Earthquake Ground Motion Modeling in Large Basins

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I. Project Summary

THE main objective of our research is to develop the capability for predicting, by computer simulation, the ground motion of large basins during strong earthquakes, and to use this capability to study the seismic response of the Greater Los Angeles Basin.

Research in both computational mechanics and computer science is necessary to achieve this goal. Computational mechanics research is concerned with the development of parallel numerical methods for simulation of large-scale wave propagation through nonlinear heterogeneous media. This includes absorbing boundaries, treatment of attenuation, and techniques for incorporating seismic excitations and nonlinear constitutive laws.

Research in computer science focuses on building a software toolchain, called Archimedes, for automated solution of PDE problems on parallel computers. Archimedes is designed to insulate the user from issues of parallelism and communication, and to allow easy and natural expression of finite element methods and solvers. A central feature of Archimedes is its support of unstructured meshes, such as those that arise in seismic modeling.

These numerical methods and parallel software tools are used to model and understand the earthquake-induced ground motion of realistic basins. The knowledge gained is essential for design of earthquake-resistant structures adapted to local site conditions, leading to the reduction of seismic risk.

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II. Area Background

The reduction of the earthquake hazard to the general population is central to the mission of the National Earthquake Hazard Reduction Program. To this end, it is essential that within seismic regions new facilities be designed to resist earthquakes and existing structures be retrofitted as necessary. Assessing the free-field ground motion to which a structure will be exposed during its lifetime is a critical first step in the design process. Ground motion is usually specified through seismic design spectra, which essentially prescribe an equivalent lateral force that the structure must withstand without failure. This force, which is a function of the fundamental natural period of the structure, is based upon past seismic history in the general geographic location and position with respect to possible earthquake sources such as active faults, expected earthquake magnitudes, and general geologic conditions.

Observations of ground motion during recent strong earthquakes have shown, however, that three-dimensional local site effects, which are normally given only passing attention in design, can be extremely significant, and can adversely affect structural safety. Three common effects often observed in basins or sedimentary valleys are an amplification and significantly longer duration of the surface ground motion with respect to that on rock, as well as a more rapid spatial variation of the ground motion which can cause large differential base motion of extended structures such as bridges or dams.

Examples of all these effects are plentiful. Perhaps the most dramatic recent occurrences are those in Mexico City in 1985 and within the San Francisco Bay area during the 1989 Loma Prieta earthquake. For both of these events and their aftershocks, amplifications greater than 4 or 5 and durations of up to 15 to 30 seconds greater than the corresponding motion on rock were quite common, due to local site conditions. Studies of these and other earthquakes indicate that the presence of large sediment-filled basins significantly amplifies the strength of the waves observed within the basins.

It is now generally recognized that while one- and two-dimensional local models can help explain observed behavior in certain situations, a complete quantitative understanding of strong ground motion in large basins requires a simultaneous consideration of three-dimensional effects of earthquake source, propagation path, and local site conditions. Furthermore, in the case of soft to medium soils, or if the excitation is unusually strong, consideration of the inelastic behavior of the soil material also becomes necessary. The large scale associated with modeling strong ground motion in large basins, as well as its nonlinearity, conspire to place enormous demands on computational resources, and place this problem among the "Grand Challenges" in high performance computing.

Simulating the earthquake response of a large basin is accomplished by numerically solving the partial differential equations (PDEs) of elastic (or elasto-plastic) wave propagation through a highly heterogeneous medium. Special considerations include

(i) the incorporation of absorbing boundaries that allow waves to pass out of the computational domain with minimum reflection, (ii) modeling the source and propagation path, and (iii) introducing attenuation into the numerical model.

A variety of numerical methods have been used for approximating the solution of these problems. While boundary element methods have been popular for moderately-sized linear models, the inhomogeneity, nonlinearity, and large scale of such basins as the Greater Los Angeles Basin preclude their use here. On the other hand, uniform grid domain methods such as finite differences become impractical for the very large problem sizes involved. Consider, for example, the Los Angeles Basin. For a shear wave velocity of 0.4km/s and a frequency of 2Hz, a regular discretization of the elasticity operator would place grid points 0.02km apart to achieve second order accuracy. The region of interest has dimensions 140km$\times$100km$\times$20km; thus, a regular discretization, governed by the softest layer, requires 35 billion grid points with three displacement components per node. At least a terabyte of primary memory would be needed, and on the order of 10^{13} operations would be required at each time step. The stability condition associated with explicit time integration of the semidiscrete equations of motion imposes a time increment at least as small as 0.004s. Thus, a teraflop computer would have to run for three days to simulate a minute of shaking.

Instead, we have been developing unstructured mesh methods that tailor the mesh size to the local wavelength of propagating waves. For a basin such as Los Angeles, shear wave velocity varies from 0.4km/s to 3.5km/s. Since mesh density varies with the cube of shear wave velocity, and since the softest soils are concentrated in the top layers, this means that an adaptive method may result in two to three orders of magnitude fewer equations than with structured grids. With the development of such methods, modeling Los Angeles for realistic values of earthquake period and wave velocity becomes practical on the largest of today's parallel supercomputers. We favor finite element methods for spatial approximation, for their ability to efficiently resolve multiscale phenomena as well as their firm theoretical foundation. For temporal approximation, we have used both explicit and preconditioned conjugate gradient-based implicit methods. We have found that our mesh generators give us such good control over mesh resolution that the Courant condition is not onerous, with the result that implicit methods are generally less efficient than explicit methods.

While unstructured mesh methods for simulating wave propagation through heterogeneous media result in many fewer equations, they introduce a number of computational difficulties that must be overcome. First, mesh resolution must closely follow wavelength; too coarse a resolution will introduce error, too fine will result in unnecessary computation as well as excessively small time steps (when explicit integration methods are used). Second, mesh aspect ratios must remain close to one; large aspect ratios will eventually result in instability in time. Third, unstructured mesh methods are not easy to program on parallel computers; their irregular data structures require nontrivial mappings onto parallel machines, and irregular communication patterns are generated. Our computer science research focuses on two areas: fast, robust computational geometry and mesh generation techniques for highly spatially-variable meshes; and compilers and tools that simplify the programming of unstructured mesh methods on parallel systems.

As we have seen, seismic wave propagation problems place special demands on mesh generators, including the need for tight control over mesh resolution and aspect ratio, and the need to support extremely large problem sizes. We have been developing fast, stable, and efficient computational geometry and meshing algorithms for generating very large scale meshes, as needed for the large basins we target. Since repeated computations will be performed with a single mesh (one or two dozen earthquake scenarios, each involving thousands of time steps), we have decided to generate and partition the meshes sequentially. However, care must be taken in designing and implementing efficient algorithms for these steps, lest they become the bottlenecks. Additionally, 3-D tetrahedral mesh generation can fail dramatically due to floating-point roundoff errors when processing near-degenerate geometric features. To overcome this problem, we have developed a new adaptive method for fast exact arithmetic, and have implemented it in a C library. We have used the resulting meshing algorithms to create a mesh of the San Fernando Basin, containing 28 million tetrahedra, in 4 hours on one processor of a DEC 8400. The mesh has a maximum aspect ratio of 5.6 and includes a spatial resolution variability of an order of magnitude. This demonstrates the speed and stability of the meshing algorithms.

Our tool and compiler effort is based on Archimedes, an integrated system for automated solution of PDE problems on parallel computers (see http://www.cs.cmu.edu/afs/cs.cmu.edu-/project/quake/public/www/archimedes.html). A central feature of Archimedes is its support for efficient mapping of unstructured mesh computations arising from numerical solution of PDEs on parallel systems. Archimedes is designed to insulate the user from issues of parallelism and communication, and to allow easy and natural expression of unstructured mesh finite element methods and solvers. The tools employ innovative algorithms for mesh generation, partitioning, and unstructured parallel computation as a base upon which advanced methods for numerical solution of wave propagation problems may be implemented by application specialists.

Input to Archimedes includes (i) the problem geometry, and (ii) a sequential program containing an element-level description of the finite element approximation as well as a MATLAB-like high-level description of the solution method. The input program is written in C, augmented with finite-element and linear algebra-specific primitive operations that include vector and matrix assembly, boundary condition imposition, sparse matrix-vector products, dot products, and preconditioning. Additional functions are specific to elastic wave propagation, and include absorbing boundaries, damping, and seismic input incorporation. Archimedes programs contain no explicit communication statements, and thus are written without any knowledge of the parallel machine's underlying communication system. Archimedes provides an implementation of the quality mesh generator discussed above, and a provably-asymptotically optimal mesh partitioner that runs in $O(N)$ time. The parallelizing compiler generates code for any parallel system with C and MPI implementations, including networks of workstations (using the Argonne/Mississippi State MPICH implementation), Intel Paragon (also using MPICH) and the Cray T3D (using the CRI/EPCC MPI implementation).

We have used Archimedes to build an explicit elastic wave propagation code. The code is currently being used to study the earthquake-induced dynamics of the San Fernando Basin. Results of a typical simulation, in which the basin was subjected to a model earthquake excitation with a maximum frequency of 2Hz, indicate a factor of amplification of eight in the softer parts of the basin compared to that on rock, suggesting substantially greater damage in these regions (see http://www.cs.cmu.edu/afs/cs.cmu.edu/project/quake/public-

/www/sf.html). The simulation involved a mesh of 14 million tetrahedra and 7.5 million equations, and was performed in 6 hours on 64 processors of the T3D at the Pittsburgh Supercomputing Center.

III. Related Research Areas

A number of the numerical and computational issues faced in modeling earthquake-induced ground motion are shared by many other applications in computational science and engineering. Unstructured mesh methods are desirable for PDE problems that exhibit multiscale phenomena, or are characterized by complex geometries—exactly the set of problems that Archimedes addresses. We are planning a public release of this software toolchain to benefit researchers in other areas who are interested in using parallel machines for unstructured mesh computations (portions have already been released). Many such researchers don't wish to bother with low level details of programming a parallel machine, yet still want the efficiency associated with a message-passing code. The Archimedes compiler/runtime system is designed so that it can be extended by users without having to rebuild the system. For example, users can write their own parallel preconditioner routines and register them with the Archimedes compiler without recompiling any code. This is a key idea because it provides a mechanism for the system to grow and evolve.

Our approach for allowing users to arbitrarily extend the Archimedes compiler/runtime system is based on a novel compile-time interpreter called Catacomb. The idea is to replace functions typically found in run-time libraries with Catacomb functions that are interpreted at compile-time. This approach provides the extensibility of interpreted systems like Matlab, while avoiding the inefficiency of run-time interpretation. Further, it eliminates the combinatorial explosion problem that plagues run-time libraries as the number of independent problem dimensions increases. The Catacomb idea of compile-time interpretation has been successfully integrated into an HPF compiler for the Intel Paragon and the Cray T3D, and is currently being integrated into Archimedes.

The mesh generation aspects of our work are applicable to a much broader spectrum of problems. Indeed, since the release of Archimedes' quality 2-D mesh generator last summer, it has been adopted by hundreds of users around the world for such diverse problems as computer graphics radiosity, stereo vision, interpolation of speech signals, computer animation, electrical currents in the heart, transport processes in estuaries, Schrödinger's equation in quantum confined structures, triangulation of survey data, and realtime simulation of terrain. Furthermore, the adaptive exact arithmetic library will soon be made publicly available to benefit other researchers in computational geometry and mesh generation.

IV. Potential Related Projects

We plan on extending the ground motion modeling work in two directions in the future. First, we intend to use our parallel codes to model other heavily-populated, seismically-active basins, such as Kanto and Kobe in Japan, Mexico City, and San Francisco. Three-dimensional site effects have been observed in these basins during recent strong earthquakes, and work on characterizing the sites is progressing, making computer simulation viable.

The second direction in which we intend to move is to model earthquake-induced liquefaction in large basins. Recent advances in the development of constitutive laws for soil materials make it now possible to take into consideration the interaction of the pore fluid (water) with the soil skeleton. This two-phase behavior allows the realistic modeling of the evolution of soil deformation up to the point of failure due to increased pore pressure under transient excitation. The highly nonlinear phenomenon of liquefaction will necessitate dynamically-adaptive meshing for tracking slip fronts, with its attendant difficulties on parallel systems. The complexity and large scale of computations associated with liquefaction modeling will require the next generation of parallel supercomputers.

Ultimately, it will be desirable to treat seismic basin models in a stochastic rather than deterministic manner. This entails running large numbers of individual simulations, stemming from the uncertainties in material properties and the need to simulate different fault scenarios, which places even greater demands on supercomputing performance. The development of petaflop-level computing will be instrumental to the success of such an approach.

V. Further Information

The project is supported under NSF's Grand Challenges Initiative, award number ASC-9318163. The NSF program area is Siting and Geotechnical Systems (CMS/ENG), with Dr. Clifford Astill as program manager. The contact for the project is Prof. Jacobo Bielak. Further information may be obtained from http://www.cs.cmu.edu/~quake.

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