High performance simulations for transformational earthquake risk assessments

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Abstract. Earthquakes occurring around the world are responsible for extensive loss of life and infrastructure damage. On average, 1100 earthquakes with significant damage potential occur world-wide per year, and a major societal challenge is to design a human environment that contains appropriate earthquake resistance. Design of critical infrastructure such as large buildings, bridges, industrial facilities and nuclear power plants in seismically active regions is a significant scientific and engineering challenge that encompasses the multiple disciplines of geophysics, geotechnical and structural engineering. Because of the great complexities in earthquake physical processes, traditional approaches to seismic hazard assessment have relied heavily on historical earthquake observations. In this approach, observational data from many locations is homogenized into an empirical assessment of earthquake hazard at any specific site of interest. With major advancements in high performance computing platforms and algorithms, it is now possible to utilize physics-based predictive models to gain enhanced insight about site-specific earthquake ground motions and infrastructure response. This paper discusses recent advancements in geophysics and infrastructure simulations and future challenges in implementing advanced simulations for both earthquake hazard (future ground motions) and earthquake risk (infrastructure response and damage) assessments.

1. The earthquake response problem

The complete end-to-end (e.g. fault rupture-to-structural response) physical processes associated with earthquakes and infrastructure response are very complex. The processes can be divided into four segments as indicated in figure 1: (1) earthquake fault rupture; (2) seismic wave propagation through rock; (3) response of the near-surface sedimentary soil deposits; and (4) the dynamic response of the particular structure under consideration. Through extensive scientific study, much has been learned in recent years about earthquake fault rupture processes, and observations of earthquake ground motions have provided important insights into the manner that sub-surface geologic structure can influence the observed earthquake ground motions at a particular site. In the engineering community, analysis of structural system performance in actual earthquakes and structural component and system testing on mechanical earthquake simulator shake tables has provided important quantitative data on the nonlinear response of structures to extreme earthquake motions. Drawing upon these engineering and

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scientific advancements, and the tremendous advancements in computational hardware and algorithms, there is a timely opportunity for advanced computational simulation to play a much larger role, and in fact transform the manner that we predict future earthquake motions and design major infrastructure.

**Figure 1.** Four segments of the source-to-structure earthquake process.

The historical approach to estimation of earthquake ground motions has been based upon Probabilistic Seismic Hazard Assessment (PSHA) through which historical information from earthquakes at many observed geographic locations is synthesized to develop a probabilistic estimate of future ground motions at a specific site. For a particular site of interest, PSHA identifies near-by active faults, interprets geologic data to infer frequency of earthquake occurrence on each fault, and utilizes generic attenuation relationships that describe the decay of ground motion intensity as a function of distance from a causative fault, all combined to yield a probabilistic representation of the potential future ground motions at the site. The defined ground motion hazard, which is used to design critical structures, is typically associated with an annual mean probability of exceedance (e.g. a $1 \times 10^{-4}$ mean annual frequency of exceedance).

This empirically based approach provides a standardized methodology with embedded statistical information, but it may not capture all of the site-specific complexities of a particular site under consideration. As more data from actual earthquakes have been obtained, the variability and complexities of earthquake ground motions has come into clearer focus. For example, ground motions measured in the 1991 Landers California earthquake (see figure 2) clearly show the influence of fault rupture directivity in which two strong motion instrument sites, GSC and PFO, have substantially different observed motions despite their almost identical distance from the causative fault. Site GSC is subjected to much larger motions as the fault rupture propagates in the direction of GSC and directs more wave energy toward that site. These data are indicative of the profound influence that the physical process can have on observed ground motions.

A realistic high performance computational model capable of representing source-to-structure earthquake processes would be a tremendously powerful tool for performing site specific evaluations of ground motion levels and structural response, and for evaluating the sensitivity of structural response to specific geologic parameters and processes. Such a model could augment, or replace, the current empirically based elements of the PSHA process.

Recently, significant progress has been made towards achieving the individual components of such an ambitious end-to-end modeling goal. With the highest-end computers, three-dimensional simulations of fault rupture and seismic wave propagation are now being solved for regional scale models at low frequency. Structural response simulations, which realistically capture the behavior of
steel and concrete structures subjected to large ground motions, and which include significant nonlinear behavior due to cracking, yielding or other damage in the structure, are being rigorously solved with numerically robust and efficient iterative, time-stepping solution algorithms.

Figure 2. The observed effect of fault rupture directivity on ground motions (1992 Landers CA).

2. Simulating earthquake ground motions at regional scale
Segments 1, 2 and 3 of the earthquake response problem (figure 1) include representation of the fault rupture process and seismic wave propagation through bedrock and alluvial deposits to the surface of the ground. Computer programs that have been developed over the last few years to address this source rupture and wave propagation problem are typically finite difference based, and limited to linear elastic and viscoelastic response behavior characterized by the three dimensional equations of elastodynamics. The time dependent solutions are typically achieved through explicit time integration, and staggered grids are often applied to the finite difference stencil [1]. The three dimensional character of these programs, and the large computational domains necessary to model major earthquakes, demands the most advanced computing resources. Numerical resolution of the higher frequencies of interest (5-15 Hz depending on the structure under consideration) represents a significant computational challenge.

An example of the level of computational capabilities associated with high performance three dimensional simulation is illustrated in figure 3, where a fully three dimensional simulation of the great 1906 San Francisco earthquake (M=7.8) and a postulated Hayward fault California earthquake (M=7.1) are illustrated. For the 1906 simulation, a significant portion of northern California was included for the very extensive earthquake fault rupture. The 1906 simulation, computed with a 11.1 billion node finite difference grid, required 1 TB of memory and 16 hours of wall clock time on a 1024-cpu Linux cluster (1.1 TFlops of sustained performance) to compute 200 seconds of simulated earthquake ground motions. This simulation resolved ground motion waveforms to only 1 Hz frequency. The computational requirements to extend the simulations to 3 or 4 Hz, which would be desirable for most evaluations of typical building structures, would demand significantly more computational resources as indicated in Table 1. For example, a model with 5 Hz frequency resolution for the 1906 earthquake simulation would require a petascale system. Such a simulation could be
Figure 3. Snapshots of seismic wave propagation and estimated Modified Mercalli Intensity of ground shaking from a fault rupture scenario of the M=7.8 1906 San Francisco earthquake and a postulated M=7.1 Hayward fault earthquake simulation.

Table 1. Computational requirements for regional earthquake simulations (metrics based on a 128 node, 1024 CPU Linux cluster with ~ 1.1 Tflop performance).

| Earthquake Scenario       | Required Number of Grid Nodes | Memory / Solution Time (1 Hz Resolution) | Memory / Solution Time (3 Hz Resolution) | Memory / Solution Time (5 Hz Resolution) |
|---------------------------|-------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| M=7.8 San Francisco       | 11.1 Billion (1 Hz)           | 1 TB / 16 hrs                            | 27 TB / 54 days                          | 125 TB / 416 days                        |
| M=7.1 Hayward             | 1.49 Billion (1 Hz)           | 0.15 TB / 1.2 hrs                        | 4 TB / 4 days                            | 20 TB / 31 days                          |

performed in a reasonable wall-clock time (e.g. 24 hours) on a commodity-base Linux cluster with 500,000 compute core and a sustained performance of about 1 PFlop. The memory required would not be excessive since large problems are more constrained by run-time. The total memory requirements would be approximately 4 GBytes for a 16 core node.
These 1906 simulations were utilized in seismological studies of the great 1906 San Francisco Earthquake [2,3,4] and provided new insight into the ground motion distribution from that event as well as insight into the earthquake hazard associated with potential future San Andreas fault earthquakes. Because strong ground earthquake ground motion instrumentation was not available in 1906, quantitative data on the actual observed motions (i.e. measured ground motion waveforms) are not available, and the forensic studies of this event have relied on estimates of human observations based on the Modified Mercalli Intensity scale to compare observed and simulated results. The intensity levels estimated from the massively parallel simulations were in good agreement with documented eyewitness accounts from the great 1906 earthquake [4]. The simulation plots clearly illustrate the significant difference in scale of a great M=7.8 earthquake versus a major M=7.1 earthquake.

3. Simulating nonlinear structural response to strong ground motions

Finite element based structural mechanics simulations of the response of infrastructure to extreme earthquake ground motions has made tremendous progress in the last ten to fifteen years both in the research community and in transferring the capabilities into the hands of practicing engineers. Due to the relatively long duration of earthquake excitations (e.g. 10-50 seconds), the stiff mechanical characteristics of steel and concrete structures, and the physically small dimensions of structural finite elements, the time history solutions of structural response have been carried out with implicit time integration schemes that are unconditionally stable and allow the utilization of large time steps, i.e. the time step size is not constrained by a Courant stability limit. Under extreme earthquake ground motions, most structures are designed so that some level of nonlinear response behavior will occur due to local yielding or member cracking. In fact, controlled and limited nonlinear behavior is desirable from an energy dissipation point of view during extreme earthquakes. Nonlinear behavior is currently permitted as an appropriate design feature in many engineering design codes [5]. To realistically represent nonlinear behavior of the structural system, accurate constitutive models of nonlinear element behavior (both steel and concrete) and robust solution algorithms with equilibrium iterations in each time step have been the focus of successful intense research.

Computational structural mechanics technologies have progressed to the point where realistic, nonlinear models can be computed for a significant range of structural types. Figure 4 illustrates a very detailed inelastic finite element model of a steel frame system of a high-rise building. In this model, each beam and column element is discretized with a fiber-based finite element with elasto-plastic material behavior. In the fiber model, the cross-section of each structural member is divided into a number of zones, or fibers, as shown in figure 4, and the nonlinear stress-strain behavior is invoked for each fiber of the cross section. The fiber modeling approach rigorously accounts for interaction between flexure (bending moment) and tension / compression (axial force) in each element, and also captures the spread and evolution of inelastic behavior through the element cross section. The nonlinear model also precisely represents the effects of structural displacements and the additional bending moments introduced by vertical gravity loads when the building sways significantly to one side.

This type of computational model has recently been used extensively to study the nonlinear seismic response of steel frame buildings to strong, near-fault earthquake ground motions [6]. A comparison of linear and fully nonlinear simulations of an actual building response is shown in figure 4. Under extreme ground motions, the nonlinear effects can be very pronounced, resulting in significant permanent deformation of the building and a significantly different distribution of member forces than what would be predicted by a simple linear elastic model. Figure 4 for example illustrates the significant influence of nonlinearities in a simulation of a forty story steel frame building response to an actual strong earthquake motion recording made in Taiwan during the 1999 Chi Chi earthquake. In this analysis, an implicit Newmark-Beta time integration was utilized with full-Newton based equilibrium iterations within each time step to drive the residual from nonlinear behavior to zero within each time step. The linear mode of the building is grossly in error for this particular strong ground motion as the building is driven well into the nonlinear regime.
4. End-to-end simulations in hazard and risk assessment

Realistically addressing the full suite of complex elements in the earthquake processes illustrated in figure 1 will require additional computational developments, but the individual computational elements of a full end-to-end simulation process are well along in development. Initial thrusts at performing fully end-to-end simulations have been completed by the authors and coworkers in evaluating the seismic hazard and risk to major long-span bridges in the San Francisco Bay area of California. As a result of limitations in existing strong motion instruments, there were major concerns about how this class of flexible, low-frequency structures will respond to long period components of ground motions that are observed in the near-field (within 20 km or so) of major earthquake faults. This concern was compounded by the fact that traditional strong motion instrumentation and companion signal processing algorithms were not designed to measure long period components of motion (waveforms with periods greater than 5 seconds) and thus there is very limited quantitative data on near-field motions.

To investigate the response of long-span bridges to near-field motions, a comprehensive geophysics-engineering simulation effort was initiated by the University of California and DOE National Laboratories to investigate the response of long-span bridges. The effort revolved around a case study for the Oakland – San Francisco Bay Bridge Suspension spans across the San Francisco
Bay (figure 5). This bridge structure is representative of long period bridge systems and is located in close proximity to the Hayward fault. In this effort, a high performance regional scale geophysics model was utilized to simulate the long-period ground motions at the bridge site, and a nonlinear structural mechanics model was utilized to evaluate the bridge response to the simulated earthquake ground motions. This effort represented the first complete end-to-end simulation of the earthquake process.

![Figure 5](image-url)

**Figure 5.** Nonlinear finite element model of a long-span steel suspension bridge; bridge response to long period, near-fault earthquake ground motions.

The simulated ground motions at the Bay Bridge site for a Hayward fault earthquake (see figure 3) contained both permanent ground displacement associated with tectonic fault slip, and low-frequency ground displacement pulses associated with directivity and wave superposition effects (see ground displacement from the geophysics simulation shown in figure 5 where these features are evident in the ground motion waveforms). The earthquake ground motions developed from the geophysics simulations provided direct input to the bridge computational model. It was discovered in these simulations that the long-period components of ground motion can have a very important effect on the response of this type of bridge system, and that the bridge system forces and displacements can be significantly underestimated if these long period effects are not appropriately considered [7,8,9]. Subsequently, these observations, which were based solely on end-to-end computational simulations,
have been confirmed through the evaluation of bridge response using newly obtained measured broad-band ground motion records [9].

5. Moving towards full end-to-end simulations

Advanced simulation tools have and will continue to revolutionize the earthquake design and analysis of major man-made structures. The goal of performing realistic end-to-end simulations that can simulate both ground motions and subsequent structural response, and develop correlations between structural response and earthquake geophysical parameters would be an extremely powerful tool. The precise manner in which such a tool would be fully implemented in design practice remains to be established. In order to simulate waveforms at the higher frequencies of engineering interest, the geophysics computational models must be populated with representative geologic structure and material parameters at fine spatial scales. To gather general insight about processes and phenomenon, it would be sufficient to simply populate a model with realistic sub-surface parameters that are not necessarily representative of any particular actual site. Much insight can be gained about earthquake processes by studying virtual sites with realistic, but “made-up” geologic structures. This is likely the most compelling near-term application of an end-to-end simulation model. To adapt advanced simulations to hazard and risk assessments at specific actual sites, it is necessary to develop a schema for generating realistic geologic models surrounding the site. There are generally two approaches to this, one includes developing a suite of stochastically generated geologic structure models that define the unknown subsurface geology in a statistical sense, and the other is to utilize measured data from frequently occurring small earthquakes in an inversion process to further constrain the subsurface geology.

To move forward, a number of computational issues must be addressed:

- Development of the most efficient computational tool for simulation of ground motions. Resolution of higher frequencies of engineering interest will be a very significant computational challenge when including features such as topography of the free surface, geologic energy attenuation in the equations of motion, nonlinearity of shallow soils, variable density grids optimized around the significant property differences between deep and shallow geologic structures, and incorporation of detailed geologic subsurface features.
- Implementation of an algorithmic framework for numerically coupling geophysics models and structural models for cases in which interaction between the supporting soil and the structure is important (the soil-structure-interaction for a massive nuclear power plant being the classic example). In light of the fact that geophysics simulations and structural simulations are typically performed in fundamentally different algorithmic manners, i.e. implicit time integration versus explicit time integration, this will complicate rigorous coupling of these models.
- Establishment of procedures for characterizing the geologic structure parameters at fine enough scale to support the numerical computation of waveforms at high frequency. The simulation of frequencies of engineering interest will require characterization of geology on finer scales than is typically available from traditional subsurface exploration sources. Procedures must be implemented for numerical implementation of the adopted approach, which can be a significant challenge when dealing with models with billions of zones.
- Development and implementation of stochastic representations of fault rupture processes in the geophysics simulations. For a given earthquake fault, geophysical information is often available on the magnitude and frequency of occurrence of potential earthquakes. However, it is unknown precisely how the fault will rupture in future earthquakes, and data have shown that the manner in which the fault ruptures can have significant influence on realized ground motions (e.g. see figure 2). It is therefore necessary to characterize a suite of potential rupture scenarios that encompass the hazard potential of a given fault. Much research has been done
on developing this suite, and this work must be implemented into a form readily implementable by geophysics codes.

End-to-end simulations offer tremendous potential for increasing insight and understanding about earthquake processes. The ability to computationally investigate cause and effect between geophysical processes, geophysical features and structural response will provide a tool for new understanding and for evaluation of the accuracy of existing simplifications and idealizations that are employed in engineering practice (e.g. the accuracy of the assumption that ground motions consist purely of vertically propagating shear waves). Building upon the major computational research advancements in each respective area of the problem, the development of a fully end-to-end capability is within our grasp.

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