time (s)	I/O percentage	Data size (GB)	Compression ratio
No compression	N/A	933	3986	23%	38912	N/A
ZFP	60x60x32	433	3568	12%	155	251
ZFP	32x60x32	284	3147	9%	164	237
ZFP	32x32x32	625	3708	17%	176	221

Once SW4 volumetric ground motion data is stored in an HDF5 container, it is necessary to interpolate from the grid points of the SW4 domain to the grid points of the local soil-structure model at the DRM boundary. To be most general, the geophysics grid and soil-structure grid do not have to be aligned (coincident) or be of the same zonation size or have the same global orientation. In order for the DRM code coupling to be most robust and work effectively, there must be an efficient and automated way to interpolate between the global geophysics grid and the local engineering grid for arbitrary orientations of the engineering model grid. For the EQSIM framework, this has been accomplished by utilizing a spline function representation to translate the displacement and acceleration fields from the discrete values at the geophysics model grid points into continuous fields defined for all (x,y,z) spatial locations throughout the HDF5 container volume. Once the continuous displacement field is developed, the interpolation to the local engineering model grid points is simple to accomplish by sampling the continuous fields at the physical spatial locations of the local engineering model DRM boundary grid points.

Specifically, to generate a continuous volumetric representation of the acceleration and displacement values within the HDF5 container domain, an order one spline interpolation in 3D space (trilinear interpolation) is used to calculate any field variable value $V(x, y, z)$ at any arbitrary spatial coordinate x, y, z located between 8 adjacent grid points with values $V(x_0, y_0, z_0)$, $V(x_1, y_1, z_1)$, …, $V(x_7, y_7, z_7)$ in the 3D space as shown in Figure 9. To obtain the interpolated result, it is necessary to first calculate and normalize the distances in each direction,

$$x_d = \frac{x - x_0}{x_1 - x_0},\ y_d = \frac{y - y_0}{y_3 - y_0}, z_d = \frac{z - z_0}{z_2 - z_0}$$

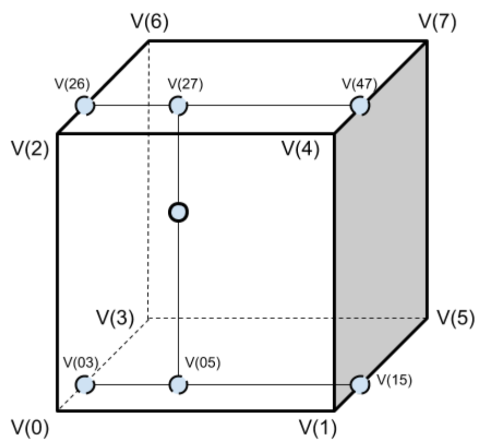

Figure 9. Spline function representation of continuous field variables based on discrete grid point values.

Next interpolation is applied along one direction (e.g. y-axis), yielding,

$$V(03) = V(0)(1 - y_d) + V(3)\, y_d$$
$$V(15) = V(1)(1 - y_d) + V(5)\, y_d$$
$$V(26) = V(2)(1 - y_d) + V(6)\, y_d$$
$$V(47) = V(4)(1 - y_d) + V(7)\, y_d$$

With these four intermediate interpolation points, interpolation can continue to the next direction (e.g. x-axis),

$$V(05) = V(03)(1 - x_d) + V(15)\, x_d$$
$$V(27) = V(26)(1 - x_d) + V(47)\, x_d$$

and finally, interpolation along the final direction (e.g. z-axis),

$$V = V(05)(1 - z_d) + V(27)\, z_d$$

This spline function interpolation is applied for any point within the HDF5 domain, and the interpolation to the DRM boundary can then be accomplished for any arbitrary DRM boundary node location and any arbitrary orientation of the DRM boundary within the HDF5 container as illustrated in Figure 10. With this spline function approach, the steps to develop the DRM boundary surface grid point acceleration and displacement time histories and execute the engineering system model include:

i) Translate the global coordinate system of the local engineering system model into the global coordinate system of the SW4 regional geophysics model with appropriate coordinate system orientation and global x,y,z locations;

ii) Develop a min/max bounding box surrounding the domain of the local engineering system model to limit the requirements of the spline-function representation of the continuous acceleration and displacement fields;

iii) Based on the spline-function representation of the acceleration and displacement fields, determine the grid point accelerations and displacements on the DRM boundary of the local engineering model;

iv) Perform the step two simulation of the earthquake response for the local engineering system domain.

As noted previously, the near-surface ground motion data size can be very large, and the interpolation process to the DRM boundary may take a significant amount of time when executed serially. For example, with serial processing it can take more than 10 hours to process a 414GB data file generated by SW4. To speedup this process, a parallel version of the interpolation program was developed using MPI which decomposes the HDF5 data domain and distributes the data across the MPI ranks in a load-balanced fashion. With the parallel converter, the processing time for the same data file can be reduced to under 20 minutes using 64 MPI ranks.

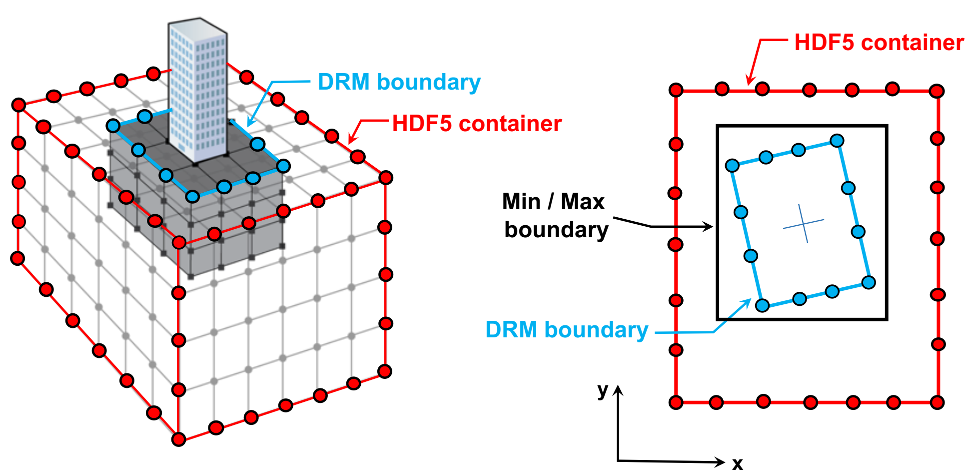

Figure 10. Ground displacement and acceleration fields interpolated to the DRM boundary via spline function generated continuous acceleration and displacement fields.

3 Regional - local code coupling representations

To test and evaluate the EQSIM code coupling implementation at scale, a representative three-dimensional regional-scale earth domain was constructed as shown in Figure 11. The earth structure in this domain consists of a horizontally layered geology and a 60 Km long strike-slip earthquake fault which runs along the length of the sedimentary basin in the model. For the purposes of testing the DRM-based code coupling, the finite difference grid for this model was discretized to resolve ground motions to 5 Hz which yielded a finite difference grid of approximately 8.9 billion grid points.

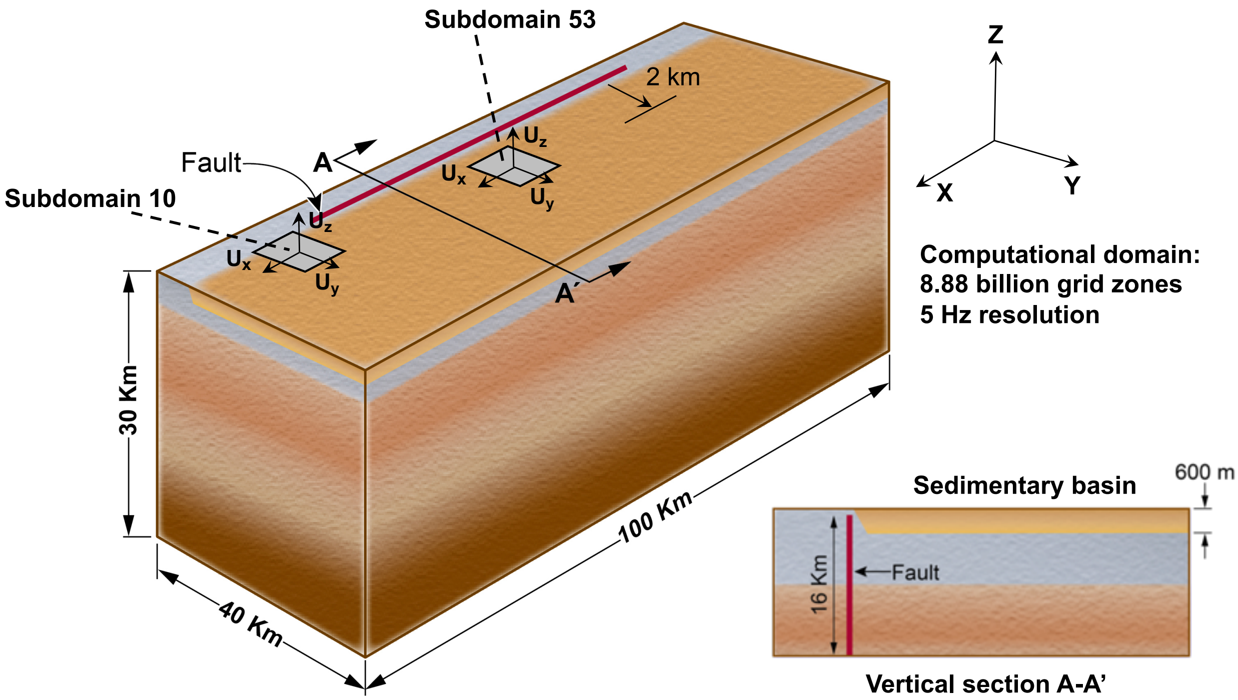

Figure 11. A representative regional domain with a strike slip earthquake fault, subdomains for HDF5 data containers indicated by grey boxes.

Specific sites near the fault were identified as shown in Figure 11 (Subdomain 10 and Subdomain 53). For these sites, local soil-building models were created for representative buildings, including a twenty-story steel moment frame building as shown in Figure 12. The local soil islands for these models were constructed so that the soil island properties were fully consistent with the regional geophysics model properties based on the soil layers at the site location and such that the damping in the local engineering model soil was equivalent to the damping of the regional geophysics model. A highly damped layer is included around the DRM domain so that outgoing seismic waves are damped and do not fictitiously reflect back into the domain. To provide an additional measure of verification testing, two independent engineering codes were utilized to model the soil-building systems. These included the OpenSees implicit, nonlinear finite element program for soil-structure systems (McKenna et. al. 2010) and the ESSI implicit, nonlinear finite element program for soil-structure systems (Jeremic et. al., 2020). Both OpenSees and

ESSI have existing implementations for applying engineering model boundary motions through the DRM.

The SW4 geophysics model of the representative regional domain was utilized to simulate a number of M7 earthquake events with differing fault rupture models. An example of the resulting regional complex seismic waves emanating from the rupturing fault for a bilateral rupture model, where the fault rupture starts at the center of the fault (star in Figure 13), are shown in Figure 13 at selected instants of time.

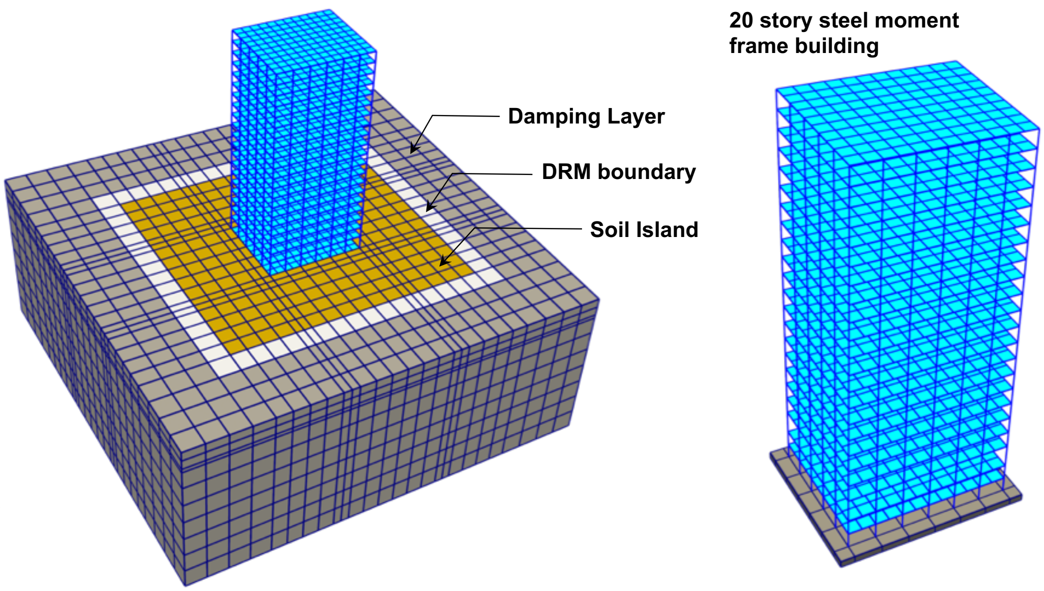

Figure 12. Local engineering system model of soil island and twenty story steel moment frame building in the OpenSees program.

To evaluate the performance of the DRM boundary implementation, tests were executed in which the simulated ground motions obtained at a point on the earth's surface from the SW4 geophysics wave propagation simulations were compared to the simulated ground motions at the same point when a local OpenSees or ESSI soil island was coupled to the geophysics domain as shown in Figure 14.

If the EQSIM DRM boundary implementation is working appropriately, the two sets of ground motions should be in very close agreement. A comparison of ground surface displacements, velocities, and accelerations are shown in Figure 14. In this figure the x direction represents the fault-parallel direction at the site, the y direction represents the fault normal direction at the site, and the z direction represents the vertical direction at the site (Figure 11). The first notable feature is the exceptional agreement between the SW4 computed motions and the motions computed with both the OpenSees and ESSI embedded soil islands using the DRM coupling. Even for the higher frequency accelerations, where some waveform deviation might be anticipated, the respective solutions exhibit an excellent waveform match, and this agreement is demonstrated for two completely independent finite element codes, i.e. both OpenSees and ESSI.

Secondly, for this near-fault site, in addition to the ground shaking due to dynamically propagating seismic waves, the ground exhibits significant permanent displacement associated with the co-seismic displacement due to slip along the earthquake fault. The fault parallel x direction displacement, Ux, shown in Figure 14a exhibits a permanent displacement due to fault slip of approximately 0.3m, which is accurately replicated by the finite element codes with the DRM coupling, thus the DRM implementation also captures the ground displacement that occurs due to fault offset during the fault rupture. The exceptional agreement for both dynamic ground shaking and permanent ground offset verifies the performance of the DRM-based coupling between the geophysics and engineering codes.

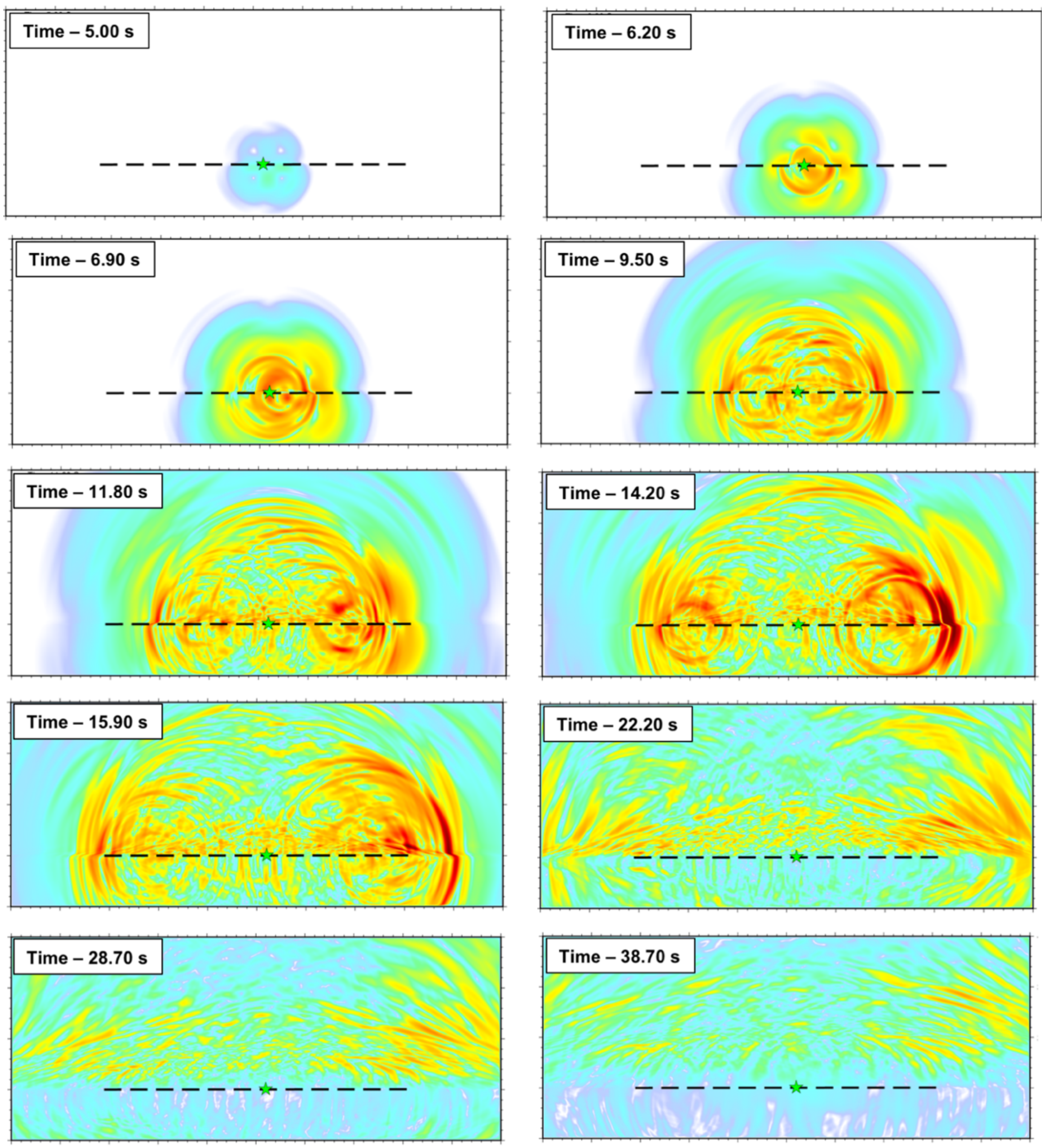

Figure 13. Simulation of a M7 earthquake rupture with SW4 in plan view, snapshots of seismic wave propagation at selected instants in time.

With confidence in the ability of the DRM implementation to accurately represent the coupling between the regional and local models while seamlessly propagating the incident seismic waves into the local soil island-structure domain, soil-building system simulations were executed for the selected subdomains. The resulting dynamic response of the 20-story building, in terms of the dynamic deformation of the soil-building system at selected instants of time, are shown in Figure 15 and building roof displacement time histories in the fault-parallel and fault normal directions are shown in Figure 15. For these simulations the inelastic behavior of the building was modeled through very detailed fiber cross-section elements of the steel members sections using classical plasticity with kinematic hardening.

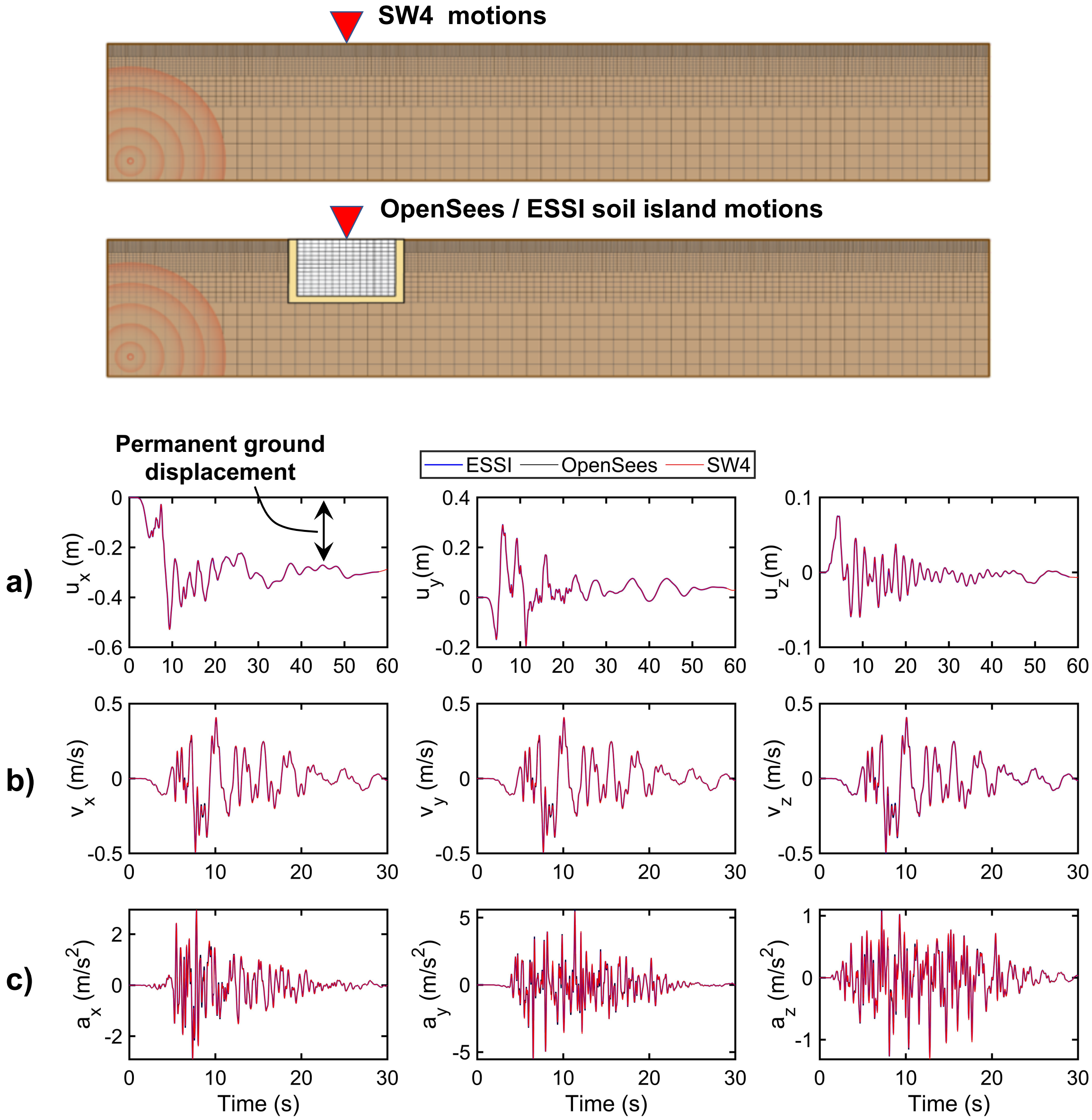

Figure 14. Comparison of simulated earthquake motions at the surface of the ground for a near-fault site (subdomain 53 in Figure 11). a) Ground displacement time histories; b) ground velocity time histories; c) ground acceleration time histories.

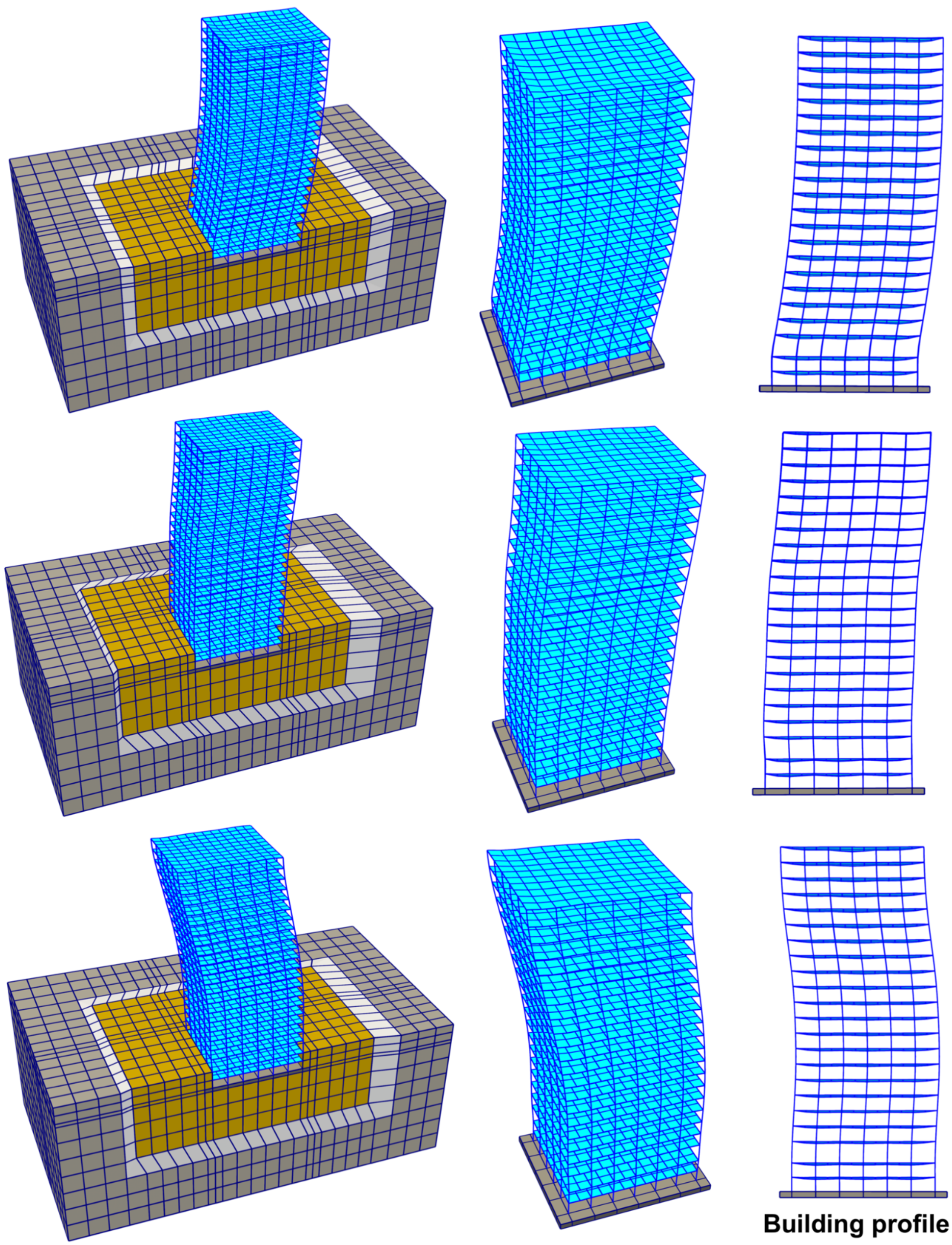

Figure 15. Soil island – building response at selected time steps of the M7 earthquake history, site location subdomain 10 in Figure 11 (displacement scale factor = 10).

For the subdomain 10 site the ground motion exhibits a very strong single fault normal pulse due to fault rupture directivity effects. This pulse results in a very large nonlinear excursion of the building with a significant permanent offset of the building due to inelastic deformation as shown in Figure 16. It is also noted that there is a significant difference in building response between a weakly coupled building ("Fixed-base model") and a model strongly coupled through the DRM ("DRM model") for this site.

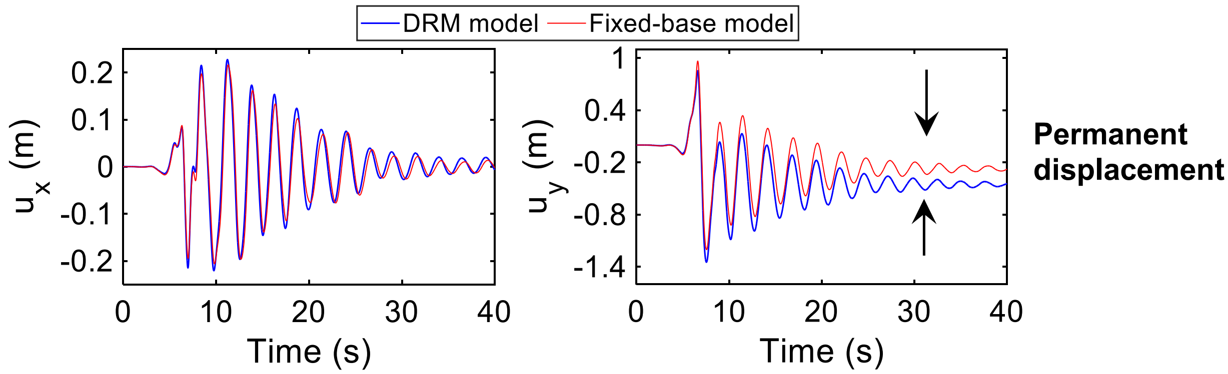

Figure 16. Roof displacement time history of the twenty-story building in fault-parallel (Ux) and fault-normal (Uy) directions. Large fault-normal ground pulse results in significant inelastic deformation of the building.

This example illustrates the completion of an effective fault-to-structure workflow including the ability to represent nonlinear, inelastic behavior associated with damage to the building superstructure.

4 Conclusions and future work

Observed regional ground motions from large earthquakes have demonstrated the strong site dependency of ground shaking as dictated by the earthquake rupture mechanism, the effects of the heterogeneous geology along the seismic wave propagation path from earthquake rupture to structure site, and finally the complex interaction between incident seismic waves and soil-structure systems. As computational limitations are overcome, physics-based simulations of the full range of fault-to-structure processes offer a transformational approach to understanding earthquake phenomena and quantifying seismic risk to critical infrastructure. Emerging exascale platforms, combined with software applications and computational ecosystems to exploit these platforms, will provide the foundation for major advancements in earthquake simulations.

The ability to rigorously couple regional geophysics and local soil-structure models in a manner that preserves the full interaction between earthquake waves and infrastructure systems at frequencies of engineering interest (e.g. up to 10 Hz) will allow unprecedented examination of the seismic response of engineered structures, and provide new insight into the most appropriate risk-informed earthquake designs. Over the past three years, the EQSIM framework has implemented advanced physics algorithms and code optimizations, and begun preparing for GPU-base accelerator platforms. Work ahead will continue towards meeting established EQSIM performance goals and being fully prepared for execution on new exascale platforms in the 2022-2023 time frame.

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Author Biographies

David McCallen is a Professor in the Department of Civil and Environmental Engineering at the University of Nevada, Reno and Senior Scientist in the Energy Geosciences Division at Lawrence Berkeley National Laboratory. His research interests include applications of high-performance computing in earthquake hazard and risk assessments. He is currently the Principal Investigator for the U.S. Department of Energy EQSIM Exascale Computing Project application development.

Houjun Tang is a Computer Research Scientist in the Computational Research Division at Lawrence Berkeley National Laboratory. His work includes development of parallel I/O techniques and methods as part of the ECP-ExaIO team at LBNL.

Suiwen Wu is a Postdoctoral Scholar in the Department of Civil and Environmental Engineering at the University of Nevada Reno. His research work includes the development and testing of computational models for regional-scale simulations of earthquake risk to buildings.

Eric Eckert is a Research Assistant at Lawrence Berkeley National Laboratory and a graduate student in the Department of Geological Sciences and Engineering at the University of Nevada Reno. His research work is focused on the utilization of high-performance computing models for the simulation of earthquake ground motions at regional scale.

Junfei Huang is a PhD student in the Department of Civil and Environmental Engineering at the University of Nevada Reno and his research studies are focused on the development of coupled regional scale ground motion and local engineering models for civil infrastructure risk assessments.

N. Anders Petersson is a Computational Mathematician at the Center for Applied Scientific Computing at Lawrence Livermore National Laboratory. His research focuses on numerical methods for wave propagation problems and advanced algorithms for high performance computing. He is the principal developer of the SW4 seismic wave propagation code.