Immersive Volume Visualization Of Seismic Simulations: A Case Study Of Techniques Invented And Lessons Learned

Prashant Chopra and Joerg Meyer*
Engineering Research Center
Mississippi State University

Antonio Fernandez+
Department of Civil and Environmental Engineering
Carnegie Mellon University

Abstract

This paper is a documentation of techniques invented, results obtained and lessons learned while creating visualization algorithms to render outputs of large-scale seismic simulations. The objective is the development of techniques for a collaborative simulation and visualization shared between structural engineers, seismologists, and computer scientists. The computer graphics research community has been witnessing a large number of exemplary publications addressing the challenges faced while trying to visualize both large-scale surface and volumetric datasets. From a visualization perspective, issues like data pre-processing (simplification, sampling, filtering, etc.), rendering algorithms (surface and volume), and interaction paradigms (large-scale, highly interactive, highly immersive, etc.) have been areas of study. In this light, we outline and describe the milestones achieved in a large-scale simulation and visualization project, which opened the scope for combining existing techniques with new methods, especially in those cases where no existing methods were suitable. We elucidate the data simplification and re-organization schemes that we used, and we discuss the problems encountered and the solutions we found. We describe both desktop (high-end local as well as remote) interfaces and immersive visualization systems that we developed to employ interactive surface and volume rendering algorithms. Finally, we describe the results obtained, challenges that still need to be addressed, and ongoing efforts to meet the challenges of large-scale visualization.

1 INTRODUCTION

This case study describes the techniques invented and lessons learned in the transition from 2D contour plots to immersive volume visualization. The application is a simulation and visualization of seismic performance of urban regions (SPUR). We present ideas, models, challenges, and algorithms that encompass every stage of the project, from 2D plots to our recent near-interactive volume visualization system. A team of civil engineers, structural engineers, and computer scientists from the University of California, Berkeley, Carnegie Mellon University at Pittsburgh, and the Engineering Research Center at Mississippi State has been pursuing this ongoing effort to model and visualize seismic performance.

* {prash | jmeyer}@erc.msstate.edu
http://www.erc.msstate.edu/~jmeyer/SPUR/

+ antoniof@andrew.cmu.edu
http://www.ce.cmu.edu

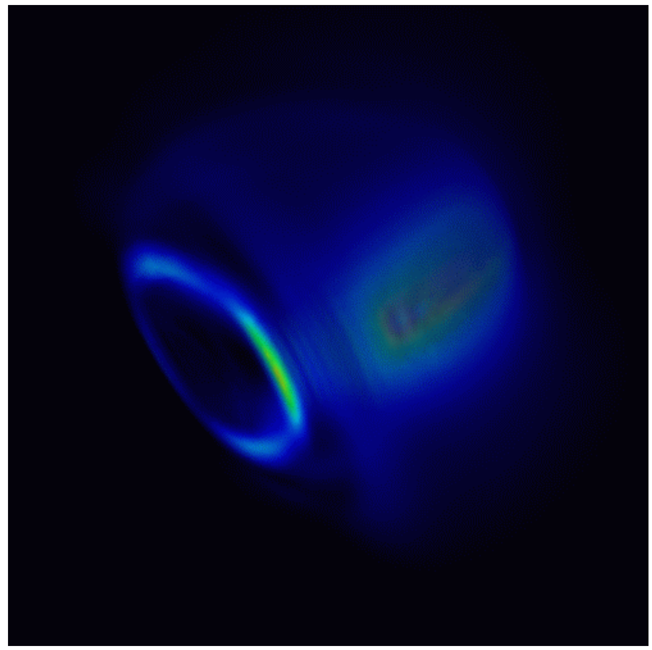


Figure 1: A snapshot from interactive volume rendering of the fault region of a simulation (200th of 800 time steps). Voxel colors indicate respective velocity vector magnitudes in the selected time step.

Civil engineers from the team at CMU created a model of ground motion in a basin with a source of seismic energy (epicenter) that travels along a fault. Structural engineers from UCB simulate the response of structural units on the top surface of this basin model based on the ground motion attributes. The computer graphics group implemented visualization algorithms and techniques to better understand these two model simulations in a single, common 'picture'. The basic geometry of the dataset consists of 11,800,639 vertices forming 69,448,288 tetrahedral cells. The domain of the dataset comprises four dimensions, and each vertex has a velocity vector in 800 time steps.

2 GROUND MOTION SIMULATION

We describe a finite element formulation for modeling earthquake ground motion in sedimentary basins. The basin is modeled as a three-dimensional isotropic, heterogeneous anelastic medium. The domain is limited by absorbing boundaries that limit the amount and magnitude of spurious reflections. Previous generation of simulation was performed over the same basin geometry but with a point source of energy (please see Figure 4 for a point set rendering of one time step from the same basin with a point source). Currently, simulation is performed over the idealized model shown in Figure 2. The model incorporates an idealized extended strike-slip fault aligned with the coordinate system. The shaded area in Figure 2 represents such a fault. The computer analysis is performed on a Cray T3E parallel computer at the Pittsburgh Supercomputing Center. A total of 128 processors took almost 24 hours to calculate and store an 8 second velocity history of approximately 12 million nodes arranged in a three-dimensional grid. The required amount of disk space for this problem was approximately 130 GB.

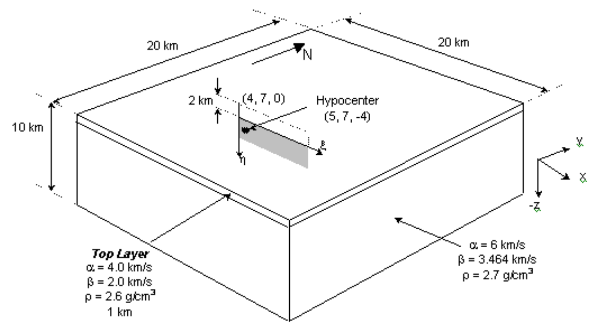
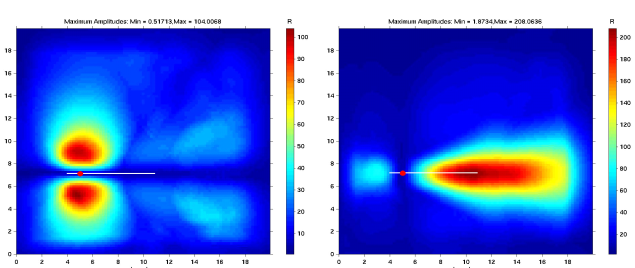


Figure 2: Layered half space with extended source fault.

3 VISUALIZATION METHODS

Figure 3 shows examples of 2D contour plots that civil engineers create as a first visualization aid for ground motion simulations. Although being just planar representations of the spread of seismic energy over time, these plots give very good insight into the behavior of the model, and also act as benchmarks to test and evaluate higher-order visualizations of the same simulations. 2D contour plots have been effective tools for civil engineers to understand the results of such simulations. However, these contours are not very intuitive when it comes to four-dimensional simulations that encompass the temporal dimension. The fact that there are two simulations that are performed over the same model (ground motion and structural response) adds to the complexity of the problem. To visualize the results of both simulations in an effective manner with today's technology has been one of the challenges of this project. The following sections describe the methods used to tackle this problem.



(a) Fault Parallel (b) Fault Normal Velocity

Figure 3: Maximum surface velocity contours for the model.

3.1 Static Point Set Rendering

Point set rendering was the first algorithm that was used to visualize the results of the simulations. The rendering was static, and the vertices were rendered one at a time. This first step gave insight into the third dimension of the dataset: it provided depth cues in addition to the surface information. All of the 11,800,639 vertices of the basin geometry were fed into the rendering pipeline of an SGI™ Octane as points, neglecting the tetrahedral connectivity information. Selected time steps were chosen, and the color represents the velocity vector magnitudes. The results matched the contour plots for a point energy source, and the energy spread symmetrically. Also, this visualization verified the deliberately higher density of vertices near the top surface of the basin (Figure 4).

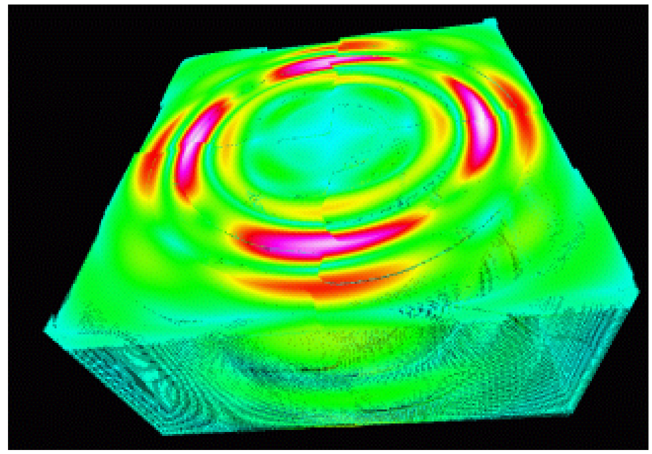


Figure 4: A view of the basin from the first generation of simulation rendered as a Point Set ('frozen' in time). Node colors indicate instantaneous velocity vector magnitudes.

3.2 Geometry-based Surface Rendering

In pursuit of a more interactive visualization system for all time steps, we explored images from point set renderings of the simulation, and identified the top layer as a region of interest (ROI). This layer was chosen because it represents best what the effects are on the structures. The top-layer extraction also reduced the amount of geometry that needs to be sent to the rendering pipeline tremendously. The layer forms a triangle mesh. Structural response simulation was performed for a select group of vertices on this mesh. Constrained random selection avoids cluttering of structural units in the rendered images. The extracted surface consists of just 57,121 nodes (222,790 triangles), and represents only the topmost layer of the layered basin model. This helped in maintaining interactive frame rates, keeping up with the 3D motion trackers for interactive display, and avoiding delayed responses in navigable environments, as described in section 3.3. The algorithm was implemented and worked well in an interactive, navigable visualization environment. We were thus able to successfully visualize all four dimensions (including time) of the two dependent simulations (ground motion and structural response) in the same animated image. As an alternative output modality and to make the visualization system available remotely, an interactive simulation and visualization web-portal was developed that generates structural response data for selected ground motion and location parameters on the fly (batch mode). The web portal enables the user to specify different views from different locations around the model. Rendered images are returned to the browser as animated GIF images, or as an MPEG movie.

3.3 Structural Response Visualization

The structural response simulation from the Civil & Environmental Engineering Department at Berkeley allowed buildings of same structural properties to be replicated on the top layer of the basin as primitive structural units (single degree-of-freedom, SDOF models). Both from a modeling and visualization perspective, each one of them could be modeled as a stick with a mass on the top, which moves in response to the shaking ground. In order to create a meaningful visualization for the Civil Engineers, we added four different visual cues to the visualization: the color of the surface nodes (velocity vector magnitude), the color of the roofs (structural response magnitude), displacement of the vertices of the basin (ground motion), and constrained motion of the tops of the buildings with their bases fixed to one of the nodes on the triangle mesh on the top layer of the basin (structural response).

3.4 Immersion

The temporal visualization of the results of the simulation was ported to interactive virtual environments, i.e., an ImmersaDesk™ and a four-walled CAVE Automated Virtual Environment (CAVE™) [2, 7, 8]. This added two more cues: stereo immersion, and audio (Figure 5).

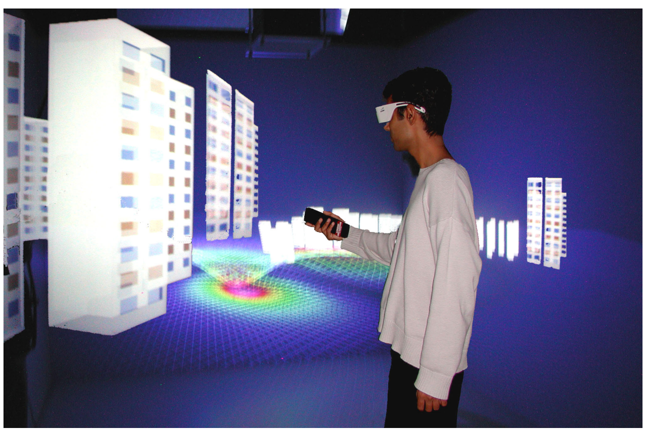


Figure 5: Geometry-based surface rendering of the top layer of the basin with structural units on selected vertices. Audio was added to give the user a feeling for the time that has elapsed since the earthquake occurred and how close it is. This snapshot is from the immersive visualization system in a CAVE™.

Although at this stage the behavior of the simulation models had been well understood, there was still much more to explore in the interior of the basin's volume. The next issue we studied was the spread of seismic energy from the epicenter before the earthquake's shock wave strikes the top layer. Thus, our next goal was to render the basin's volume with sufficient interactivity to allow the visualization of the eruption of seismic energy and its spread to the structural units on the top layer. We implemented novel progressive data reduction techniques for level-of-detail (LOD) prototyping of tetrahedral meshes of this scale (of the order of a 100 million cells), employing both geometry decimation and wavelets to re-organize the interior of the dataset for a more efficient representation (section 4).

3.5 Volume Rendering

After geometry decimation and data reduction as pre-processing steps to reduce the size-complexity of the whole dataset, the geometry was sampled into a regular rectilinear voxel grid. Special precautions were taken to avoid aliasing and super-sampling artifacts. This drastically reduced the size of the dataset from 14.16 GB to just 1.27 GB for the first 100 time steps. The dataset was then mapped into a 3D texture buffer. This compressed, node-indexed, binary re-organization aided in achieving near-interactive frame rates (< 3 sec.) for 3D texture-based volume visualization of the model. Applying affine transformations on 3D texture coordinates of the volume provided the desired interactivity to the visualization system. Figures 1 and 6 show the resulting snapshots from this system.

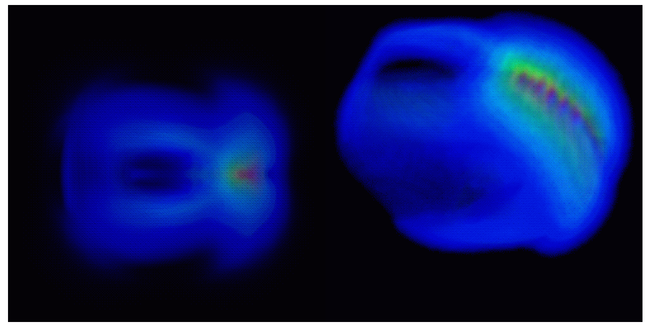


Figure 6: Two snapshots from volume rendering of select time steps of second-generation ground motion simulations (with extended point source fault region) on the basin (11,800,639 nodes), 'frozen' in time (selected time step). Node colors indicate respective velocity vector magnitudes in the selected time step.

Results of near-interactive volume visualization of the first few time steps (when the earthquake is still in its early stages) provided evidence that this visualization method is suitable for large-scale rendering. The resulting animated images comply with the orthogonal response of the fault region of the simulation model. The later time steps show the eruption and the effects on the soil and the surface.

Currently, a desktop visualization system and a CAVE™ system are operational. The desktop application supports a flight around the fault region where the seed cell of the earthquake can be seen in its early stages, as if it were breathing; ready to erupt, which is a breath-taking sight! Immersion adds additional cues (stereo vision, sound, walk-through navigation, etc.) to stimulate the senses of the observer.

4 DATA SIMPLIFICATION TECHNIQUES

The need for ever increasing high-end interactive visualization methods for large-scale datasets has been one of the driving forces for a survey of existing geometry based data-reduction techniques. Inspired by some of such existing algorithms [1, 3, 4, 5, 6, 9, 10, 11, 12, 13, 14, 15, 16], we created adapted tetrahedral-based simplification schemes to reduce the size-complexity of the model [8]. As a result, we are now ready to navigate in an immersive, near-interactive, temporal volume model of the simulation outputs.

5 ONGOING AND FUTURE WORK

This large-scale data research study aims at enabling interactive visualization of large datasets in a virtual environment (ImmersaDesk™, CAVE™) in real-time using hierarchical visualization techniques and level-of-detail methods. Specifically, new data-based techniques need to be explored, such as top-layer extraction, regions-of-interest in the spatial and temporal domain, etc. The goal is to make effective digital story-telling possible for simulation engineers and scientists using virtual environments.

We are currently working on the following four aspects of the project:

- Better simulation, i.e., more complex datasets, with geological faults.
- Hierarchical data organization techniques that will aid in near-interactive volume rendering of the entire model, e.g., progressive simplification and wavelet-based compression in four dimensions.
- Near-interactive volume rendering techniques, e.g., point-set-based methods, 3D texture-based volume rendering, etc.
- Better vector visualization paradigms and multi-data item representations.

Acknowledgements

Contributors: Gregory L. Fenves, Bozidar Stojadinovic (UC Berkeley), Jacobo Bielak, Antonio Fernandez, et al. (Carnegie Mellon University), Tomasz Haupt, Michael L. Stokes, Purushotham Bangalore (Mississippi State University). Supported by the National Science Foundation under award grant no. 6066047–0121989 for the SPUR project [2, 7, 8].

References

[1] Alliez, Pierre, and Mathieu Desbrun. Progressive Compression For Lossless Transmission Of Triangle Meshes. In *Proceedings of SIGGRAPH'01 (Los Angeles, California, August 2001)*, Computer Graphics Proceedings, Annual Conference Series, pages 198-205. ACM SIGGRAPH, ACM Press. August 2001.

[2] Chopra, P., J. Meyer, and Michael L. Stokes. Immersive Visualization Of A Very Large Scale Seismic Model. In *Sketches and Applications of SIGGRAPH'01 (Los Angeles, California, August 2001)*, page 107. ACM SIGGRAPH, ACM Press. August 2001.

[3] Cignoni, P., D. Costanza, C. Montani, C. Rocchini, and R. Scopigno. Simplification Of Tetrahedral Meshes With Accurate Error Evaluation. In Thomas Ertl, Bernd Hamann, and Amitabh Varshney, editors, *Proceedings of IEEE Visualization'00 (Salt Lake City, Utah, October 2000)*, pages 85-92. IEEE Computer Society. 2000.

[4] Garland, M. Multi-resolution modeling: Survey & Future Opportunities. In *EUROGRAPHICS'99, State of the Art Report (STAR) (Aire-la-Ville, CH, 1999)*, pages 111-131. Eurographics Association. 1999.

[5] Hoppe, Hugues. Progressive Meshes. In *Proceedings of SIGGRAPH'96 (New Orleans, Louisiana, August 1996)*, pages 99-108. ACM SIGGRAPH, ACM Press. August 1996.

[6] Isenburg, Martin, and Jack Snoeyink. Face Fixer: Compressing Polygon Meshes With Properties. In *Proceedings of SIGGRAPH'00 (New Orleans, Louisiana, July 23-28, 2000)*, pages 263-270. ACM SIGGRAPH, ACM Press. 2000.

[7] Meyer, J., and Prashant Chopra. Building shaker: Earthquake Simulation In A CAVE™. *Work in progress, IEEE Visualization'01 (San Diego, California, October 2001)*, Abstract, page 3. 2001.

[8] Meyer, J., and Prashant Chopra. Strategies For Rendering Large-Scale Tetrahedral Meshes For Earthquake Simulation. *SIAM/GD'01 (Sacramento, CA, November 2001)*, Abstract, page 30. 2001.

[9] Popovic, J., and Hoppe, H. Progressive Simplicial Complexes. In *Proceedings of SIGGRAPH'97*, pages 217-224. ACM SIGGRAPH, ACM Press. 1997.

[10] Renze, K. J., and J. H. Oliver. Generalized Unstructured Decimation. *IEEE Computer Graphics and Applications* 16 (6), pages 24-32. 1996.

[11] Schroeder, William J., Jonathan A. Zarge, and William E Lorensen. Decimation Of Triangle Meshes. *Computer Graphics* 26(2), pages 65-70. 1992.

[12] Schroeder, William J. A Topology Modifying Progressive Decimation Algorithm. In *Proceedings of IEEE Visualization '97*, pages 205-212. 1997.

[13] Staadt, O. G., and M. H. Gross. Progressive Tetrahedralizations. In *Proceedings of IEEE Visualization '98 (October 1998)*, pages 397-402. 1998.

[14] Trotts, Isaac J., Bernd Hamann, and Kenneth I. Joy. Simplification Of Tetrahedral Meshes. In *Proceedings of Visualization* 98 (October 1998), pages 287-296. 1998.

[15] Trotts, Isaac J., Bernd Hamann, and Kenneth I. Joy. Simplification Of Tetrahedral Meshes With Error Bounds. *IEEE Transactions on Visualization and Computer Graphics* 5 (3), pages 224-237. 1999.

[16] Turk, Greg. Re-tiling Polygonal Surfaces. *Computer Graphics*, 26(2), pages 55-64. 1992.