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# Simulation for determining the seismic performance of urban regions

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ABSTRACT: Dynamic simulation of earthquake mechanisms, ground motion, and the resulting performance of buildings and infrastructures in a region are used to supplement the limited availability of empirical data on strong ground from large magnitude earthquakes. Such knowledge is essential for understanding the effects of large earthquakes and investigating the effect of mitigation policies. Simulation of fault rupture mechanisms, wave propagation through geological structures, and dynamic response of buildings provides valuable information about the effects of strong ground motion on urban regions. Information technology is critical in organizing and visualizing the large amount of data generated by regional simulations and for providing access to users and nontechnical decision-makers over a web portal using Grid-services middleware.

## 1 INTRODUCTION

Earthquakes are one of the most severe natural hazards affecting many highly populated regions of the world. In the United States, a recent report by the Federal Emergency Management Agency (FEMA, 2002) estimated the annualized losses of buildings due to earthquakes at more than $4 billion in direct costs. When infrastructure systems and indirect economic impacts are included, the annualized loss in the United States could exceed $10 billion. Moreover, a single earthquake in a densely populated urban region could result in thousands of casualties and losses in excess of $200 billion. Potential losses from earthquakes will grow in time because of the increased interconnectedness of communities and increasing economic valuations. New business approaches, such as just-in-time delivery systems, place a high premium on the reliability of transportation, communication, and utility systems. Since earthquakes affect a large region, disruption of infrastructure systems can have a profound impact on cities and their populations and economies.

A collaborative research program is developing methodologies for simulation of the dynamic response of entire regions from the earthquake source to the building inventory and infrastructure. Researchers at Mississippi State University, Carnegie Mellon University, University of California, Irvine, and University of California, Berkeley have made significant progress on an NSF-sponsored project to use simulation and visualization methods for investigating the impacts of earthquakes. The SPUR project (for *Seismic Performance of Urban Regions*) uses information technology to link high-end simulations of earthquake ground motion, advanced models for building performance, large-scale databases, and visualization to develop new knowledge about the spatial distribution of structural damage in a region and the effectiveness of building codes on controlling damage. We have developed new visualization methods for understanding the dynamic processes in a large region, for communicating this information to scientists and engineers, and for conveying the effects of earthquakes to non-technical decision-makers. Using Grid-services middleware we have developed portals to access the databases for the regional models and computational resources, selecting scenarios and regional inventories for simulation, and visualizing the results.

The objective of this paper is to provide an overview of the motivation and methods developed for large-scale regional simulation of seismic performance, and to describe the tools developed for integrated simulation of fault rupture mechanisms, wave propagation in geological structures, and building response simulation for inventories over large regions. Information technology tools for managing the large amounts of data, for visualization, and for providing access to the simulations are discussed.

## 2 GROUND MOTION SIMULATION FOR A REGION

As a motivation for the problem of regional earthquake simulation, we have located a scenario in the Los Angeles basin (LAB) (Fig. 1) because (a) it is the most densely populated seismic region in the country, (b) large amounts of data are available on the geology and built infrastructure, and (c) it is one of the most heavily seismically instrumented regions in the U.S. Although LAB is proxy for an urban region, the simulation approach is applicable to other regions with varying amounts of data.

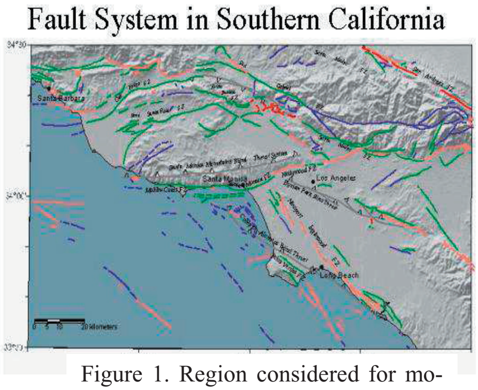


Figure 1. Region considered for motivating scenario.

The first step in the regional simulation is to develop the knowledge of the ground motion in the event of a major earthquake. Such knowledge is an essential ingredient for the assessment of damage in the affected region. A vast amount of information will come from strong ground motion sensors; hundreds of these have been deployed in the Los Angeles basin over the last 35 years. Recent cooperative seismic networks, such as TriNet and the USArray of EarthScope, which feature both broadband and strong-motion sensors, have added hundreds more. Despite this significant number of permanent seismographs, their density over the LAB remains quite small, with an average separation on the order of 4 km. On the other hand, direct observations of damage and data from dense networks of portable instruments used to record aftershocks have shown that ground motion can vary dramatically over distances of only a few hundred meters, e.g., Meremonte (1996), Hartzell, (1997), and Baher (2002). This large spatial variability makes it practically impossible to determine from sensors alone the spatial distribution of ground motion to the resolution required for assessing the distribution of damage.

Over the last fifteen years, we have made substantial progress on addressing this problem by modeling earthquakes in large geological structures, such as basins, using wave-adaptive mesh algorithms By their very nature, these unstructured meshes introduce significant complexities on parallel machines. However, in geological structures like sedimentary basins, where seismic wavelengths vary significantly throughout the domain, wave-adaptive meshes allow a tremendous reduction in the number of grid points (compared to uniform meshes) because element sizes can adapt locally to the wavelengths of propagating waves, as described in Bao, (1998), Hisada (1998), Bielak (2003), and Yoshimura (2003). We have recently extended our code to include octree-based trilinear hexahedral elements, which are more accurate, and local dense element-based data structures (Kim, 2002, 2003). More importantly, the element-based data structures produce much better cache utilization by relegating the work that requires indirect addressing to vector operations, and recasting the majority of the work of the matrix-vector product as local element-wise dense matrix operations. The hexahedral meshes stem from wavelength-adapted octrees, which are more easily generated than general unstructured tetrahedral meshes. Finally, the hexahedra all have the same element stiffness matrices, modulo element size and material properties, and thus there is no need for matrix storage. Consequently, the hexahedral version of the code is several times faster, a factor of ten more memory-efficient, and easier to scale up to large problem sizes than the tetrahedral version. Our latest version combines the best of structured and unstructured mesh methods, the low memory per grid point characteristic of regular grid codes, along with the local adaptivity and multiresolution of unstructured codes.

Our goal is to simulate the distribution in space and time of the ground motion that will be generated when a large earthquake occurs. The essential difficulty is the large uncertainty associated with the location and properties of fault rupture. From the geological setting of the LAB, however, we know that future earthquakes are most likely to occur along faults that are mapped (Fig. 1) or blind thrust-fault zones that can be inferred from geological data (Shaw, 1999). Since scientists cannot predict exactly where the next large earthquake will hit a region, we propose an approach that provides increasingly smaller levels of uncertainty. The approach involves large numbers of large-scale simulations, which will require radical improvement IT tools for the amount of computation and data.

Our previous ground motion simulations have been limited to frequencies below about 1 Hz, both due to computational limitations and to physical limitations of the existing models. For assessing the impacts on the built-environment, however, we need to consider ground motions with frequencies up to the order of 10 Hz. To this end, we use a hybrid scheme that combines a deterministic and a stochastic approach for incorporating, respectively, the effects of low and high frequencies. Low frequency (< 1 Hz) ground motion is simulated deterministically with the finite element models. High frequencies (> 1 Hz) are calculated by the stochastic Green's function method (e.g., Kamae, 1998). We calculate the strong motion using the results from the finite ele-


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ment method for frequencies from 0 to 1 Hz, and from the stochastic Green's function method from 0.5 Hz to 10 Hz, and the two sets are superposed with tapered filters. We have implemented this procedure and applied it for several locations on the surface of the San Fernando Valley for a simulation of the 1994 Northridge earthquake.

As example of this approach, Fig. 2a shows the distribution of the simulated peak ground velocity over the region of interest and Fig. 2b compares the observed and simulated velocity values at a number of stations in the San Fernando Valley.

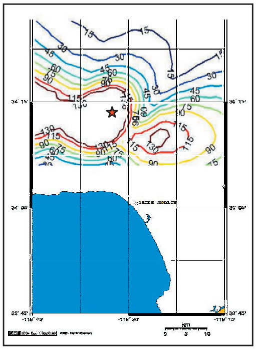

Figure 2a. Contour map for the simulated peak ground velocities in San Fernando Valley.

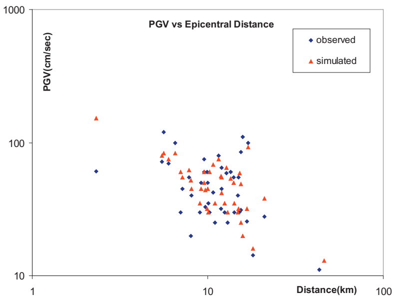


Figure 2b. Comparison of observed peak ground velocity values with the simulations.

## 3 PERFORMANCE BASED SIMULATIONS FOR THE BUILT ENVIRONMENT

Using the simulation models for ground motion to generate synthetics that match the criteria for an earthquake event, the next problem is to determine the impacts of the ground motion on the built-environment in an entire urban region. A new paradigm for designing buildings, bridges, and the lifeline systems is based on the fundamental concept that the desired performance of an individual structure to fulfill a specific function can be defined. The definition of performance must be probabilistic because of the unknown properties of expected earthquakes, as described previously, and uncertain information about the building itself. For example, a performance specification could be that a building has a suitably low probability of collapse over a specified period of time (such as 100 years). Performance objectives must include protection of human life. It is becoming increasingly important, however, that performance objectives also include the cost of economic losses, resulting from damage and downtime. The performance approach is ideal for expanding beyond single structures to systems of structures, which can include for example networks, such as transportation networks, or the economic impacts on an entire city.

We work closely with the NSF-sponsored Pacific Earthquake Engineering Research Center (PEER) in its research mission on *Performance-Based Earthquake Engineering* (PBEE). PEER is developing methods that represent the likelihood of failing to achieve a desired performance level given the aleatory and epistemic uncertainties associated with performance evaluation and design. The power of the performance-based approach is that performance objectives are formulated on the engineering (prevention of collapse), functional (preserve operation of the facility), social (enable service of emergency facilities) and economic (reduce direct and indirect costs) plans considering a portfolio of extreme events that vary in their intensity and likelihood. Such performance-based decisions are made using a sparse set of realizations because relatively few earthquakes occur in time-scales of interest in engineering. This is a major limitation that must be overcome.

Our work in PEER and the SPUR project is beginning to address the fundamental question of how to determine the performance of an entire urban region in a major earthquake by a spectrum of measurements. We have developed structural simulation models and performance measures for individual structures for inventories of specific classes of structures (housing, business infrastructure, education campuses) within an entire region. Individual structures will have on the order of 100 to 1000 degrees-of-freedom, which is not unusual in structural analysis practice today, but these numbers are multiplied by hundreds of thousands of structures considered in the LAB region. For each structure, we have developed parallel computing methods to analyze efficiently the entire inventory for ensembles of ground motions, and process the performance measures (Park, 2004).

As an example of this approach, we have examined an idealized strike-slip fault earthquake of M=6 in a region of 12 km square. The ground motion simulations are used to define the horizontal acceleration on a grid of 120 m spacing. As one example, at each of the approximately 25,000 grid points the dynamic response of 9-story steel moment-resisting frames are computed with inelastic frame elements under large-displacement. Based on the individual nonlinear dynamic analyses at each grid point, Fig. 3 shows the distribution of maximum plastic rotation in the beams for frames oriented in the fault normal direction. The effect of the forward directivity effect (from the epicenter at the west end of the fault) is clear with buildings at the east end of the fault having plastic rotations greater than 0.025 rad. The maximum plastic deformation decreases very quickly at distances more than 1 km from the forward directivity zone. Extending the methodology to structural design, Fig. 4 shows the required seismic coefficient to limit the interstory drift of 9-story buildings to 2% (0.02) based on the ground motion simulations for the idealized event.

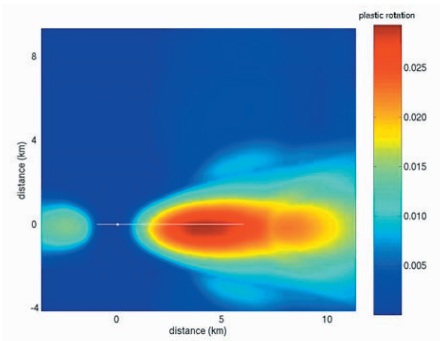


Figure 3. Maximum plastic rotation in beams of 9-story steel buildings to idealized M=6 strike-slip fault for frames in the fault normal direction.

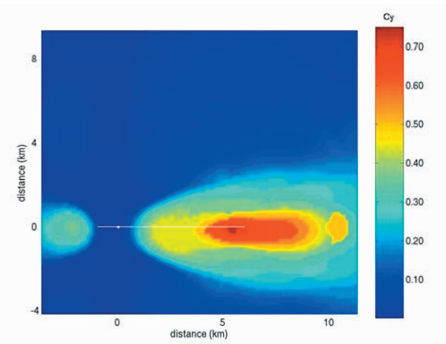


Figure 4. Seismic coefficient required to limit interstory drift to 2% for steel moment resisting building frames oriented in fault normal direction for M=6 idealized strike-slip fault.

The performance-based approaches not only individual structures, but also interconnected systems that will include building inventories and lifeline systems. Dynamic interactions between these components, such as through structure-soil-structure interaction will be included based upon our preliminary investigations (Fernández, 2003). Using this simulation approach, entire transportation systems can be represented, including individual components, such as bridges, and interconnections such as roadways.

## 4 VISUALIZATION AND INFORMATION TECHNOLOGY TOOL

As part of the SPUR project, we have developed visualization methods to show the ground motion and building response (Meyer, 2001; Chopra, 2003). These visualization tools allow users to select regions of interest and view ground motion and building response in the region at various scales, which presents tremendous challenges for multi-scale rendering on a variety of displays.

The entire simulation methodology is being made accessible to users and decision-makers by utilizing distributed resources and portals. A combination of recent technology trends and research advances make it feasible to utilize the Grid for this ambitious project (Foster, 2004). The middleware aggregates low-level Grid Services into high-level, functional blocks augmented with application domain-specific services.

As example of this approach, Fig. 5 shows a screen-shot of a web portal developed for the SPUR project (called SPURport) that allows users to access a variety of the models and data from a database, select building models and inventories to examine, schedule a simulation on a remote compute resources, and visualize the regional response after the simulation has completed (Haupt, 2004). The details of the communication and resource allocation are hidden in the middleware level, for which the user need not be concerned.

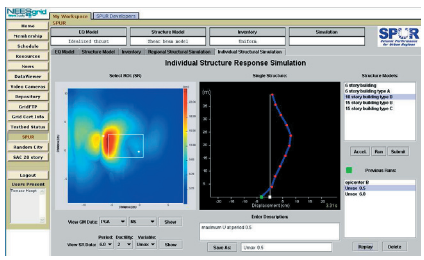


Figure 5. Web portal for regional simulation in SPUR project.


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## 5 CONCLUSIONS

The significant findings of the SPUR research include:

- A new methodology for introducing the spatial variation of the incoming ground motion into a localized and detailed model of the soil and structures whose seismic behavior is of interest (Bielak, 2003).
- An understanding of the spatial effects of damage, particularly the near-fault effects, as measured by the interstory drift and plastic deformations in structures designed according to a range of seismic design requirements (Park, 2004).
- New real-time volume rendering algorithms for time-variant data to visualize the dynamic fault mechanisms on ground motion and multi-story building response in a region (Chopra, 2003).
- *SPURport*--a Web portal that demonstrates the integration capability of NEESgrid for real-time simulations and visualizations of the structure performance (Haupt, 2004).

The SPUR research program has served to demonstrate that simulations can provide essential knowledge about the effects of large earthquakes on urban regions at a scale that has not been available to date. The current project has focused on developing essential core simulation and visualization methods. Further research is needed to use the simulation approach as a sophisticated tool for loss estimation in a region. Seismic risk analysis typically relies on a stochastic model describing the occurrences of earthquakes in time and space, and a model to assess damages and related costs for given earthquakes. In current practice, loss estimation for individual structures and building inventories is based on simple predictors of damage, typically the peak ground acceleration or other such measure estimated from attenuation laws. These estimates do not fully account for the effects of source mechanism and regional characteristics, nor do they provide detailed modeling of local site effects or structural characteristics. New approaches are needed to provide a realistic characterization of the regional seismic setting and its supported infrastructure. Together with a stochastic earthquake occurrence model, it will be possible to develop a predictive loss estimation model for a variety of societal-scale applications. These may include life-cycle cost estimation for critical buildings for use in design or retrofit decisions, or loss estimation for urban regions for zoning and planning decisions. Such applications are of considerable value to insurance companies and to owners of major buildings as well as to local and state governments.

Modeling alone, however, does not support a full spectrum of societal-scale applications for pre-event emergency planning and seismic micro-zonation, and post-event emergency response and recovery planning. These applications require the following:

1. Probabilistic representation of earthquakes and their effects on the built-environment for unbiased assessment of damage and risk appropriate for decision-making.
2. A probabilistic information processing mechanism, whereby post-earthquake observations and those recorded during the event itself can be used to update and refine predictive simulation models.
3. An information infrastructure capable of handling the multi-dimensional spatial and temporal nature of the urban region problem, as well as the enormous amounts of data.
4. Analysis and visualization tools to enable probabilistic spatial and temporal fusion of post-earthquake observations and pre-computed simulation data.
5. Scalability of simulations, databases, and visualization methods to regions 100s of kilometers in extent, 100s of fault scenarios, $O(10^6)$ buildings, and lifeline systems such as transportation and utility networks.

These important issues are under investigation to extend the simulation results developed for the SPUR project.

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