Regional Seismic Damage Prediction Based on High-performance GPU Computing: A case study of Tsinghua University campus

Zhen Xu[1], Xinzheng Lu[1,*], Bo Han[1], Chen Xiong[1], Aizhu Ren[1]

[1]Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing, P.R. China, 100084

ABSTRACT

The prediction of seismic damage to buildings in urban areas is an important technique for the mitigation and prevention of earthquake-induced destruction. A methodology is proposed for such predictions, based on high-performance graphics processing unit (GPU) computing, which is applied to a case study of a real university campus. Specifically, an overall framework is designed based on cooperation between the GPU and CPU. A high-fidelity structural model suitable for GPU computing is built and the thread structure of the GPU-based seismic damage prediction is discussed. Taking Tsinghua University campus as an example, the seismic damage to the entire campus is predicted efficiently by the proposed method and the detail of local damage on different stories is obtained explicitly. Furthermore, an increase in speed of approximately 21 times is achieved in comparison with a traditional CPU approach. The outcome of this study provides a critically important reference for the prevention and mitigation of urban disaster.

INTRODUCTION

A strong earthquake could cause large numbers of casualties and significant financial losses in urban areas because of the dense population and infrastructure. In recent years, very severe earthquakes, such as the 2008 Wenchuan earthquake 2010 Chile earthquake, and 2011 Tohoku earthquake have caused more than 10,000 casualties and great financial losses in the affected urban areas (Gonzalez-Huizar et al. 2012; Lorito et al. 2011; Ye et al. 2010). Therefore, the prediction of seismic damage in urban areas is extremely important both for assessing the potential seismic risk and for preventing earthquake-induced damage and losses.

Many studies have been investigated the prediction of seismic damage to urban buildings (FEMA 2012; Steelman and Hajjar 2009; Tang et al. 2011). Refined structural models and nonlinear time-history analysis (THA) are two major

[*] Corresponding author. Tel.: 86-10-62795364; E-mail: luxz@tsinghua.edu.cn.

improvements proposed in the above studies. Refined structural models improve the depiction of the dynamic characteristics of buildings, and nonlinear THA is able to consider fully the features of ground motion. Although refined models and nonlinear THA are widely adopted for individual buildings, it is difficult to use these two methods for urban areas, because numerous buildings cause a large amount of computational workload. For example, Hori (2011) proposed a seismic damage simulation system for urban areas, using nonlinear THA and refined models, called "integrated earthquake simulation". However, only supercomputers are able to meet the computational requirements demanded in simulating a large urban region (Wijerathne et al. 2013), which hinders the widespread application of such systems. Thus, a high-performance, but low-cost simulation method is required for regional seismic damage prediction.

Recently, high-performance computing based on graphics processing unit (GPU) has been developed. The GPU located within the display card of a computer was designed originally for graphics display purposes. However, due to the advantages of GPU in massive parallel computing, general-purpose computation using GPU (GPGPU) has grown far beyond the field of graphics (Sanders and Kandrot 2010). Although the performance of a single core of a GPU is relatively weak, there are many more cores on a GPU than there are on a CPU, which leads to much higher computing performance for a GPU compared with a similarly priced CPU (Lee et al. 2010). In 2006, the compute unified device architecture (CUDA) programming model was released by the NVIDIA Corporation (NVIDIA 2013), which solved many of the software and hardware problems of the GPGPU. Since that time, GPU computing has become widely used in many fields, e.g., biology, electromagnetism, and geography (Owens et al. 2007).

The GPU provides a good computing platform for seismic damage prediction in urban areas. Although there are thousands of buildings in an urban area, a GPU has hundreds of cores and each GPU core can be used for the simulation of one building. If each building is treated as a subtask and a proper structural model is adopted, the computational workload of each subtask can be very suitable to be performed on a single GPU core. In such a simulation, the CPU is only required to implement several task assignment rounds, and the vast majority of the computational load can be run on the GPU platform. Furthermore, data exchange between different GPU cores can be ignored, because there is little interaction between individual buildings during an earthquake. Thus, the GPU can reach its full potential of parallel computing, which means that the computational efficiency of regional seismic damage prediction using GPU should be very high.

However, GPU-based seismic damage prediction has not yet been widely studied and thus, the number of related case studies is limited (Lu et al. 2014). Hence, there are some challenging problems to be solved, e.g., proposing a reasonable framework for cooperation between the GPU and CPU in seismic damage prediction, and constructing a proper structural model of the buildings for the GPU computing.

In this study, a parallel computing methodology based on GPU is proposed for seismic damage predictions in urban areas. Specifically, an overall framework is proposed for cooperative work between the GPU and CPU in seismic damage prediction. A high-fidelity structural model is built, which is suitable for GPU computing, and the thread structure of GPU-based seismic damage prediction is discussed. Taking a typical Chinese university campus (i.e., Tsinghua University) as an example, the detailed processes both of modeling the entire campus and of predicting the seismic damage results are presented, demonstrating the advantages of the proposed technique. The outcome of this study provides a critically important reference for the prevention and mitigation of urban disaster.

COMPUTATIONAL METHOD

The difference in floating-point capabilities between the CPU and the GPU is that the GPU is specialized for compute-intensive, highly parallel computation, whereas the CPU is more suitable for problems that can be expressed as complicated logic computations (NVIDIA 2013). To exploit the advantages of the GPU and CPU, respectively, the CPU should be in charge of task assignment and the GPU is used to implement the seismic damage predictions of massive buildings. A framework for the GPU/CPU cooperative computing is proposed for regional seismic damage prediction, as illustrated in Figure 1.

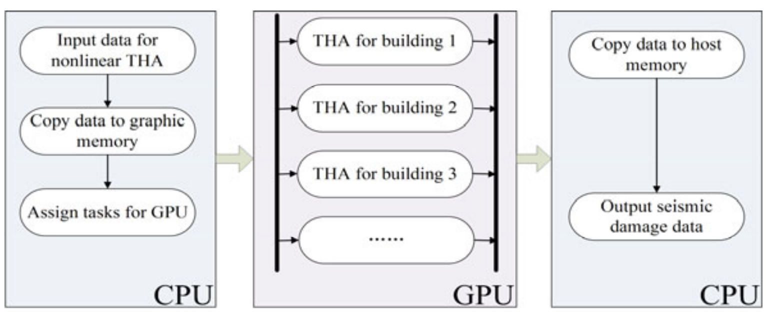

Figure 1. Framework of GPU/CPU cooperative computing.

In this framework, each building corresponds to a thread. Therefore, as many threads as possible should be run on the GPU to guarantee high efficiency. However, there are two important problems with this framework: (1) building a proper structural model is suitable for GPU threads, and (2) determining a reasonable structure of GPU threads that can exploit fully the GPU computational capability.

High-fidelity structural model. To balance the computational workload and accuracy, the multi-story concentrated-mass shear (MCS) model is adopted for the GPU-based seismic damage prediction, as illustrated in Figure 2. Compared with other refined finite element models, the MCS model does not demand extreme computational workload or complex logic computations. Furthermore, there is no interaction between individual buildings during an earthquake in the MCS model. Hence, it is very suitable for the computing capability of a single GPU core.

The accuracy of the MCS model is dominated by the inter-story hysteretic behavior model. In this study, the inter-story hysteretic behavior model is determined according to the method proposed by Xu et al. (2013). Using the MCS model, the seismic damage to buildings in a dense urban area, especially the local seismic damage to different stories of each individual building, can be predicted accurately.

Thread structure. Owing to hardware limitations of the GPU, the thread structure has an important influence on the efficiency of GPU computing. In this study, the CUDA is adopted as the development platform for GPU computing. There are three levels in the thread structure of CUDA: grid, block, and thread (NVIDIA 2013). In this study, the entire area is organized into one grid, so that the block size (i.e., the number of threads in a block) determines the thread structure.

To determine the block size, a benchmark of regional building seismic damage prediction is implemented. In this benchmark, a 2.4-GHz Intel Celeron E3200 CPU and an NVIDIA GeForce GTX 460 with 1 GB graphics memory are adopted as the hardware platform. Then, 1,024 buildings with different structure types and different numbers of stories are generated randomly. The well-known El-Centro earthquake ground motion with the peak ground acceleration (PGA) of 200 cm/s^2 is selected as the earthquake input. When implementing single-precision GPU-based computing, the relationship between computing time and block size is obtained, as presented in Figure 3. It shows that the peak computing performance is achieved when the block size is equal to 32. Therefore, the block size is set to 32 in this study.

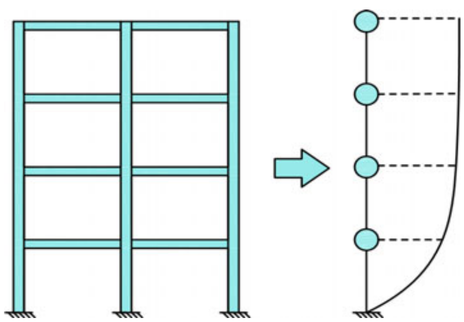

Figure 2. MCS model for a building.

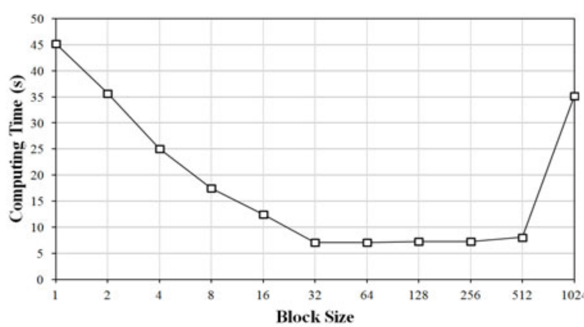

Figure 3. Relationship between computing time and block size.

CASE STUDY

A typical Chinese university campus, Tsinghua University, is selected as the case study. It covers an area of 389.4 ha and has more than 600 buildings of differing structural type and with various numbers of stories.

Structural model. Determining the parameters in the inter-story hysteretic model is the most important task in establishing the structural model for seismic damage prediction.

According to the building types proposed in HAZUS (FEMA 2012), the buildings of the Tsinghua campus can be divided into several groups. Typical buildings are selected from each building group. Then, using the fiber beam element model and multi-layer shell model (Lu et al. 2013), refined finite element building models are created for the selected typical buildings, and the inter-story force-displacement relationships are obtained via a cyclic pushover analysis. Simultaneously, using the hysteretic model recommended by Xu et al. (2013), a cyclic pushover analysis of the MCS model is also conducted for the same building. The parameters of the hysteretic model in the MCS model are continuously modified until the two inter-story force-displacement relations agree with each other. Once the parameters of the inter-story hysteretic model of a typical building have been determined, these parameters are mapped to the inter-story hysteretic model of all the remaining buildings within the same group, according to certain factors (e.g., number and area of stories) (Hori 2011; Xu et al. 2013).

Using this modeling method, only a few typical buildings require detailed design data, and most of the buildings simply require common factors, which can be obtained from the GIS database of the campus. For some special buildings that do not belong to any specific building group, the inter-story behavior can be determined by a pushover analysis using more detailed numerical models.

GPU-based computing. The main task of GPU-based computing is solving the dynamic equations of the MCS model. If implicit dynamic computing is adopted, the GPU computing time will increase significantly because of the additional logical operations induced by the nonlinear iterations. Furthermore, the convergence problem might occur when using an implicit dynamic algorithm. Thus, in this study, the central difference method is used to solve the dynamic equations.

Setting up the thread structure is a necessary step prior to the GPU computing. In CUDA, the thread structure is defined as a specific form, i.e., <<<grid, block, thread>>>. According to the above discussion, a block should include 32 threads with which the GPU can attain peak computing performance. There are 615 buildings within the Tsinghua campus, which means that the number of blocks within a grid should equal 615/32 + 1, i.e. 20. This guarantees that the number of threads can cover all the buildings within the campus.

Prediction results. The well-known Chi-Chi earthquake ground motion with a

PGA of 431 cm/s^2 is selected as the ground motion for the seismic damage prediction of Tsinghua campus. The computational time and number of time steps are 40 s and 8,000 steps, respectively.

To compare the computing efficiency of a GPU with that of a CPU, two different platforms are adopted as follows:

CPU platform: A 2.93-GHz Intel Core i3 530 processor with 4 GB of 1333-MHz DDR3 RAM.

GPU platform: A 2.4-GHz Intel Celeron E3200 CPU & an NVIDIA GeForce GTX 460 with 1 GB graphics memory.

The hardware of the two platforms was similarly priced (approximately 150 US dollars) in 2011; thus, they can be used to compare their performance-to-price ratio. Only one CPU core is used in this prediction. To prevent the bottleneck effect caused by the reading and writing speed of the hard disk, the time of data input and output is not included in the computational time. Furthermore, both platforms use single-precision computing for the seismic damage prediction.

For the seismic damage prediction of all 615 buildings within the campus, the GPU-based computing costs 7.03 s, whereas the CPU-based computing costs 149.22 s, i.e., a performance-to-price ratio of 21.2 is achieved. The relationship between computational time and the number of buildings is presented in Figure 4. Note that the slope of the CPU curve is significantly larger than that of the GPU curve. This means that with the increase in the number of buildings, the performance-to-price ratio of the GPU will increase. Using GPU computing, the seismic damage prediction of an urban area with 7449 buildings costs only 22 s, and the efficiency is 40 times that of CPU computing (Lu et al. 2014). Therefore, the proposed GPU-based method is very suitable for the regional seismic prediction of a large number of buildings.

Based on the proposed method, the seismic damage of the entire campus is predicted, as demonstrated in Figure 5. Referring to HAZUS (FEMA 2012), five damage states (i.e., none, slight, moderate, extensive, and complete) are defined to evaluate the building damage. The MCS model adopted in this study can explicitly provide details of the local damage inflicted on the different stories, as shown in Figure 6. This provides a more detailed seismic damage result, which can better serve the evaluation and prevention of earthquake-induced disaster.

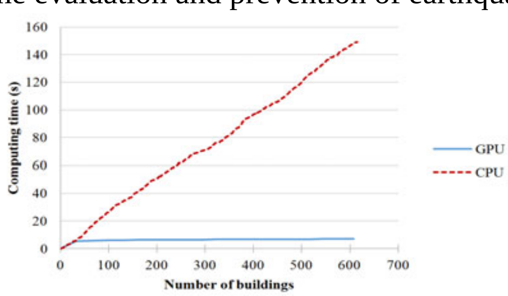

Figure 4. Relationship between computing time and number of

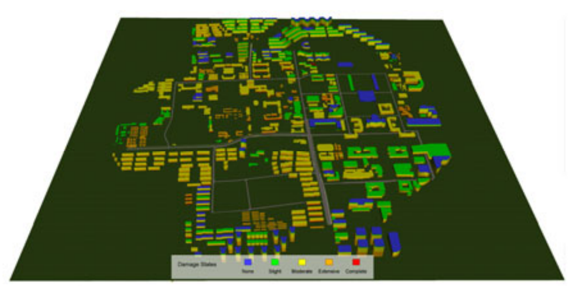

Figure 5. Global view of seismic damage prediction in Tsinghua campus.

buildings.

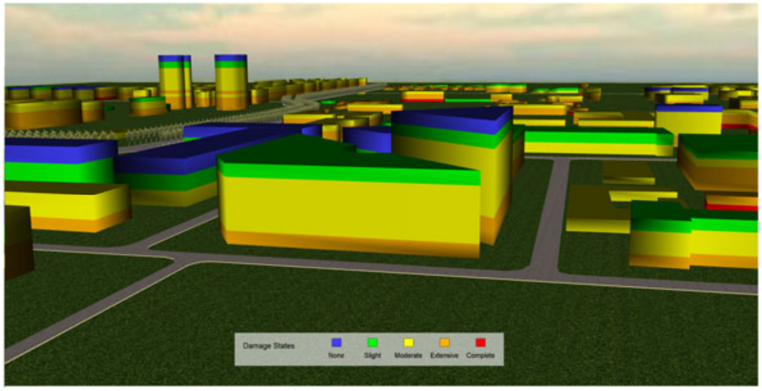

Figure 6. Local view of seismic damage prediction in Tsinghua campus.

CONCLUSIONS

In this study, a methodology for regional seismic damage prediction is proposed, based on high-performance GPU computing, and a case study of Tsinghua University campus is investigated. The case study indicates that the computing efficiency of the proposed method is very high. The GPU to CPU performance-to-price ratio can reach 21.2 for the case of Tsinghua campus, and this ratio will increase for higher numbers of buildings, which means it is a highly efficient seismic damage prediction method for large cities. Based on the proposed method, the seismic damage of the entire campus is predicted efficiently, and the local damage values of different stories are obtained explicitly. This study serves both as a critically important reference and as technical support for urban earthquake-induced disaster prevention and mitigation.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support received from the National Key Technology R&D Program (No. 2013BAJ08B02), the National Nature Science Foundation of China (Nos. 51308321, 51178249, 51222804), and China Postdoctoral Science Foundation (2013M530632).

REFERENCE

Federal Emergency Management Agency (FEMA). (2012). *Multi-hazard loss estimation methodology HAZUS–MH 2.1 advanced engineering building module (AEBM) technical and user's manual*, Washington, D.C.

Gonzalez-Huizar H., Velasco A.A., Peng Z.G., and Castro R.R. (2012). "Remote triggered seismicity caused by the 2011, M9.0 Tohoku-Oki, Japan earthquake." *Geophys. Res. Lett.*, 39(10), L10302.

Hori M. (2011). *Introduction to computational earthquake engineering (2nd ed.)*. Imperial College Press, London.

Lee V.W., Kim C., Chhugani J., Deisher M., Kim D., Nguyen A.D., et al. (2010) "Debunking the 100X GPU vs. CPU myth: an evaluation of throughput computing on CPU and GPU." Proc., 37th Annual International Symposium on Computer Architecture, ACM, New York, NY, USA.

Lorito S., Romano F., Atzori S., Tong X., Avallone A., McCloskey J., et al. (2011). "Limited overlap between the seismic gap and coseismic slip of the great 2010 Chile earthquake." *Nat. Geosci.*, 4, 173–177.

Lu X., Lu X.Z., Guan H., and Ye L.P. (2013). "Collapse simulation of reinforced concrete high-rise building induced by extreme earthquakes." *Earthq. Eng. Struct. D.*, 42, 705–723.

Lu X.Z., Han B., Hori M., Xiong C., and Xu Z. (2014). "A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing." *Adv. Eng. Softw.*, 70, 90–103.

NVIDIA. (2013). "CUDA Programming Guide." http://docs.nvidia.com/cuda (Dec. 5 2013)

Owens J.D., Luebke D., Govindaraju N., Harris M., Krüger J., Lefohn A.E., et al. (2007). "A Survey of General-Purpose Computation on Graphics Hardware." *Comput. Graph Forum* 26, 80–113.

Sanders J., and Kandrot E., (2010). *CUDA by Example: An Introduction to General-Purpose GPU Programming*. Addison-Wesley, Boston, MA, USA.

Steelman J., and Hajjar J. (2009). "Influence of inelastic seismic response modeling on regional loss estimation." *Eng. Struct.*, 31(12) 2976–2987.

Tang B.X., Lu X.Z., Ye L.P., and Shi W. (2011). "Evaluation of collapse resistance of RC frame structures for Chinese schools in seismic design categories B and C." *Earthq. Eng. Eng. Vib.*, 10(3), 369–377.

Wijerathne M., Hori M., Kabeyazawa T., and Ichimura T. (2013). "Strengthening of parallel computation performance of integrated earthquake simulation." *J. Comput. Civil Eng.*, ASCE 27, 570–573.

Xu Z., Lu X.Z, Guan H., Han B., and Ren A.Z. (2013). "Seismic damage simulation in urban areas based on a high-fidelity structural model and a physics engine." *Nat. Hazards*, DOI: 10.1007/s11069-013-0972-8.

Ye L.P., Lu X.Z., and Li Y. (2010). "Design objectives and collapse prevention for building structures in mega-earthquake." *Earthq. Eng. Eng. Vib.*, 9(2), 189–200.